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صاحب السمو الشيخ تميم بن حمد آل ثاني

أمير دولة قطر

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كلمة سعادة وزير البيئة والتغير المناخي

تهتم دولة قطر في ظل التوجيهات السامية لحضرة صاحب السمو الشيخ تميم بن حمد آل ثاني أمير البلاد المفدى – حفظه الله ورعاه – بدعم وتعزيز البحث العلمي والابتكار، حيث بذلت دولة قطر جهوداً كبيرة في تطوير التعليم والبحث العلمي، وذلك من خلال بناء ثقافة وبيئة متكاملة للبحث العلمي والابتكار والتطوير، بالإضافة إلى استثمارات واسعة في البنية التحتية لقطاع البحوث العلمية والابتكار وبناء شراكات علمية مع مراكز بحوث عالمية حققت إشادة واعترافا عالميا بمخرجات البحوث العلمية والتطبيقية القطرية.

ومن هذا المنطلق فقد اهتمت وزارة البلدية والبيئة سابقا بالبحوث العلمية التطبيقية التي تساهم في معالجة العديد من التحديات التي تواجهها الوزارة في قطاع البيئة والزراعة والثروة الحيوانية والسمكية والمدن الحضرية المستدامة وغيرها. كما تشجع الوزارة الباحثين بإجراء البحوث العلمية الهادفة لأنها الوسيلة الناجعة لنشر العلم والمعرفة بين افراد المجتمع.

لذلك فقد أنجز فريق البحث العلمي برئاسة وزارة البلدية والبيئة سابقا بحثاً علمياً حول انتاج أحجار بناء معاد تدويرها من المخلفات الانشائية وهي من التحديات البيئية التي عالجت تراكم هذه المواد الملوثة للبيئة، وبالتالي استطاعت الوزارة باستخدام مخرجات هذا البحث بإصدار مواصفة قياسية قطرية والتي تعتبر الأولى من نوعها في هذا المجال، بالإضافة الى اعتماد اشتراطات ومعايير فنية لاستغلال هذه الثروة الوطنية بدلا من استيراد أحجار بناء من الخارج.

ومناسبة اصدار هذا الكتاب العلمي أود أن أتقدم بالشكر الجزيل لفريق البحث العلمي الذي انجز هذا العمل الكبير وضمّنه جميع المعلومات والبيانات العلمية والفنية والتقنية والتي استغرقت أكثر من ثلاث سنوات، كما اود أن اشكر أيضا الصندوق القطري لرعاية البحث العلمي بمؤسسة قطر على اشرافه وتمويله هذا البحث وتعاونه الدائم مع وزارة البلدية والبيئة، والشكر موصول الى جميع الجهات الحكومية والأكاديمية والقطاع الخاص الذي تعاون مع فريق البحث العلمي في هذا البحث الهام والذي يتماشى مع رؤية قطر 2030.

والله ولي التوفيق

سعادة الشيخ الدكتور فالح بن ناصر آل ثاني

وزير البيئة والتغير المناخي

كلمة سعادة وزير البلدية

أن دولـة قطـر في ظـل القيـادة الحكيمـة لحـضرة صاحـب السـمو الشـيخ تميـم بـن حمـد آل ثـاني، حفظـه اللـه ورعـاه، حريصـة كل الحـرص عـلى حمايـة البيئـة وتوازنهـا الطبيعـي، تحقيقـا للتنميـة الشـاملة والمسـتدامة لـكل الأجيـال، حيـث وضعـت التنميـة البيئيـة كإحـدى الركائـز الأربعـة لرؤيـة قطـر الوطنيـة 2030.

وتعمـل وزارة البلديـة ووزارة البيئـة جاهـدة لتعزيـز حمايـة البيئـة واسـتدامتها مـن خـلال تنفيـذ العديـد مـن المشـاريع والمبـادرات لتحقيـق الأهـداف الاسـتراتيجية البيئيـة. كـما تـولي الـوزارة اهتمامـا بالغـا بالبحـث العلمـي باعتبـاره السـبيل الوحيـد للتعلـم والمعرفـة في مختلـف المجـالات وبالأخـص الاسـتدامة البيئيـة، وبالتـالي تشـجّع الباحثـين والمختصـين عـلى إجـراء البحـوث العلميـة والعمليـة الهادفـة والقابلـة للتطبيـق بحيـث تنعكـس عـلى تطويـر مشـاريع وخدمـات الـوزارة.

ومـن هـذا المنطـلق، فقـد نفّـذ فريـق البحـث العلمـي برئاسـة وزارة البلديـة والبيئـة سـابقا بحثـاً علميـاً حـول معالجـة مشـكلة المخلفـات الإنشـائية وغيرهـا، لإنتـاج الأحجـار والمـواد المعـاد تدويرهـا واسـتغلالها الاسـتغلال الأمثـل في مشـاريع المبـاني والطـرق، لخدمـة الوطـن والمجتمـع في قطـر، تنفيـذا للاسـتراتيجية الشـاملة للـوزارة في التعامـل مـع كافـة أنـواع النفايـات سـواء الناتجـة عـن المواقـع السـكنية أو التجاريـة أو الصناعيـة، أو قطـاع البنـاء والتشـييد وغيرهـا.

وبهـذه المناسـبة، أشـيد بالجهـود التـي بذلهـا فريـق البحـث العلمـي في انجـاز هـذا العمـل الهـام، وكذلـك في إعـداد وإصـدار هـذا الكتـاب عـن « تنفيـذ الأحجـار المعـاد تدويرهـا في أعـمال البنـاء» والـذي يُعتـبر أحـد المشـاريع والمبـادرات العلميـة التـي ستسـاهم في دعـم وتعزيـز جهـود الـوزارة في مجـال حمايـة البيئـة وتحقيـق التنميـة المسـتدامة لدولـة قطـر.

والله ولي التوفيق

سعادة الدكتور عبدالله بن عبدالعزيز بن تركي السبيعي

وزير البلدية

Disclaimer

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Preface

The purpose of the book is to support the government strategy of sustainable development through the effective implementation of recycled aggregates in construction. The Qatar National Vision 2030 reinforces sustainable development and places great emphasis on preserving and protecting the environment, as one of four pillars of national development, alongside social, economic and human development. With the vast investment made in infrastructure projects, the government set targets for the efficient use of natural resources, with a recycling target to use 20 % of recycled aggregate to replace primary aggregate in government construction projects by 2022. Government initiatives for facilitating the implementation of recycling included the development of relevant standards and specifications, guidelines, and manuals that permit the use of recycled aggregate in various construction applications, and a consistent supply of recycled aggregates at regulated prices.

The use of recycled aggregate in Qatar and the Gulf region is relatively new, and can make significant contribution to the vast infrastructure development witnessed over the last decade. Lack of experience with recycled aggregates in the aggressive conditions of the Gulf, particularly lack of long-term performance data, have raised concerns on the durability and long-term performance of recycled aggregate in service, as compared to primary aggregates.

The approach adopted in the book is to use practical evidence, based on site data in real exposure conditions up to 5 years in service, for the performance assessment of recycled aggregates. Recycled and alternative aggregates were used to replace primary aggregate at different proportions is various construction applications of asphalt, concrete and unbound granular products. The assessment was based on the basis that the construction products made with recycled and alternative aggregate should give at least equivalent performance to that of conventional construction products made with primary aggregate. The cost and environmental benefits associated with the use of local recycled and alternative aggregate materials are also presented. An innovative water footprint study was carried out to review the use of water by the construction industry in Qatar, and how it can be used most effectively. Recommendations are made for the wider and more efficient implementation of recycled aggregate in construction.

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The Ministry of Municipality and Environment (MME): for the continuous support received from the different departments; especially the Research Office, at the various stages of the project.

Public Works Authority (Ashghal): for providing valuable information and access to sites data, and conducting the testing of recycled aggregate and products at the Ashghal Centre for Research & Development.

Qatar Primary Materials Company (QPMC): for the information provided on the production and uses of recycled aggregate, and their support to the MME workshops made on recycled aggregates for producers and users.

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Contents

1 Introduction

The construction boom witnessed in Qatar over the past two decades is associated with increased consumption of materials and intensive use of energy. With sustainability being the main factor in its 2030 National Vision (GSDP, 2008), the government set targets to balance between development needs and protection of the environment. The use of recycled materials in construction contributes to sustainable development. It enables conservation of primary materials and reduces accumulated wastes in landfill sites, with cost savings and lower energy consumption.

Over the last two decades, the government has placed great emphasis on sustainability and set its national vision and national development plans with targets across the different sectors. Specifications, guidance documents, and manuals have been published to support recycling, but limited information is available on the performance of recycled materials in service, in real exposure conditions. This document presents information on the performance of recycled materials in service, including a range of recycled materials in various construction applications. It reviews the government strategy for sustainable development with set recycling targets by 2022, the recycling roadmap and manual developed by the Public Works Authority (Ashghal), together with relevant recycling standards and specifications. The performance of various recycled aggregate materials up to 5 years in service is reported with comparison to conventional construction materials and recommendations are given for the wider and more efficient use of recycled materials in construction.

Most of the work presented in this document is part of a research project funded by the Qatar National Research Fund (QNRF) project NPRP 7 – 795 – 2 - 296 on the "Innovative use of recycled aggregate in construction – Implementation". The project was delivered by a consortium led by the Ministry of Municipality and Environment (MME) in collaboration with Infrastructure Research and Development (IRD) at the Qatar Science & Technology Park (QSTP), the Quality and Safety Department (QSD) at the Public Works Authority (Ashghal) and key stakeholders in the construction industry. The project commenced in May 2018 and was completed in 3 years. The recycling implementation project builds up on the outcomes developed in an earlier QNRF project NPRP 4 – 188 – 2 – 061, and documents including the first Qatar Standards on recycling (QS 29, 2012), the fifth edition of the Qatar Construction Specifications (QCS 2014), and the first Gulf Cooperation Council (GCC) Standardisation Organisation for recycling (GSO 2489, 2015).

Construction in hot desert areas poses many challenges (Walker 2012; Fookes and Lee 2019). As well as the difficulties of dealing with excessive heat and humidity for large parts of the year, ground conditions are often aggressive, with high sulfate and chloride contents, weak or unstable soils and rocks and a high water table. This is particularly the case in coastal areas, such the Arabian Gulf, which is often where the largest cities are located. Additional problems are caused by the lack of suitable aggregates in such areas, such as the case in Qatar. Bedrock often consists of geologically young limestone which are often weak and subject to solution cavities, interbedded with bands of potentially expansive clays and gypsum (Fookes and Higginbottom 1980). These challenges have raised concerns on the durability of recycled aggregate and how they will perform in the long-term under such aggressive exposure environments.

The approach adopted in the book for assessing the long-term durability is based on site performance of recycled aggregate, up to 5 years in service. Monitoring of site performance is essential to demonstrate that the new material or product, made with recycled aggregate, can be applied in a practical context, especially in aggressive exposure environments, such as in Qatar and the Gulf region. The remarkable diurnal and seasonal humidity and temperature variations, coupled with strong winds carrying moisture and salts, create one of the most severe exposure environments for construction materials. It was essential to demonstrate the durability of recycled aggregate in service and to compare its performance to conventional construction products made with primary aggregate materials. Such an approach offers a practical validation of the performance of recycled aggregate in real exposure conditions, and provides confidence for the industry to implement in practice.

The government strategy for sustainable development is presented in chapter 2, together with the government initiatives to support the implementation of recycling in construction projects. The 20% recycling target set by 2022 is discussed within the context of guidance documents on the appropriate selection of recycled aggregate for different construction applications and national standards and specifications (QCS 2014), including the Ashghal Recycling Manual (Ashghal, 2021). The government commitment for the sustainable supply of recycled aggregate is also presented to support effective implementation in practice. Chapter 3 covers the main local and recycled aggregate materials, with basic properties and potential use in various construction applications.

Chapters 4 to chapter 7 provide case studies on the successful performance of recycled and alternative aggregate materials in various construction applications of asphalt, concrete, road base and subbase material, and pipe beddings. The site performance of bound and unbound recycled aggregate materials was assessed up to 5 years in service, and compared to conventional construction materials, made with primary aggregate. When the application is relatively new to Qatar, such as cement bound materials, mix designs were initially developed in the laboratory and selected mixtures were used in field investigation for assessing the performance of recycled materials.

With the high priority placed by the government on sustainable development, chapter 8 presents the environmental and economic benefits associated with the use of recycled aggregate in construction. Carbon and water footprints calculations are conducted on primary and alternative / recycled aggregate sources and aggregate derived products, including asphalt and concrete. The government approach of regulating the prices of both primary and recycled aggregates is also presented in chapter 8. Chapter 9 provides recommendations on the wider utilisation of recycled aggregate in construction towards a more efficient implementation of recycling in construction projects.

The book informs practitioners on best practices for selecting appropriate materials and methods for replacing primary materials, while maintaining at least similar performance to conventional materials. It is of interest to engineers, clients, contractors, producers, suppliers, consultants, and others involved in the specification and design of construction projects. The aim is to complement existing documents on recycling and provide more details on their performance in service, with associated environmental benefits, to enable wider and more efficient use of recycled materials in construction, and to achieve the desired recycled targets.

2 Government Strategy and Support to Recycling

2.1 Qatar National Vision 2030

The Qatar National Vision (QNV) 2030 has been effective since 2008 and aims to transform Qatar into an advanced society capable of achieving sustainable development by 2030 (GSDP, 2008). The importance of sustainability was clearly reflected within its four pillars of human, social, economic and environmental development. The latter is defined as a balance between development needs and protection of the environment. Main environmental issues considered in the QNV 2030 were diminishing water and hydrocarbon resources and the potential impact of global warming. The QNV 2030 provided the foundation for the formulation of national strategies for setting and prioritising development goals and time-bound targets. The QNV 2030 logo is presented in Figure 2-1, where the central element is designed in the form of an eye for the vision. The traditional culture and map of Qatar are also presented in the middle of the logo, to reflect development progress while preserving national culture.

Figure 2-1 QNV 2030

2.2 Qatar Second National Development Strategy (NDS-2, 2018-2022)

The Qatar National Development Strategy 2011-2016 (NDS-1), the first comprehensive development strategy in Qatar, was developed in 2011 (GSDP, 2011) and provided details on how to implement the government vision of QNV 2030. One of the main achievements of the NDS-1 is that it created a national culture of development planning across all government entities and development stakeholders. The second NDS-2 (2018-2022) was issued in 2018 as a continuation of the NDS-1 and aiming to achieve the goals and aspirations of QNV 2030, ensuring and maintaining commitment of the implementing agencies, and highlighting the achievements and lessons learned from the NDS-1 (PSA, 2018). One of the main success factors emphasised in the NDS-2 for preserving the environment is the efficient use of natural resources and recycling, which will be discussed in more detail in the following sections.

2.2.1 *Solid Waste*

Waste generation in Qatar has been identified as one of the most pressing environmental problems, mainly due to the increasing rate of generation from infrastructure development projects. The importance of waste management and recycling were addressed from the early NDS-1 for sustaining the environment. Solid waste was identified as the main waste stream and the waste hierarchy was endorsed as the guiding principles for waste management, with avoiding producing waste at the top of hierarchy and waste disposal to landfill as the least preferred option. A recycling target of 38% was set in the NDS-1 with another target for limiting the domestic waste generation to 1.6 kg per capita per day. Feedback from the NSD-2 indicated that the NDS-1 focused mainly on domestic waste, and the recycling target of 38% was too ambitious to achieve. However, the domestic waste generation was maintained at 1.3 kg per capita per day, below the set target of 1.6 kg per capita per day.

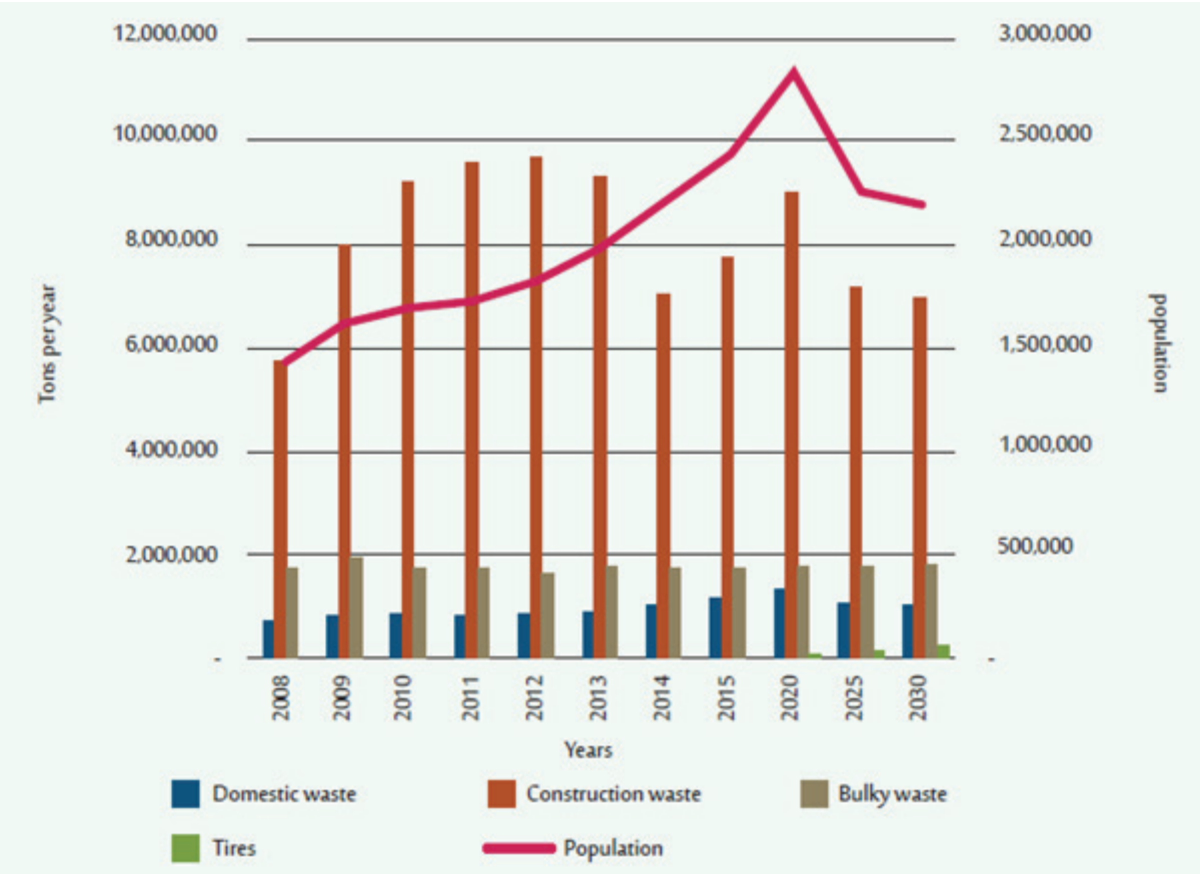

Figure 2-2 Historic and projected waste generation (NDS-2)

The QND-2 recognised construction waste as the largest component of solid waste and provided information on quantities of total waste generation since 2008 up to the projected future scenario to 2030, Figure 2-2. The total solid waste generated increased from approximately 8.0 million tonnes (Mt) in 2008 to reach the first peak of 12 Mt in 2012-13. The rate then reduced in 2014 to just over 8.0 Mt, followed by a second peak of 10.0 Mt in 2020. Beyond the 2020, the rate of waste generation is expected to decline as the infrastructure work for the FIFA 2022 World Cup is near to completion. However, construction waste will remain the largest generation with estimated quantities of 6.0 to 7.0 Mt/y.

The NDS-2 accounted for construction waste to constitute approximately 80% of solid waste generation across the country, with estimated stockpiles of 80 to 100 Mt accumulated in landfill sites, similar to figures reported earlier by Hassan et al. (2015). Considering the large quantities of solid and construction wastes generated in Qatar every year, the NDS-2 set the following national targets for recycling:

- Solid waste: Recycle 15% of the total solid waste generated by the end of 2022.
- Construction waste: Increase the proportion of recycled materials in projects to 20% of the total materials used by 2022.

The NDS-2 acknowledged the existing recycling activities in the construction industry and set the target to increase recycling levels to 20% by the end of 2022. The main solid waste materials identified in the NDS-2 with potential recycling in construction are:

- Construction and demolition waste (CDW)
- Excavation waste (EW)
- Wadi gravel aggregate
- Steel slag aggregate

The increased recycling target for construction waste, compared to solid waste, is mainly due to the large quantities of materials and the high demand in construction projects. The use of local recycled materials to replace expensive imported aggregate would also have economic and environmental benefits to further support the government strategy of sustainable development. More information on the reduction of logistics burden and energy consumption associated with the use of local and recycled materials, compared to imported materials, are presented later in the document.

2.2.2 Energy and Water

Energy and water were identified within the main success factors for preserving the environment. Qatar is the largest supplier of liquefied natural gas, and holds the World's third largest natural gas reserves, but lacks fresh water. There are no rivers or lakes to provide fresh water supply, with a very hot tropical climate and low rainwater rate (80 mm/year).

Infrastructure projects constitute the largest share of the government expenditure. According to the Qatar Ministry of Finance (MOF, 2021) a budget of QR 72.1 billion has been allocated for major projects in the 2021 Budget, with priority spending on major infrastructure projects including highways and local roads; advanced sanitation networks; and road beautification. The NDS-2 set targets for the production and use of renewable energy and reduction of emissions for different industries, but no specific target was set for the construction industry. The use of construction materials that have low embodied carbon, such as the recycled materials listed above, will have less impact on the environment and climate change than imported primary aggregates.

The NDS-2 also encouraged the controlled usage of desalinated water and more use of alternative TSE water. It was reported that approximately 194 million m^3 of Treated Sewage

Effluent (TSE) water was generated in 2015, with only 50% used in irrigating and animal feed farms. The NDS-2 set a higher target to use 70% of the TSE water in different projects by 2022.

Water is widely used in the construction industry in various applications including washing of aggregate, mixing and compaction of various products. Currently this water is largely potable water from desalination plants. Thus introducing TSE into the construction industry will provide a sustainable and cheap solution for conserving natural water, with positive impact on the environment. An innovative water footprint study was accomplished to review the use of water by the construction industry in Qatar, and how it can be used most effectively. This is reported in section 8.3.

2.3 MME Recycling Initiatives

The Ministry of Municipality and Environment (MME) is the government entity entrusted with managing solid waste materials in Qatar. They have responsibilities for supervising the solid waste plants, waste collection, transfer stations, and waste landfill sites. The MME implements the government plan of solid waste management and treatment, in order to maintain safe environment for the community to achieve sustainable development. Construction and municipal solid wastes are the main solid waste materials managed by the MME, and both materials have the potential for use in construction as discussed in section 3.

Construction waste is by far the largest volume of solid waste materials generated in Qatar, and the majority of the material is dipped in a landfill site in Rawdat Rashid, approximately 30 km from the centre of Doha. Currently, approximately 8Mt of construction waste materials are generated every year, and the rate is expected to reduce to 6.0-7.0 Mt/y over the next decade, Figure 2-2, but remains the highest volume of solid waste generation.

Figure 2-3 MME and QPMC recycling agreement (Qatar Tribute, 30 Dec 2019)

Various contractors were appointed by the MME for managing the construction waste at Rawdat Rashid over the last decade. Each contract agreement was set for a period of 4 years, and the appointed contractor managed, with some success, to process part of the stockpiled materials in Rawdat Rashid and sold the products to the construction industry. However, due to the relatively short-term contract, none of the previous contractors invested heavily in the equipment for the appropriate processing of construction waste materials.

The latest recycling agreement was signed at the end of December 2019, between the MME and the Qatar Primary Materials Company (QPMC) for the recycling of construction waste recycling at Rawdat Rashid landfill site, Figure 2-3. The agreement aims to provide a local supply of recycled aggregate, reduce reliance on imported aggregate, rehabilitate and clean the Rawdat Rashid site to support sustainable development and protection of the environment. The recycling agreement also served to support one of the government objectives of Public-Private Partnership (PPP), by allowing the private sector to participate in the implementation of waste processing and handling to convert into high-value recycled products for use in infrastructure and construction projects. More details on this agreement and the supply of recycled aggregate are provided later in this chapter.

Domestic waste is generally collected by the local authorities, whereas the MME disposes the collected waste either by recycling or dumping in landfills. Waste recycling is carried out in an Energy-from-Waste plant at the Domestic Solid Waste Management Centre (DSWMC), located near Mesaieed to the south of Doha. The plant has the capacity to treat 2,300 kg of mixed domestic solid waste per day. The treatment includes mechanical separation and combustion. The larger size materials (>40mm) are subjected to further separation using magnets, whereas the undersize materials (<40mm) are mostly organic that are incinerated to produce ashes. Incinerator bottom ash (IBA) has the potential for use as aggregate in selected construction applications (Hassan et al., 2020a).

2.3.1 Recycling Guidelines

In 2016, the MME published a book entitled "Recycled Aggregate in Construction – Qatar Experience" in recognition of the outcomes of the QNRF NPRP 4-188-2-061 project. The project "Innovative use of recycled and secondary aggregates in construction" was led by the UK-TRL in collaboration with the MME, Qatar Standards, Ashghal, and key representatives from the construction industry. The project was delivered between 2012 and 2015, and demonstrated collaboration between research institutions, government authorities and the construction industry to achieve the government strategy of sustainable and green construction (Hassan et al., 2016). The project outcomes contributed to the development of the first national specification in the Middle East and North Africa (MENA) on the use of recycled aggregates in construction.

The project began with a survey to identify the main types of waste materials available in Qatar with potential for use in construction. Construction and demolition waste (CDW) and excavation waste (EW) were by far the biggest potential sources of recycled aggregates, with smaller amounts of steel slag, tyre rubber, and IBA. Wadi gravel aggregate was also identified as a by-product material, from sand washing plants, with potential use in concrete (Hassan et al., 2020b).

A comprehensive laboratory investigation was conducted to assess the properties of each recycled material, and suitability for use in a range of construction applications. Mix designs were prepared with different proportions of recycled aggregate, replacing primary materials, and tested for compliance with the relevant Qatar Construction Specifications. Selected mixtures, with at least similar performance to conventional aggregate, were used for full-scale site trials to assess their practical applications and performance in service. Two site trials were constructed. In the first, three buildings were constructed to test the performance of recycled aggregates derived from EW, CDW, and IBA as partial replacements for imported aggregate in structural concrete and concrete blocks. The second trial used EW and recycled concrete aggregate (RCA) as unbound subbase in a new road construction.

Based on the project outcomes, a matrix was developed to guide practising engineers on the potential suitability of the recycled aggregates for use in various construction applications. Table 2-1 presents an updated matrix, based on the matrices given in the MME book (Hassan et al., 2016). In addition to the MME book, a guidance document on the use of recycled aggregates was also published by the project team (Hassan et al., 2015). The outcomes of these particular projects, and other related projects, have made a significant contribution to the development of recycling specifications in Qatar.

Table 2-1 shows that aggregates produced from EW and CDW are suitable for use in almost all applications, provided they comply with the relevant specification, with the exception of asphalt wearing course applications. Both EW and CDW are unlikely to provide the high abrasion resistance required for the wearing surfaces. The percentage limit of recycling in structural and non-structural concretes was intended for gradual implementation in high value applications, with the aim to raise the recycling levels as the industry developed more experience with the use of the materials. Reclaimed asphalt pavement (RAP) was not considered as a separate recycled material in the recycling guidelines, but as part of the CDW. With the development of large quantities of RAP, the material has received more attention from Ashghal as discussed later in Section 2.5.

Wadi gravel was considered suitable for concrete and pipe bedding applications, but the material was not recommended for use in pavement as bound or unbound layers. Wadi gravel with its smooth surface texture and spherical particle shape make it unsuitable to provide aggregate interlock and high stiffness required for pavement layers. Therefore, the material was recommended for concrete mixtures as it improves workability and drainage in pipe bedding. The crumb rubber was mainly identified for use in hot asphalt mixtures of wearing, binder and base courses. The use of IBA was recommended for unbound pavement application and concrete blocks, but not in high value applications of asphalt and concrete. Steel slag was not included in the recycling guidelines due to the government restriction on its use in construction. Its use was only considered after Qatar Standards issued a No Objection Letter for the restricted use of steel slag in construction.

Table 2-1 Suitability of recycled aggregate for use in construction (Based on Hassan et al., 2016)

Material	Unbound applications					Asphalt mixtures		Concrete applications		
	Fill	Subgrade	Subbase	Road base	Pipe bedding	Asphalt base/binder	Wearing course	Structural concrete	Non-structural concrete	Blocks
Excavation Waste (EW)	√	√	√	√	√	NP	X	20%	50%	√
Construction & Demolition Waste (CDW)	√	√	√	√	√	NP	X	20%	50%	√
Reclaimed Asphalt Pavement (RAP)	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Wadi gravel (WG)	X	X	X	X	√	X	X	NP	√	√
Crumb Rubber (CR)	NP	NP	NP	NP	NP	√	√	X	X	NP
Steel Slag (SS)	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Incinerator Bottom Ash (IBA)	√	√	√	√	X	X	X	X	X	√

Key

√	Suitable for the application if it complies with the specification
X	Not suitable for the application
%	Suitable with a maximum level of replacement of primary aggregate
NP	Not proven, further work is required

2.4 Qatar Construction Specification

The Qatar Construction Specification (QCS) is a regulatory document that is updated periodically to improve the use of construction materials and construction practice. It is issued by the Qatar General Authority for Standardisation and Metrology (QGASM), Qatar Standards, and is managed by a National Committee representing key stakeholders in the construction industry. Under the QCS National Committee, there are twelve specialised subcommittees that are working on reviewing and updating specific sections of the QCS, such as concrete, road works, quality assurance and quality control, green construction, drainage, health and safety, etc. Any change made to the QCS, either developing a new specification or updating an existing specification, is generally based on a pilot trial for up to 2 years to ensure suitability for local conditions. This practical approach is essential, especially for new recycled materials or products, to assess performance in service before adopting in the national construction specifications.

Various site trials were constructed in Qatar within the last decade to demonstrate the use of recycled materials in various construction applications. As a result the fifth edition of the QCS, published in 2014, allowed the use of recycled materials in a range of construction applications including earthworks, unbound materials, asphalt and concrete (QCS 2014). In some applications, there is a limit on the maximum amount of recycled materials, such as 20% in coarse aggregate for structural concrete (QCS 2014: Section 2: Part 2).

The QCS 2014 requirements for the use of recycled materials in various construction applications are generally similar to those for primary aggregates. This is the case for unbound material such as fill, subgrade, subbase and base applications. In some cases, relaxed requirements are made for recycled aggregate, such as increased values of water absorption of recycled aggregate compared to primary aggregate for structural and non-structural concrete applications. Such relaxation is based on laboratory and site data that confirmed at least similar performance of the recycled materials compared to conventional primary aggregates (Hassan et al., 2015). As the composition of recycled materials could vary from those of primary aggregates, the QCS 2014 provides additional tests that are specifically required for recycled aggregate, such as constituent and floating materials of recycled materials for use in concrete.

The QCS is considered as the minimum requirements that apply to national projects, including high rise buildings, major roads, as well as small private buildings. Developing general specifications for such a range of construction projects is rather complicated. However, a choice is always provided to the clients or their representatives to raise the limits above the minimum specified in the QCS to produce desirable products. For example, the QCS 2014 specifies a maximum limit of 20% recycled materials in structural concrete, with the permission to use a higher proportion when approved by the relevant authority. Such relaxation in national specifications is intended to lead to aimed at innovation and wider implementation of recycling provided they meet with the desired end-product specifications.

The QCS 2014 is the first national specification in Qatar and the GCC region to permit the use of recycled aggregate in various applications. It made a positive change in the construction industry towards sustainability and provided a route for implementing recycling, especially with the shortage of local quality aggregate in Qatar. The recycling specification of the QCS

2014 was also adopted in 2015 as the first GSO Standardization Organisation “Specifications of Recycled Aggregates from Construction Waste to be used in Construction Work” (GSO 2489, 2015).

Work by the QCS National Committee and subcommittees continued beyond 2014, with further updates and wider use of recycled materials for the development of the next QCS edition. Draft versions of the QCS 2018 have been developed and have gone through continuous updates, with the aim of publishing in the near future.

2.5 Ashghal Implementation of Recycling

The Public Works Authority (Ashghal) is the government authority responsible for the design, construction, delivery, and asset management of all infrastructure projects and public buildings in Qatar. The successful delivery of Ashghal projects is essential to support the economic and social development process required to achieve the Qatar Vision 2030 and to host the 2022 FIFA World Cup. Ashghal projects are also the main consumer of aggregate and other construction materials in Qatar.

2.5.1 Ashghal Recycling Roadmap

In line with the government initiatives, and due to the delay in publishing the QCS 2018, Ashghal initially issued a roadmap for recycling initiatives to allow a wider use of recycled materials in road projects (Ashghal, 2018). The recycling approach developed by Ashghal was based on collecting construction waste, from demolished Ashghal projects, and processing them for reuse in new projects. This approach is in line with the NDS-2 to achieve the recycling target in government construction projects. Table 2-2 lists the main recycled materials and applications considered in the Ashghal recycling roadmap. The aim of the Ashghal recycling roadmap was to recycle 100% of all construction waste in 18 months, as shown in Figure 2-4.

Table 2-2 Recycled materials and applications in the Ashghal Roadmap 2018

Application	% Recycled aggregate
Duct, pipe and cable bedding	100%
General fill and select fill materials	30 – 50%
Subgrade materials	50 – 100%
Subbase materials.	30 – 50%
Road Base materials	20 – 30%
Non-structural concrete (20MPa)	100%
Hollow blocks	100%
Paving blocks	100%
Asphalt Base course (BC)	15% Reclaimed asphalt pavement (RAP)
Asphalt Base course (BC)	20% Steel slag

For effective implementation, the Ashghal Recycling Roadmap highlighted the importance of including recycling in future tenders and contracts, outsourcing the operation of processing facilities, and pilot projects to demonstrate the use of recycled materials in various applications. The Ashghal Roadmap provided guidance on the proportion of recycled materials for use in various applications. For asphalt works, the Ashghal Recycling Roadmap focused on reclaimed asphalt pavement (RAP) and steel slag for use in base course. No information was provided on the quantities of construction waste, generated form old projects, and the recycling level to be achieved within 18 months schedule. However, the Ashghal Recycling Roadmap provided a clear message to contractors and suppliers on the planned changes for the use of recycled aggregate and alerted them to carry out the required modification for implementing recycling in government projects.

2.5.2 Ashghal Recycling Manual

As a follow up to the recycling roadmap, the Ashghal Recycling Manual was issued in January 2021 by the Ashghal Centre for Research & Development (Ashghal, 2021). The manual looks like a standard document for the use of recycled materials in different construction applications, but with more information on material processing, quality production, and storage of recycled materials. The recycled materials considered in the Ashghal recycling materials, covers those listed in the NSD-2, and include:

- Excavation waste (EW)
- Construction demolition waste (CDW)
- Reclaimed asphalt pavement (RAP)
- Wadi gravel
- Crumb rubber
- Steel slag aggregate

The manual provides technical information on the suitability of each of the above recycled materials in construction applications and permissible levels. A summary of the materials permitted and permissible levels is presented in Table 2-3. The manual also provides a register log of the type and quantities of construction waste generated from different projects, materials transfer to the Ashghal recycling sites, procedures for the processing different wastes, and requirements of recycled aggregate products.

Excavation waste (EW), which is a relatively clean source of limestone aggregate, is permitted for use in all construction applications provided compliance with the aggregate requirements provided in the QCS 2014. Construction demolition waste (CDW) is defined in the manual as material generated from concrete structures. There is no clarity on whether the CDW is purely recycled concrete aggregate (RCA), as defined in the QCS 2014 Section 5: Part 2, or mixed with other foreign materials. However, the manual provides additional requirement for the composition of recycled aggregate as described later in this section. Similar to EW, CDW is permitted for use at 100% for all unbound applications, with the exception of subbase and road base applications. The Ashghal manual limits the maximum level of CDW to 50% in subbase and 30% for road base. No explanation in provided in the manual for such restrictions.

Similar to the QCS 2014 for concrete, the Ashghal Recycling Manual limits the contents of foreign materials and lightweight particles in both EW and CDW. As the concrete specifications are based on British and European standards, the amount of foreign materials is determined by the mass fraction and the floating materials by the volume fraction in accordance with BS EN 933-11 (2009). However, the roadwork specifications are based on US standards, and both foreign and lightweight materials are determined for the determination of the percentage high density materials, low density materials, and compressible materials by mass of the recycled materials.

The use of reclaimed asphalt pavement (RAP) is only provided for asphalt base course applications. For up to 15% RAP, there is no modification required to the asphalt mixture. RAP in excess of 15% and up to 30% is permitted but would require a new mix design. RAP is regarded as a valuable source of recycled aggregate as it contributes to the replacement of both gabbro aggregate and bitumen binder. The Ashghal Recycling Manual provides comprehensive information on the milling operation, and handling, processing, and storage at the recycling site. It also provides a revised specification of the QCS 2014 for asphalt mixtures containing RAP, with additional performance requirements based on tensile strength ratio and rut depth.

Wadi gravel aggregate is permitted for use in unbound aggregate application and concrete products at 100% replacement level. Its use in unbound subbase is limited to 50% and 30% for unbound road base. The Ashghal manual also permits the use of Wadi gravel in asphalt work for footways and cycleways. It could be argued that Wadi gravel, with its spherical and round particles, may not be suitable to provide the required aggregate interlock in pavement applications and it should maintain its high value applications in structural and non-structural concrete and pipe bedding (Hassan et al., 2020a). For all applications, Wadi gravel must be thoroughly processed to remove gypsum before use as aggregate (Hassan et al., 2020b).

Crumb rubber is permitted for use in the wearing course of low traffic roads, up to 3 million standard axles, as a binder modifier. The crumb rubber has to be ground to passing 30 mesh size (600 microns) with an application rate of 10% to 25% of the total binder weight. The mix design requirements and performance criteria are set out in the Ashghal manual together with the requirements for processing, handling and storage at the recycling unit.

Steel slag aggregate is permitted in all unbound, non-structural concrete and asphalt base-course applications with a maximum replacement level of 20%. The Ashghal manual was based on the No Objection Letter (NOL) for the use of steel slag aggregate issued by the Qatar Standards in 2013. The processed slag must meet the QCS 2014 aggregate requirements for the desired applications. An additional requirement is the 7-day expansion test, as per ASTM D5106 (2015), for controlling the potential volumetric expansion of the slag aggregate.

In addition to developing a recycling roadmap and manual, Ashghal has set its internal strategy to support the QNV 2030 and NDS-2 on environmental and sustainability objectives. A website was developed for the register of construction waste generated from demolished projects, with a tracking system to identify source and processing unit. Instructions were provided by the Ashghal President to the various Ashghal department to implement recycling at new construction projects with the aim of achieving the NDS-2 recycled target ahead of time.

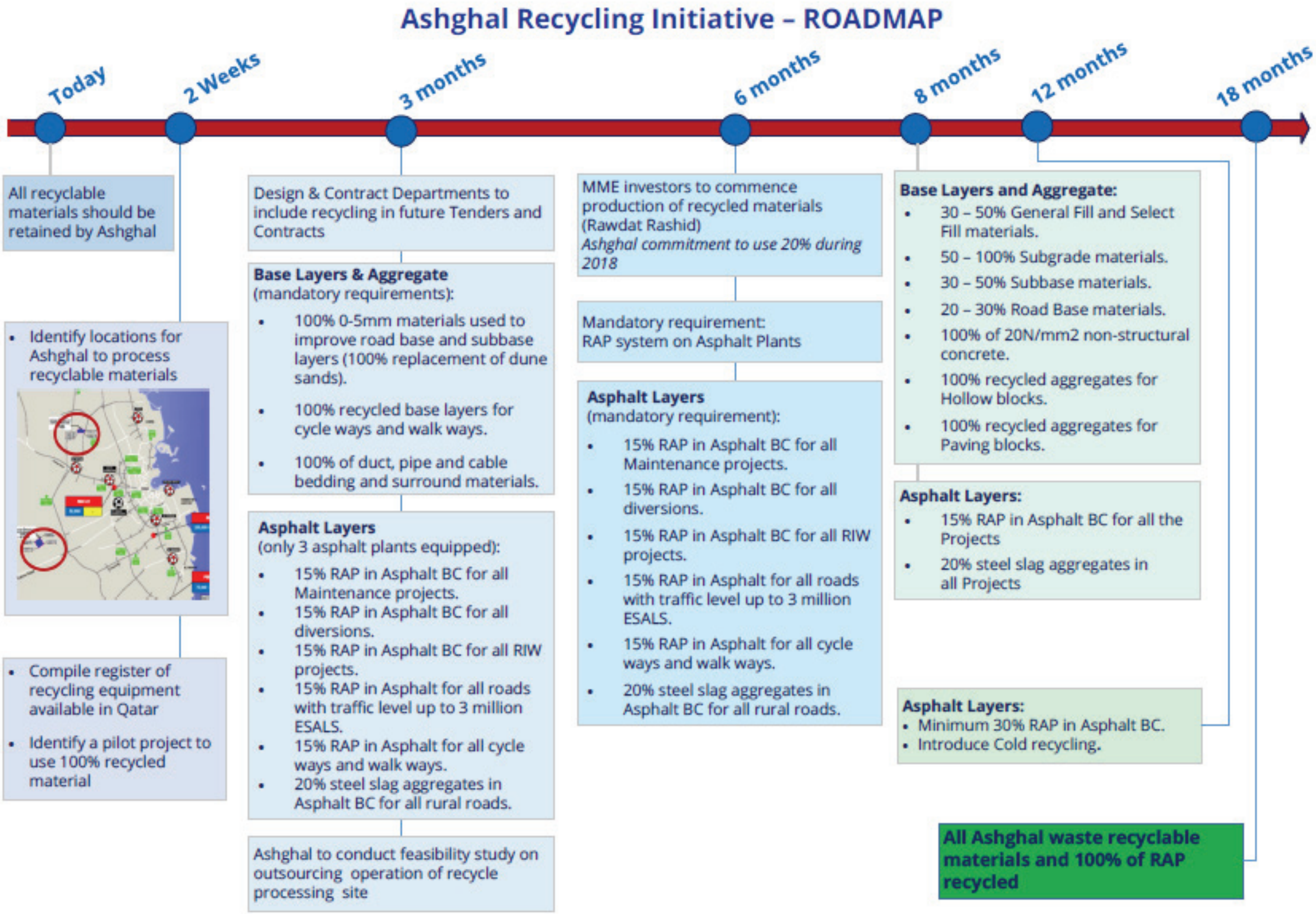

Figure 2-4 Ashghal Recycling Initiative Roadmap (2018)

Table 2-3 Material suitability for use in construction applications – Ashghal Recycling Manual (2021)

Material	Unbound applications					Asphalt mixtures		Concrete applications		
	Fill	Subgrade	Subbase	Road base	Pipe bedding	Asphalt base/binder	Wearing course	Structural concrete	Non-structural concrete	Blocks
Excavation Waste (EW)	√	√	√	√	√	√	X	20%	50%	√
Construction & Demolition Waste (CDW)	√	√	50%	30%	√	-	-	20%	50%	√
Reclaimed Asphalt Pavement (RAP)	-	-	-	-	-	15%	-	-	-	-
Wadi gravel (WG)	√	√	50%	30%	√	√*	√*	√	√	√
Crumb Rubber (CR)	-	-	-	-	-	-	0.15%	-	-	-
Steel Slag (SS)	20%	20%	20%	20%	20%	20%	-	-	20%	20%

Key

√	Suitable for the application if it complies with the specification
X	Not suitable for the application
%	Suitable with a maximum level of replacement of primary aggregate
√*	Suitable for footways and cycleways
-	Not included in the Ashghal Recycling Manual

2.6 QPMC Supply of Recycled Aggregate

There is a need for a sustainable supply of recycled materials to enable their wider use in construction projects and to achieve the government target of 20% recycling in 2022. Developing new specifications, guidance, and manuals alone would not be adequate to cover the high demand for high quality recycled aggregates.

Qatar Primary Materials Company (QPMC) is a government body established in 2006 for the purpose of ensuring the continuous supply of aggregate and other construction materials in the State of Qatar and has been the main supplier of primary aggregate materials for both government and private sector construction projects since the time of its incorporation. QPMC was also entrusted by the government with the sustainable supply of recycled aggregate. A long-term contract of 20 years, effective from January 2020, was set between the MME and QPMC for managing the supply of recycled aggregate from the construction, demolition and excavation waste already deposited at Rawdat Rashid. Similarly, a long-term agreement was set between Ashghal and QPMC for managing the supply of recycled materials generated from the demolition of Ashghal projects and reuse in new projects. A list of the QPMC-managed recycling sites, with estimated quantities and production rates are given in Table 2-4.

Table 2-4 Recycling sites managed by QPMC

Item	MME Site (Rawdat Rashid)	Ashghal Recycling sites			Total
		Umm Al-Zubar	Jary Alsamar	Bu Salba	
Area (million m^2)	7.9	2.3	0.9	1.8	12.9
Stockpiles (Mt)	40.0	12.0	3.0	1.0	56.0
Current production (tonne/month)	60,000	200,000	300,000	100,000	660,000

With the government growing interest in Public-Private Partnership (PPP) to support projects connected to the Qatar National Vision 2030 and Qatar 2022 FIFA World Cup, QPMC set up partnerships with contractors for the production of recycled aggregate. The PPP was set up because of the scale of investment in infrastructure projects and the government's interest in increasing the role of the private sector. Various contractors are currently working with QPMC for the quality production of recycled aggregate in different recycling sites. To ensure quality production and supply, QPMC also appointed a third party of an Ashghal-approved laboratory to continuously check the quality of recycled aggregate and products at source and provide assurance for use. QPMC also provided regulated prices for both primary and recycled aggregate, as discussed in chapter 8. QPMC is currently managing the recycling of construction wastes at:

- MME Recycling site at Rawdat Rashid
- Ashghal Recycling sites: three recycling sites for Ashghal at Umm Al-Zubar, Jary Alsamar and Bu Salba

2.6.1 MME Recycling Site – Rawdat Rashid

The MME site is approximately 8 million square metres, with more than 60% of the site occupied by construction waste and the remaining 40% covered by tyre rubber. A site visit was made by the project team to the MME Recycling site in February 2021. Production was noticed at different locations of the site. It was observed that approximately 2 million square metre were cleared from the site, with a total production of 0.5 Mt (million tonnes) of recycled aggregate over 1 year, including 3 months for mobilisation. Current procedures include manual separation of large items of foreign and lightweight materials, followed by crushing and screening with additional mechanical separation using magnets and air-blow. A total of 100,000 tonnes of recycled aggregate have already been sold, mainly for use in non-structural concrete products of concrete blocks and paving blocks, and unbound subbase materials.

QPMC is planning to double the production of recycled aggregate to 1 Mt/y at the MME recycling site and introduce washing facilities for the production of fine aggregate for use in structural and non-structural concrete. The long-term agreement of 20 years set with the MME, and the PPP agreement with industry have facilitated such investment in washing plants to meet the high demand of quality aggregate. This will improve the quality of recycled aggregate and reduce the high demand of imported gabbro and concrete sand, from the diminishing sand deposits in Qatar.

The main challenge facing QPMC in marketing the recycled products from the MME recycling site is the presence of lightweight materials within the final recycled aggregate/products. This is mainly attributed to the nature of mixed construction waste at Rawdat Rashid, with more than 90% of the material arriving at site as mixed construction demolition and excavation waste, and small quantities of clean concrete, and reclaimed asphalt pavement. This could be improved by better practice on construction sites in Qatar, such as segregation of different waste types on site and stripping out furnishings and fittings before demolishing buildings. Details of suitable procedures that could be adopted are given in Hassan et al. (2015).

2.6.2 Ashghal Recycling Sites

QPMC is managing the construction waste generated from Ashghal demolished projects in 3 recycling sites. Recycling work commenced in October 2020 with 4 contractors working on the processing of excavation waste, reclaimed asphalt pavement, and recycled concrete. The recycled products generated from the Logistic sites are used back in Ashghal's new projects. QPMC has currently processed approximately 1.8 Mt at the Logistic sites, with approximately 25,000 to 30,000 t/day.

Table 2-4 shows that the production at the logistic sites are 10 times the production at the MME recycling site. This is mainly attributed to the cleaner nature of construction waste from Ashghal projects, mainly from roads with separated pavement layers and concrete units of block paving and kerbstones. There is also a high demand for recycled aggregate in Ashghal projects that are developing rapidly to support the government vision and strategy.

2.7 Summary

Qatar's long-term development strategy, QNV 2030 and NDS-2 (2018-2022), are based on the principles of sustainable development, with emphasis on sustaining a balance between current and future demands. Construction waste represents 80% of total solid waste generation in Qatar, with current quantities of 8.0 Mt/year, and expected generation to remain above 6.0 Mt/y to 2030.

A recycling target of 20% was set for the use of recycled aggregate to replace primary materials in construction projects by 2022. Energy and water are other environmental issues with set targets to reduce carbon emissions and increase the use of TSE water in different industries. Government initiatives – include development of standards and specifications, guidelines, manuals, and sustainable supply of materials, to facilitate the implementation of recycling in construction. A summary of the permitted use of recycled materials in a range of construction applications is given in Table 2-3.

Recycling initiatives have been established across the government entities and industry for integrated strategic planning aligned with the recycling target set in the NDS-2. Qatar Standards introduced the first national recycling specifications in the region, which was adopted as a GCC standard in 2015. The MME set long-term contracts for the recycling of main solid waste streams, construction and municipal wastes, and published a book on recycling guidelines for the effective implementation of recycling in construction. More recently, Ashghal issued a recycling manual that is like a specification document but with more details on recycled materials available in Qatar, percentage of use in various construction applications, quality production, and materials properties to meet the desired application.

A long-term contract was set between the MME and QPMC for the consistent supply of recycled aggregate from Rawdat Rashid landfill, and a similar arrangement was made for the Ashghal logistics sites. The production of recycled materials is expected to reach 8.0 Mt/y by 2020, with more investment in washing plants to improve the quality of mixed CDW materials. The potential to use large quantities of recycled aggregates safely and effectively in construction in Qatar and to meet the NDS-2 recycling target therefore exists, if clients and construction professionals are aware of the possibilities and committed to taking them.

The local materials are described in Section 3 and details of how they can be used in various applications are given in Sections 4 to 7.

3 Local and Recycled Aggregates in Qatar

Large quantities of local and recycled aggregate materials are available in Qatar, with potential use in various construction applications. Limestone is the main source of natural aggregate in Qatar and has been used in construction for many years. Natural aggregate of quartz sand (concrete sand) and Wadi gravel are also available locally, but in smaller quantities and mainly used in concrete. In addition, large quantities of construction waste materials are also available for use as recycled aggregates. This chapter reviews the main local and recycled aggregate materials, with basic properties and potential applications, which can contribute to achieving the NDS-2 recycling target of 20% by end of 2022.

3.1 Local Limestone

Qatar is underlain almost entirely by limestone. However, not all of the limestone is strong enough to be suitable for use as aggregate in asphalt or concrete. Previously, quality limestone came from quarries in the north and was capable of meeting the desired requirements for various applications. Since 2018, limestone quarries are mainly limited to Umm Bab area, with approximately 10 quarries supplying limestone aggregate for low-strength concrete and unbound applications.

A quarry face in the Umm Bab area is shown in Figure 3-1. Thin, irregular bands of brown clay are visible in the white limestone. The quality of processed limestone aggregate can vary from different sources and even within the same source due to contamination with clay particles. The best quality limestone is generally obtained from the top layer of the quarry, up to 4m from the surface, but this has relatively high clay content. The amount of clay is reduced at deeper layers of limestone, but the aggregate becomes weaker.

Figure 3-1 An exposure of limestone quarry face in Umm Bab

The method of processing the limestone in the quarry includes blasting up to 15m depth followed by 3 lines of production:

- Line 1 of Jaw crusher and screening: most of the clay contamination is present with the fine particles of 0-2mm, and therefore this material is removed to landfill. Material passing 75mm are used for backfill applications.
- Line 2: Impact crusher and screening: materials retained on 75mm from Line 1 are crushed and screened into different sizes (between 0 and 40mm) for use in road base and subbase applications.
- Line 3: Secondary Impact crusher and screening: materials retained on 40mm in Line 2 are crushed again and screened into different sizes for use in pipe bedding.

The advantage of sourcing aggregate from a quarry as opposed to processing excavation waste is that the product is likely to be much more consistent, as it is coming from a single source. The limestone will not be mixed with soil, construction or demolition waste and materials such as wood, plastic, rubber and metal, and will therefore be cleaner than aggregate derived from excavation waste. The processing required to produce quality aggregate will be simpler if the natural limestone is a relatively uniform, high strength material, rather than a mix of strong and weak materials from a range of sources as in excavation waste. There are therefore definite advantages to using aggregate from quarries, if suitable sources are available. It may be that the best sources have already been identified and worked out.

Local limestone aggregate was the main aggregate for construction before the boom in construction witnessed in Qatar over the last 2 decades. The material was assessed for compliance for use in bound and unbound construction applications using the test method 1-97 “Immersion Rotation Test, IRT” (CML, 1997). The test was mainly developed for assessing the quality of local limestone aggregate by breaking down the weak particles resulting from the combined actions of abrasion, impact and grinding immersed in water in a rotating drum with both fixed and rotating blades. A sample of 50 kg of the coarse aggregate (> 4 mm) is placed in the drum of a concrete mixer of 50 litre capacity. The drum is revolved at 50 revolutions per minute for a period of 10 minutes, after which the aggregate is sieved for the removal of particles finer than 4 mm in size. The Loss Factor is determined from the original weight and materials retained on 4 mm and 0.075 mm sieves as a measure of the aggregate resistance to degradation in a saturated condition. A loss factor of 5% maximum was used for bound applications of asphalt and concrete and a value of 10% for unbound applications such as subbase and pipe bedding.

The presence of large quantities of clay restricts the use of limestone aggregate in construction due to the potential swelling of clay particles in wet conditions. Most of the clayey particles are present in the fine particles, and current practice in Qatar is to blend the fine aggregate limestone with cement to improve its plasticity and sand equivalent properties.

3.2 Excavation Waste

Large quantities of excavation waste are available in Qatar as a result of the massive amount of infrastructure development that has taken place over the last twenty years. Much of this material has been taken to Rawdat Rashid landfill sites, MME and Ashghal logistics recycling units, for processing and recycling. QPMC are currently managing both MME and Ashghal recycling sites with the aim of regulating the price of recycled materials and producing consistent products. A meeting was held by the project team and QPMC management in December 2020, Figure 3-2, to discuss the current production and uses of recycled aggregates, and to present the outcomes of the research project to the current users of recycled materials to provide good understanding of the performance of recycled materials in service. A follow up site meeting was held in the Rawdat Rashid MME recycling site to observe current processing and recycled products.

Figure 3-2 Project team meeting with QPMC management

The processing of EW involves mechanical, manual and magnet separation of foreign, metal and lightweight materials before crushing and screening into different sizes. Similar to the natural limestone, processing is carried out via 3 lines of jaw crusher and screening, impact crusher and screening, and the secondary impact and screening to produce the recycled products for various applications. Figure 3-3 shows one of the QPMC production lines of EW aggregate.

Despite coming from a range of sources, all of them probably unknown, the processing of EW employed at Rawdat Rashid enabled good quality single size aggregates to be produced. A typical 10 mm EW recycled aggregate product is shown in Figure 3-4. The material looks relatively clean and is currently used for concrete blocks and pipe bedding applications.

As discussed with the production team at Rawdat Rashid, the main EW product is unbound subbase materials (0-40 mm). Only about 5 – 10% of the feedstock ended up as single size aggregate due to the variable nature of the weak limestone material, which broke down during the processing, producing dust. It was also noted that if the settings of the crushers were not regularly checked there was a tendency to produce elongate particles, making it unsuitable for use in pipe bedding or concrete applications.

Figure 3-3 Processing of EW materials – MME Recycling Site

Figure 3-4 EW of 5-10 mm for use in concrete blocks and pipe bedding

3.3 Construction and Demolition Waste

Construction and demolition waste (CDW) covers a range of materials and includes concrete, asphalt materials, blocks and interlocks, and other materials that arise from the demolition of buildings, roads and other structures. CDW may contain a proportion of wood, glass, plastic, paper or other impurities and lightweight materials. The main categories of CDW materials available and currently processed in Qatar are:

- Reclaimed asphalt pavement (RAP): Relatively clean granular asphalt aggregate; crushed and graded into different sizes.
- Recycled concrete aggregate (RCA): Relatively clean concrete aggregate; crushed and graded into different sizes.
- Mixed recycled materials: Mixed construction waste aggregate; crushed and graded into different sizes.

CDW makes up the most significant component of the total construction waste and can be variable in composition, properties and impurities. The reliability and quality control of the material is therefore an essential requirement. QPMC strongly support the development of national construction specifications, MME guidelines, and Ashghal manual that permit the use of recycled materials in various construction applications, as discussed in Chapter 2. These documents have greatly widened the material acceptance from both client and contractor's perspective.

3.3.1 Reclaimed Asphalt Pavement (RAP)

RAP is the main waste stream generated from old government infrastructure projects with estimated quantities of 1.8 Mt currently processed at the Ashghal logistics sites. RAP can be generated from several sources such as milling of existing roads, full-depth pavement removal, and waste asphalt materials generated at the plant. The RAP materials obtained from milling of old pavement are sent back to Ashghal logistic sites for recycling. RAP provides a relatively clean recycled material for potential use in new asphalt. To improve its quality use, Ashghal provides full traceability from source of RAP (project, road, plant) to the Job Mix Formula (JMF) and projects where the RAP asphalt has been laid (Ashghal, 2021). Ashghal conducted various training courses and demonstration to their contractors on the milling and use of RAP materials in asphalt. An example of the Ashghal demonstration of asphalt milling is shown in Figure 3-5, whereas the RAP material is shown in Figure 3-6.

RAP offers recovered bitumen binder and aggregate for use in new asphalt mixtures. As both bitumen and gabbro are imported to Qatar, there is an economic motivation for the recycling of RAP in addition to its environmental benefits. Recycling reduces the demand for non-renewable natural resources and reduces the energy and emissions associated with the extraction and transportation of imported aggregate. Recycling also reduces landfilling of construction waste and contributes to sustainable construction and development.

The highest value application of RAP is back into asphalt, where the material replaces expensive imported aggregate and binder. RAP is currently recycled in hot mix asphalt as 15% replacement of gabbro aggregate, and without modification of the JMF. The proportion of RAP can be increased to 30% but would require a new mix design, as specified in the Ashghal Recycling Manual (Ashghal, 2021). RAP can also be used as unbound granular material in road base and subbase applications, with the additional benefit of some binding properties from the bitumen surrounding the aggregate particles.

Figure 3-5 Ashghal demonstration on asphalt milling to their contractors

Figure 3-6 RAP materials

The use of RAP in concrete and cementitious bound applications is rather limited in Qatar. RAP aggregate is expected to reduce the strength properties but would enhance the ductility and high strain capacity of concrete, making the concrete more suitable for use in pavement base and subbase applications with improved performance properties (Hassan et al., 2000).

RAP can also be used in unbound applications such as granular base and subbase. Although the use of RAP in granular applications does not recover the bitumen binder surrounding the aggregate, it does provide an alternate application where the market for asphalt pavement is not available. According to the FHWA (2016) RAP materials should be blended with conventional aggregate immediately after crushing to avoid agglomeration, i.e. particles sticking together due to softening of the bitumen. Stockpiling RAP material for a considerable period of time, particularly in hot weather, may also require re-crushing and re-screening due to agglomeration. In practice, high quantities of RAP in the pipe bedding material would not be desirable as the particle agglomeration would prevent the material from flowing freely into the trench, leading to poor compaction and potentially long-term settlement (Reid et al., 2008).

3.3.2 Recycled Concrete Aggregate (RCA)

Recycled concrete provides a clean source of RCA aggregate, as shown in Figure 3-7. RCA generally comprises crushed stone aggregate partially coated with mortar or cement paste. The mortar is the cause of the main difference between natural aggregate and RCA, of being more porous and lighter in weight with impact on the water absorption and density of RCA. Minimising the mortar content during processing of RCA results in stronger and more durable aggregate for high-value construction applications, but would require additional efforts in crushing for the removal of mortar.

Figure 3-7 Recycled concrete is a clean source of RCA

RCA is processed by crushing and screening into different sizes, with the potential to utilise 100% of the materials. An example of the RCA 10-20 mm aggregate product is shown in Figure 3-8. The production of RCA from concrete results in a significant amount of fines. Attention has been mainly focused on coarse RCA aggregate with limited use of the RCA fines. RCA fines mainly contain higher levels of cement and possible contamination of chloride and sulphate salts, depending on the material source, but could also possess some self-hardening properties.

Figure 3-8 RCA coarse aggregate (10-20mm)

RCA fines, 0-5 mm, is currently used in Qatar in subbase applications, by blending with EW materials, gabbro fines, Portland cement and water to create a mix that meets the plasticity and sand equivalent requirements of the QCS 2014.

The RCA coarse aggregate could also be used in unbound applications such as subbase and base applications but probably not in pipe bedding. RCA aggregate has the potential to develop self-cementation, which is a desirable property in subbase, but not in pipe bedding as it makes it more difficult to access the pipes for maintenance and repair works. RCA can also be used in structural and non-structural concrete applications as specified in the QCS 2014. RCA may be best reserved for use in concrete, cement bound materials and unbound subbase, provided compliance with the specification requirements.

The QCS 2014 limits the composition of RCA by specifying the maximum limits of masonry content, RAP, foreign materials of glass, plastic, metal etc., and lightweight materials. Additional requirement of the volume of lightweight materials is made as per BS EN 933-11 (2009) due to the low density of lightweight materials.

3.3.3 Mixed CDW

Mixed CDW comprises a wide variety of materials including concrete, metals, timber, ceramics, soil, plaster, asphalt, and polymers which arise either during construction, renovation, or demolition activities. The material is very variable in composition, Figure 3-9, and can contain varying amounts of foreign and lightweight materials such as plastics, glass, paper, cardboard, cloths, etc.

Figure 3-9 CDW of mixed materials

Currently there is no segregation taking place, at source, of the CDW waste into different categories, e.g. clean concrete and blocks or material with more wood, plasterboard and other contaminants. At the processing unit, the separation is carried out using the dry methods of manual and mechanical segregation through magnet and air blowing.

The MME is currently planning new procedures for demolition waste in Qatar, with the aim of reducing pollution and maximising recovery of waste materials by segregation at source. A pre-demolition audit will be required before obtaining a demolition permit, to identify demolished materials that can be removed for reuse or recycling, such as furnishings and fittings, and to identify possible presence of any hazardous materials such as asbestos. Based on the pre-demolition audit, the total amount and nature of the demolition wastes will be determined for the preparation of a waste management plan. Such procedures will clarify how the materials will be handled before and after demolition, with the aims of minimising waste contamination, and maximising the value and recycling of the demolished materials. The waste management plan should indicate how the materials will be stored on site, methods undertaken for segregation and prevention of contamination during stockpiling, and the quantities of materials for reuse, recycling and disposal.

Figure 3-10 Washed CDW aggregate (A UK Recycling Plant)

For the existing mixed CDW at Rawdat Rashid, QPMC indicated their intention to install washing plants at the MME recycling site, as mentioned earlier in section 2.6. An example of the washed mixed CDW is shown in Figure 3-10, as obtained from a site visit conducted by the project team to one of the CDW recycling site in the UK. It is clear that washing effectively removes the lightweight materials and produces clean aggregate with potential use in concrete and unbound granular materials of road base and subbase applications.

3.4 Wadi Gravel

Whilst the majority of Qatar's geological succession is made of limestone and dolomite with inter-bedded clay, shale, gypsum and marl (Cavelier et al 1970, Leblanc 2008), in the south these strata are overlain by scattered outcrops of the Hofuf Formation of Upper Miocene to Pliocene age. The Hofuf Formation deposits consist of coarse sand weakly cemented by gypsum with pebbles of various rocks, mostly derived from the Arabian Shelf and the Arabian Shield, transported by large river systems (Al-Saad et al., 2002). The Hofuf Formation is referred to as "Wadi gravel" and has been exploited over many years as fine aggregate for use in concrete. Current practice is to screen and wash sand before use as fine aggregate in concrete. The screening is for the removal of oversize particles (> 4 mm) and the washing for the removal of clay, fines and any loose gypsum.

Large quantities of the oversize Wadi gravel are available in Qatar, exceeding 4 Mt, but the material has not been fully utilised as a source of coarse aggregate. This is mainly due to the presence of gypsum, which in many cases are adhering to the Wadi gravel particles, and hence is difficult to remove. Recently, Hassan et al. (2020b) reported a method for the successful processing of Wadi gravel to reduce the sulfate to acceptable levels for use as coarse aggregate in concrete, which was also adopted in the Ashghal Recycling Manual (Ashghal, 2021). The process is schematically presented in Figure 3-11, and involves intensive treatment using multistage crushing, screening and washing. Processed Wadi gravel, using this methodology, successfully met the sulfate and other requirements of the QCS 2014 for use as coarse aggregate in concrete. Photos of the Wadi gravel aggregate before and after processing are given in Figure 3-12 and Figure 3-13, respectively. Processed Wadi gravel is produced in different sizes of 0-5 mm, 5-10 mm, 10-14 mm and 14-20 mm sizes, with the potential of use in various applications of structural and non-structural concrete, concrete blocks, interlocks, cement bound materials, and pipe bedding.

The composition of Wadi gravel may include different rock types. Petrographic examination to BS 812-104 (1994) on Wadi gravel, as obtained for 2 sources of Mekaines and Al-kharaij sand deposits, is presented in Table 3-1. The petrographic examinations identified 6 rock constituent types, which accounted for at least 94 % of the Wadi gravel as shown Table 3-1 (Sims et al., 2021). The main difference between the raw (as received) and processed Wadi gravel is the gypsum-bound deposits which are attached to the gravel particles. Extensive processing of crushing, screening and washing reduces the gypsum content to less than 1%.

Table 3-1 Wadi gravel constituents (% by mass) before and after processing

Main constituents	Raw Wadi gravel		After processing	
	Mekaines	Al-kharaij	Al-kharaij 10-14mm	Al-kharaij 14-20mm
Limestone	36	41	48	51
Gypsum-bound deposits (GBD)	20	16	-	-
Quartz	17	12	23	20
Rhyolite	9	7	9	10
Granite	7	14	8	8
Quartzite	5	7	7	7
Total	94	97	95	96

There is not much variation of the composition of Wadi gravel aggregate obtained from different sand deposits in Qatar, before and after processing into different sizes. The main rock constituents of the Wadi gravel are limestone and quartz, with small proportions of rhyolite, granite, and quartzite. The unprocessed Wadi gravel contains up to 20% GBD, which is reduced after processing to small traces less than 1%. Such reduction in the sulfate content is encouraging for a wider utilisation in the construction industry, especially in Qatar with shortage of quality local aggregates and the high cost of imported aggregates.

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3.5 Steel Slag

Steel slag is a by-product of steel manufacturing and is produced by the Qatar Steel Company at their plant at Mesaieed. The slag is predominantly electric arc furnace (EAF) in origin; in excess of 350k tonnes is produced every year, with an estimated two million tonnes of stockpiled materials. The molten slag is conditioned by immediate quenching with water and weathering in air for one year before processing. The slag processing includes primary crushing for the recovery of ferrous metals, followed by secondary crushing into different aggregate sizes.

In support of the government strategy of sustainable development, Qatar Standards issued a No Objection Letter (NOL, 2013) to allow the use of steel slag as an aggregate in construction. The NOL imposed a maximum replacement rate of 20% of the gabbro coarse aggregate in asphalt and concrete applications. For asphalt works, the use of slag aggregate was limited to the base course and for concrete works to blinding concrete and non-structural elements that are outdoors or underground. The non-structural element included manholes, soakaways and cable covers applications.

Additional requirements are made for weathering the steel slag for a minimum period of 1 year before production, and for the processing and production of the materials to be carried out under a quality control system with regular testing for all the key technical parameters required by the NOL and the QCS 2014. The extra tests required by the NOL include tests for the expansion potential of the slag and leaching tests to assess whether there is any likelihood of contamination of natural sources from the use of steel slag aggregate. The regular tests demonstrated that the aggregate has very low potential for expansion and for leaching of contaminants, and hence is safe to use in the proposed applications.

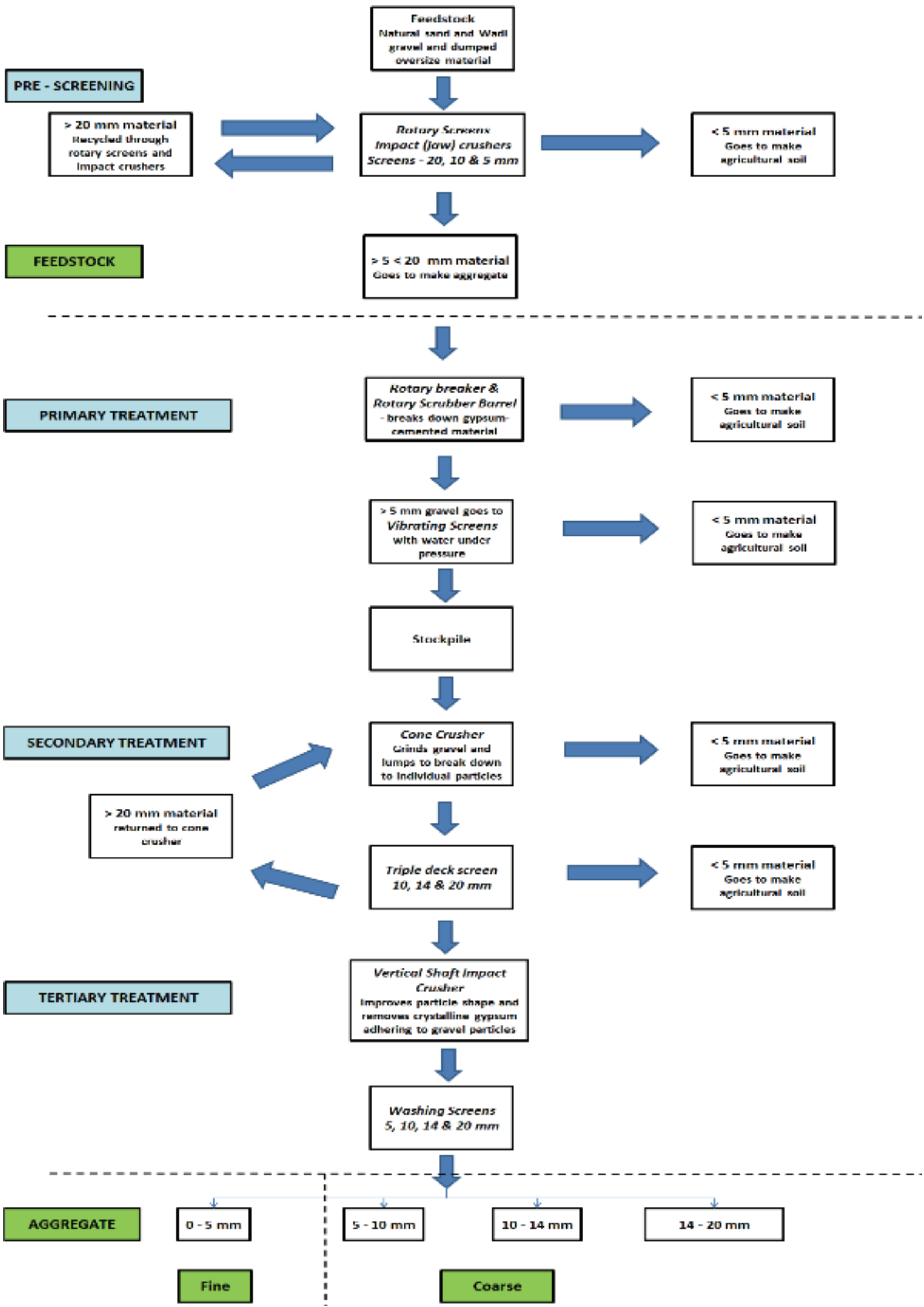

Figure 3-11 Schematic diagram of the Wadi gravel processing

Figure 3-12 Unprocessed Wadi gravel; the sandy lumps are gypsum-bound deposits (GBD)

Figure 3-13 Processed Wadi gravel; GBD almost completely removed

Figure 3-14 Steel slag aggregate

Dimensional instability is the main technical concern facing steel slag aggregate when used in bound applications of asphalt or concrete. The propensity of slag to expand is due to the presence of free lime and magnesium oxides that can hydrate in humid environments, producing volume changes. Coomarasamy and Walzak (1995) reported extensive map cracking and premature failure in some constructed slag-asphalt pavements due to excessive expansion of the slag aggregate. It is therefore recommended to expose the slag for a few months to outdoor weathering before use in construction. Work by Autelitano and Giuliani (2015) suggested a minimum aging period of 4-6 months for EAF slag aggregates used in road construction, for both bound and unbound applications. In hot countries with lack of rainfall, a weathering period of 6 months could easily contain little or no rain, and therefore the NOL specified a minimum period of 1 year.

An accelerated weathering trial was conducted to validate the requirement made on pre-conditioning the EAF slag in air for one year before its use in construction. A representative sample of approximately 20 tonnes of slag was crushed and screened into different sizes of 0-5, 5-10, 10-20, 121 and >20mm. The stockpiles were stored near each other in an open area in the Qatar Steel plant, as shown in Figure 3-14. The stockpiles were sprayed with treated sewage effluent (TSE) water twice a day to accelerate any weathering reactions. The pH was determined periodically for the water draining from the slag, and the results showed only very minor changes during the 1-year trial, indicating no uptake of water and hydration of the oxides components of the slag (Hassan et al., 2021). Regular laboratory testing of the products is carried out according to the schedule set out in the Quality Control System.

3.6 Incinerator Bottom Ash (IBA)

Following the collection and the mechanical separation of the domestic wastes into different sizes, the large size fraction (>300mm) is transferred to the incineration unit for energy production. The Energy-from-Waste plant is managed by the MME, with the capacity to incinerate 1500 tonnes per day. The material is incinerated at 800-900°C for a duration of 45 minutes.

Figure 3-15 Incineration bottom ash (IBA) aggregate

The amount of ash generated ranges from 15-25% (by weight) and from 5-15% (by volume) of the raw municipal solid waste processed (EPA, 2019). Fly ash refers to the fine particles that are removed from the flue gas and includes residues from other air pollution control devices, and typically amounts to 10-20% by weight of the total ash. The remaining 80-90% is IBA, Figure 3-15, which has the main chemical components of silica (sand and quartz), calcium, iron oxide, and aluminium oxide.

After combusting, the IBA is discharged and quenched with water. The main purpose of water quenching is to quickly cool the material and reduce the amount of dust. After water quenching and cooling, the ash is divided into different size fractions:

- IBAA (0-8mm): produced at a capacity of 80 tonnes/day

- IBAA (8-40mm): produced at a capacity of 40 tonnes/day

Approximately 50,000 tonnes are produced every year from incinerated municipal ash, with potential use as aggregate in construction. The material is not utilised in Qatar and is generally stabilised with cement and sent to landfill.

3.7 Summary

The principal sources of coarse aggregate in Qatar include local limestone, excavation waste (EW), reclaimed asphalt pavement (RAP), clean recycled concrete (RCA), mixed construction and demolition waste (CDW), Wadi gravel, steel slag and incinerator bottom ash. All have been shown to be capable of yielding good quality aggregate that will meet the requirements of the QCS 2014 for a variety of applications; however, achieving the required level of quality often involves extensive processing of the materials.

The quality of local limestone aggregate varies from different sources, or even from the same source due to localised contamination with clay. It is currently used in unbound construction applications, and sometimes blended with Portland cement and gabbro fines to improve plasticity and sand equivalent properties.

CDW and EW provide the largest quantities of recycled materials in Qatar with potential use in construction. RAP, RCA and EW are relatively clean aggregate and would only require crushing and screening into different sizes, whereas the mixed CDW would require additional treatments. The government plan of the MME pre-demolition audit to segregate the mixed demolition waste at source and the QPMC washing plants at Rawdat Rashid should improve the quality of mixed CDW products for wider applications in construction.

Wadi gravel is a by-product produced from the sand washing plants as oversize materials. Processing of Wadi gravel, through intensive multistage washing, crushing and screening is essential to reduce the sulfate content to acceptable levels. Petrographic analysis indicates the Wadi gravel aggregate is composed of 6 principal types of rocks, and the composition does not change much from different sources of sand deposits. Steel slag aggregate is another source of clean aggregate for use in construction. Weathering the materials for at least 1 year, as specified by the NOL, is essential for the dimensional stability of the slag aggregate. IBA is generated from the incineration of municipal solid waste and is currently stabilised with Portland cement and sent to landfill.

Recycled and alternative aggregates were used to replace natural imported and local aggregate in various structural applications of structural concrete, concrete blocks, and unbound subbase. Based on monitoring in-service performance after 5 years for the building trials and 4 years of the road trials, the following conclusions are made.

4 Recycling in Asphalt Pavement

The Qatar road network has grown significantly from 18,000 lane kilometres in 2017 to 28,000 lane kilometres in 2020 to support the economic and social development of the QNV 2030. Asphalt or flexible pavement is the main pavement type used in Qatar for road construction. Hot mix asphalt (HMA) comprises graded aggregate and a bituminous binder, and both materials are currently imported to Qatar. Therefore, there is economic and environmental benefits for the use of recycled materials in asphalt.

This chapter presents the performance of asphalt pavement made with recycled aggregates of RAP and steel slag, as partial replacement to imported gabbro aggregate. It also provides site data on the performance of asphalt wearing course made with crumb rubber modified binder (CRMB). Site trials were constructed with different proportions of recycled aggregate and the performance was assessed by visual inspections and core testing immediately after construction and up to 3 years in service. The results are compared to those of control pavement sections made with conventional gabbro aggregate, and with national construction specifications of the QCS 2014 and the Ashghal Recycling Manual (Ashghal, 2021). As no control section was included in the CRMB asphalt case study, the results are compared to the requirements of national specifications.

4.1 Reclaimed Asphalt Pavement (RAP)

Asphalt pavement tends to age with time, and the rate of binder aging is accelerated at higher temperatures such as the exposure conditions in Qatar and the Gulf region. Aging results in a hard and stiff binder, with more susceptibility of the pavement to crack and disintegrate during its service life. To reinstate the pavement, the existing surface layer is usually replaced by a fresh HMA layer, thus generating large quantities of RAP materials. RAP is one of the main recycled aggregates implemented in Ashghal projects, due to its dual benefits of recovering the aggregate and the bituminous binder. The material has been widely used to replace 15 % of imported gabbro, without modifying the mix design, in almost all new construction and maintenance pavement projects. Two projects were selected for investigating the performance of RAP in asphalt. The RAP contents ranged from 15 % to 40 % and the RAP was used to replace imported gabbro in asphalt road base applications.

4.1.1 Al-Wakrah Metro Car Park – RAP base course

As part of the Al-Wakrah Main Road Project, the car park of the Metro Station was constructed with asphalt base course containing 15% RAP. The car park is approximately 12,000 m^2 and was constructed in October 2018, Figure 4-1. The pavement construction consisted of layers of:

- 50 mm of asphalt wearing course (WC)
- 100 mm of asphalt base course (BC, Class A)
- 200 mm unbound road base
- 500 mm of subgrade.

To provide a consistent grading of RAP aggregate, the milled asphalt material was initially sieved into different fraction sizes and remixed again in pre-determined proportions. The RAP properties considered in the mix design were grading, binder content, moisture content, specific gravity, density, and water absorption. RAP with coarse aggregate size exhibited higher specific gravity and lower values of binder content and water absorption, when compared to the finer RAP fraction. This is mainly attributed to the higher specific gravity of aggregate when compared to bitumen, and the higher proportion of bitumen in the fine RAP fraction, due to the lower specific surface area of the large aggregate particles compared to the finer aggregate particles, which hence require less binder to coat the surface of the coarser particles.

The RAP aggregate was cold fed and added directly into the asphalt mixer without pre-heating. The natural gabbro aggregate was heated at a relatively high temperature of 190°C to compensate for the RAP materials.

Figure 4-1 Al-Wakrah Metro car park – RAP asphalt

4.1.1.1 Construction Data

During construction of the Metro car park, samples of loose asphalt were collected at different locations of the 15% RAP asphalt and an adjacent control section made with a 100% gabbro asphalt. Cores were also taken immediately after construction for the determination of the in-place voids content and degree of compaction. The average values of construction data are summarised in Table 4-1 for the control and 15% RAP asphalt base course sections, together with the mix design (Job Mix Formula, JMF) and the revised QCS 2014 requirements for BC-Class A, as per the Ashghal Recycling Manual (2021). Values highlighted in “yellow” are those not complying with the QCS 2014.

The bitumen content of the asphalt mixtures were determined as per ASTM D2172 (2017), and the values were 4.0% for the control asphalt and 3.6% for the 15% RAP. The 15% RAP binder content of 3.6% is identical to the Job Mix Formula (JMF), approved by Ashghal. The results fall within the range specified in the QCS 2014 of 3.2 % - 4.4 % for asphalt BC-Class A. The binder content of the 15% RAP mixture included 3.0 % of virgin bitumen (60/70 pen) and 0.6 % recovered binder form the RAP aggregate, i.e. 25 % saving of the virgin bitumen binder.

Sieve analysis was conducted as per ASTM D 5444 (2015), and the grading results are shown in Figure 4-2. The results show identical grading for the control and 15 % RAP BC-A, falling within the permitted grading envelope in the QCS 2014. Figure 4-2 also presents the grading of the JMF of the 15 % RAP with identical grading to the construction mix. The identical grading curves obtained from the mix design (JMF) and construction data indicate consistent supply of asphalt materials with 15 % RAP during the construction period.

Table 4-1 Marshall mix design and construction data of RAP asphalt – Al-Wakra car park

Parameter		QCS 2014 limits*	Mix design (RAP JMF)	Construction data	
				Control	RAP 15%
Loose asphalt	Binder Content (%)	3.2-4.4	3.6	4.0	3.6
	Stability (kN)	12.0 min	16.5	15.0	16.0
	Flow (mm)	2.0–4.0	3.2	3.0	2.8
	Marshall quotient (kN/mm)	5.25 min	5.2	5.0	5.7
	Retained Stability (%)	75 min	90	83	86
	Voids in Mix (VIM, %)	4.0-8.0	5.7	6.2	6.3
	VMA (%)	13 min	14.0	15.0	14.9
	VFA (%)	50-70	58.8	58.0	57.6
	Voids VIM-400 blows (%)	3.2 min	4.1	4.0	4.0
	Filler/Binder Ratio	0.8-1.5	1.3	1.0	1.1
	Bulk density (kg/m^3)	-	2.568	2571	2565
	Max specific gravity (G_{mm})	-	2.723	2.749	2.747
Cores	Core in-place air voids (%)	5.0-8.0	-	6.8	7.3
	Degree of compaction (%)	97-101.8	-	100.2	99.3

*Revised as per the Ashghal Recycling Manual (2021)

The Marshall properties were conducted as per the QCS 2014. The Marshall stability is a useful parameter in determining the appropriate binder content and providing an indication of the deformation resistance of asphalt. The asphalt samples were tested for stability as per ASTM D6927 (2015), and the results are presented in Table 4-1. At the mix design, the 15 % RAP asphalt exhibited the highest value of 16.5 kN, with a slightly lower value of 16.0 kN at construction. The control section exhibited the lowest value of 15.0, but greater than the minimum specified limit of 12.0 kN. Marshall flow testing provides an indication of fatigue resistance and flexibility of asphalt and the results showed values between 2.8 mm and 3.2

mm, within the specified range of 2 to 4 mm. The Marshall quotient (stiffness) is the ratio of Marshall stability and flow. The 15 % RAP mix design exhibited a value of 5.2 kN/mm, marginally lower than the minimum specified value of 5.25 kN/mm. At construction, the control asphalt failed to meet the specified requirement, whereas the 15 % RAP gave a value of 5.7 kN/mm. The Marshall retained stability test is for determining the resistance of asphalt to moisture damage. The revised QCS 2014 specifies a minimum value of 75 % as the ratio of wet to dry stability. Values obtained for the 15% RAP mix design and construction data of both mixtures were above the specified value.

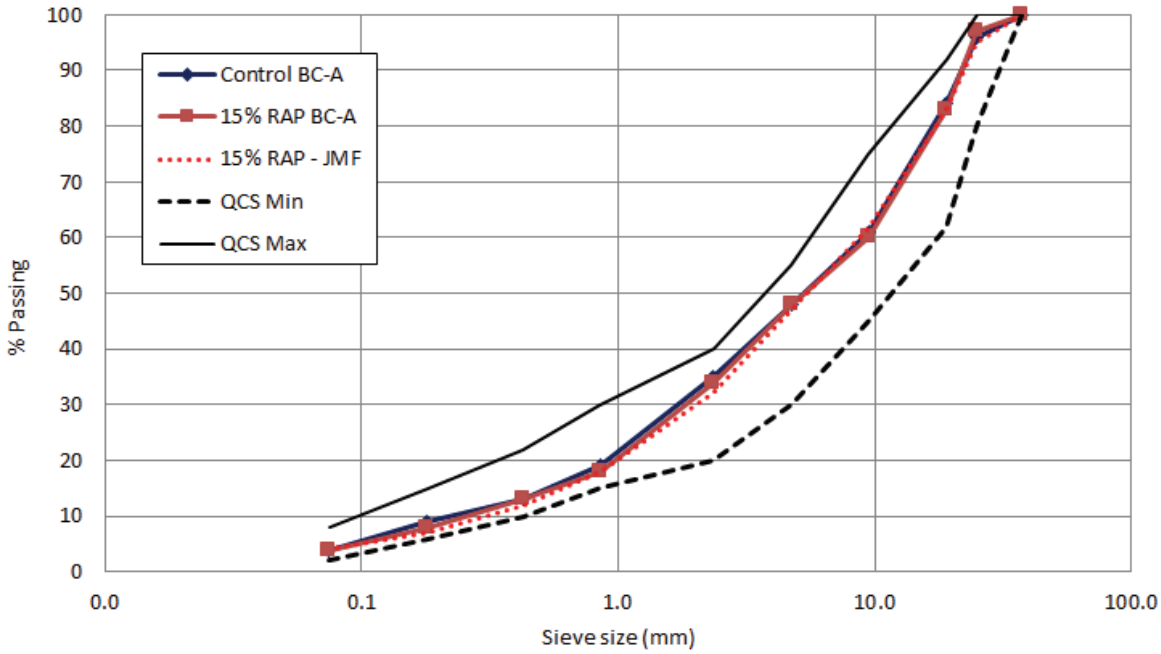

Figure 4-2 Grading of extracted aggregate – Al-Wakra Car Park

For the volumetric properties, the bulk density values were 2571 and 2565 kg/m^3 for the control and 15% RAP mixtures, respectively. Similarly, the variation of the maximum specific gravity values (Gmm) was small between 2.749 for the control and 2.747 for the 15 % RAP. The air voids requirement of asphalt base course is between 4 % and 8 %, as specified in the QCS 2014 and the Ashghal Recycling Manual (2021). The average air voids content for the control and 15 % RAP were 6.0 % and 6.3 %, respectively, and within the mid-range of the QCS 2014 specified limit of 4-8 %. When comparing to the JMF, the 15% RAP exhibited a lower voids content of 5.7 % at the mix design stage.

Voids in the mineral aggregate (VMA) must remain high enough to achieve an adequate asphalt film thickness, in order to get a durable asphalt pavement (Asphalt Institute, 2014). The voids in mineral aggregate (VMA) exhibited very similar results of 15.0 % and 14.9 % for the control and 15% RAP mixtures, respectively, and greater than the minimum specified value of 13% for base course Class A. The Marshall mix design method does not specify a maximum value for VMA, however the Superpave mix design method recommends that a maximum VMA shall not be exceeded otherwise the mix may be prone to flushing and rutting (MS-2 7th edition, Asphalt Institute, 2014).

The voids filled with asphalt (VFA) were 58.0 % for the control and 57.6 % for the 15 % RAP, complying with the QCS specified range of 50 % to 70 %. The filler/binder ratio (FBR) results fell within the specified range of 0.8 to 1.5, with values of 1.0 for the control and 1.1 for the 15% RAP. Voids at 400 blows are specified in the QCS 2014 to ensure that the additional compaction in service, under severe traffic loading, cannot reduce the VIM below 3.2% for BC Class A. The results in Table 4-1 show identical value of 4 % for the control and 15 % RAP asphalt BC, higher than the minimum specified value.

Core samples were obtained from the laid asphalt, immediately after construction, and tested for the in-place air voids and degree of compaction as per the QCS 2014. Compaction is essential to the long-term performance of asphalt due to its effects on stiffness, fatigue life and aging. The results in Table 4-1 show in place voids values of 6.8 % for the control and 7.3 % for the 15 % RAP asphalt, within the QCS 2014 specified range of 5 % - 8 %. The QCS 2014 also specifies a range of field density (degree of compaction) between 97 % and 101.2 %, as determined from the cores and related to the daily Marshall density. The results in Table 4-1 show values of 100.2 % and 99.3 % for the control and 15 % RAP asphalt, respectively. In general, the construction data indicate very similar results for the control and 15 % RAP BC-A. Both mixtures complied with the revised QCS 2014, with the exception of the lower Marshall quotient than the minimum specified value for the control mix.

4.1.1.2 Performance Data – 1 Year

The performance of the RAP mixture was assessed after 1-year in service by coring and testing the asphalt cores. Six different locations were selected from the 15 % RAP section and two locations from the adjacent control asphalt, made without RAP materials. Three adjacent cores were drilled through the full asphalt layers at each location, as shown in Figure 4-3, making a total of 18 RAP and 6 control cores. The core dimensions were 150 mm in diameter and 150 mm height (50 mm WC and 100 mm BC-A). Visual inspection of the constructed car park after 1-year in service was also conducted and the asphalt material was visually in very good condition, with no evidence of defects and no obvious difference in appearance between the 15 % RAP and control asphalt sections.

Core testing and assessment were conducted at the Ashghal Centre for Research and Development. The cores were in very good condition with no cracks or excessive voids on the surface for the RAP and control asphalt. The core diameter and height were recorded before the density determination by measuring the weight in air and water as per ASTM D2726 (2019). After density testing, the cores were divided into two groups with each group consisting of three cores. One group of cores was used for the dry indirect tensile test (IDT) and the second for the tensile strength ratio (TSR). The broken cores were tested as loose materials for the G_{mm} determination (ASTM D2041, 2019).

The average test results for the control and 15 % RAP asphalt BC-A mixtures are summarised in Table 4-2, together with the revised QCS 2014 requirements as per the Ashghal Recycling Manual (2021). The average values of core density were 2554 kg/m^3 for the control and 2565 kg/m^3 for the 15 % RAP asphalt. The QCS 2014 for Marshall Mix Design specifies the air voids for base course (Class A) to be between 5 % and 8 % at construction. The results show average VIM of 6.1 % for the control, which is similar to that of the construction data (Table 4-1). The 15% RAP exhibited a lower value of 5.5 % than the control asphalt, which is also lower than the value obtained at construction.

Figure 4-3 Coring of RAP asphalt at a single location– Al-Wakrah Metro car park

Table 4-2 Average performance results – Wakra car park

Parameter	QCS 2014 limits	Control BC-A	15% RAP Construction
Density (kg/m^3)	-	2554	2565
Gmm	-	2.728	2.747
Air voids (%)	5.0 – 8.0	6.1	5.5
IDT (kPa)	-	1120	1150
TSR (%)	60 % min	63	61

The results of indirect tensile test (IDT) and tensile strength ratio (TSR) are also presented in Table 4-2. Whilst there is no specific requirement in the QCS 2014 for the IDT, the Ashghal Recycling Manual (2021) specifies a minimum value of 60 % TSR for the unmodified bitumen, determined as per ASTM D4867 (2014). The average IDT of the control asphalt is almost the same as the 15% RAP at construction with values of 1120 kPa and 1150 kPa, respectively. The TSR was 63 % for the control asphalt and 61 % for the 15 % RAP, both higher than the minimum specified value of 60%.

The properties of recovered bitumen from the asphalt cores of the control and 15% RAP base course (Class A) are given in Table 4-3, together with the QCS 2014 specified limits for new construction. The QCS 2014 specified values are based on fresh binders and not for aged asphalt, as per the results in Table 4-3, but were used for comparison. The binder content of the control asphalt was 3.8% and 3.5% for the 15% RAP, with both values falling within the specified range in the QCS 2014 (3.2-4.0%). The binder content of the 15% RAP mixture was slightly lower than the 3.6% approved in the JMF.

Table 4-3 Properties of recovered pen 60-70 binder (Al-Wakra project)

Parameter	QCS 2014 limit	Control BC-A	15% RAP (BC-A)
Binder content	3.2-4.4	3.8	3.5
Penetration @ 25°C (0.1mm)	60-70	46	37
Softening Point (°C)	46 min	51.4	54.8
Ductility @ 25°C (cm)	100 min	150	54
DSR (G*/sinδ), minimum 1.00 kPa, Test temperature (°C) at 10 rad/s	PG 64	75.4	78.1

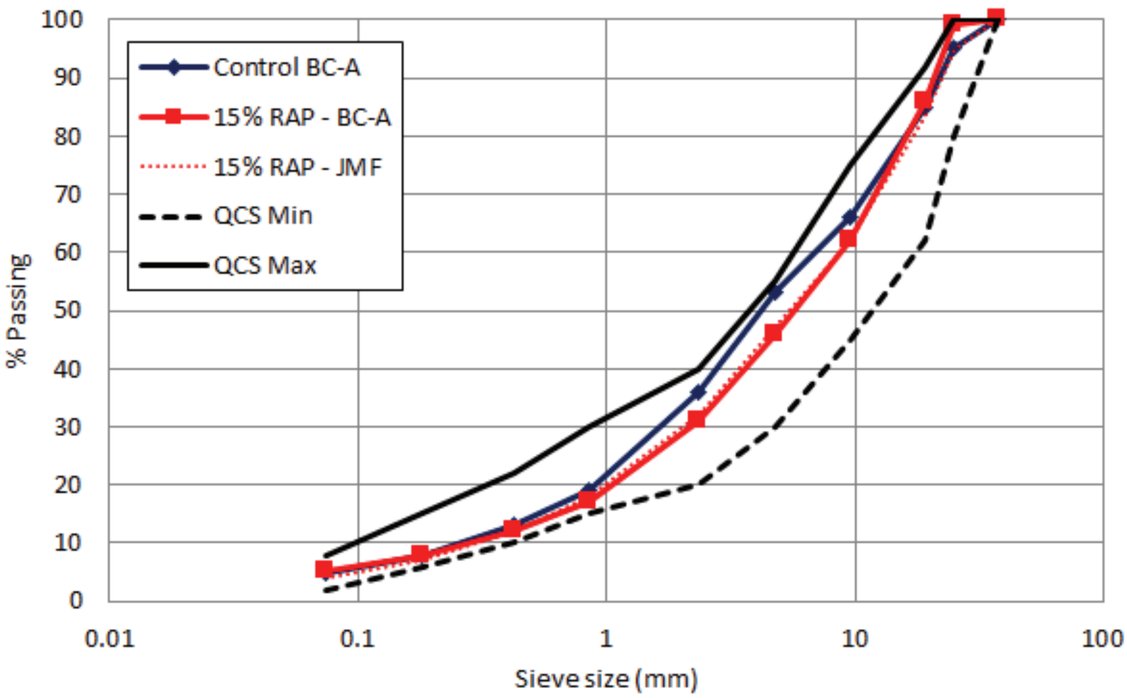

Figure 4-4 Grading of extracted aggregate from cores – Al-Wakra car park

Sieve analysis of the extracted aggregate from cores are shown in Figure 4-4. Similar to the construction data, the grading curves of the control and 15 % RAP asphalt BC-A were within the envelope specified in the QCS 2014. However, the control grading exhibited higher proportions of passing materials between 10 and 1.0mm (sieve sizes 9.5 mm and 0.85 mm) towards the maximum specified curve, indicating finer grading than the 15 % RAP. The results also show identical grading of the 15 % RAP asphalt and the JMF for the same mix, with the exception of sieve size of 25mm.

For hot mix asphalt, the elasticity of the bitumen binder will reduce during mixing and in service with age. The penetration of fresh bitumen is expected to harden by approximately 30% during mixing and laying (Read and Whiteoak, 2003). The bitumen will continue to harden with age, depending primarily on the ambient temperature and voids content. The results in Table 4-3 show that the penetration of the recovered bitumen from the control and 15 % RAP cores are 46 and 37, respectively. Assuming a 30% reduction of penetration after manufacturing, the retained penetration of the 60/70 pen is expected to be within the range of 42-49. After 1-year in service, the control asphalt exhibited a value of 46 within the expected range, whereas the 15 % RAP showed a lower value of 37. The lower value of RAP asphalt is attributed to the proportion of RAP in the mix and presence of oxidised bitumen around the RAP (McDaniel, 2012). The hardening of the recovered binder was mirrored with an increase in the softening point as shown in Table 4-3. The softening point of the control was 51.4 °C and 58.4°C for the 15% RAP.

The recovered binder from the control and 15% RAP asphalt cores was also tested for ductility as per ASTM D113 (2017). The ductility value of the 15 % RAP binder was 54 cm, which is lower than the min specified value in the QCS 2014 of 100 cm. The control asphalt gave a ductility value of 150cm. Low ductility indicates harder binder with susceptibility to early failure due to fatigue cracking. The DSR testing was conducted as per AASHTHO T315 (2019) at different temperatures between 64 and 82^{o}C, with an interval of 6^{o}C. The results in Table 4-3 show that the performance grade of the control asphalt increased from 64^{o}C at construction to 75.4^{o}C (PG 72) after 1-year in service, and the 15 % RAP asphalt increased from 64^{o}C to 78.1^{o}C (PG 78). The results indicate hardening of the binder with potential improved rutting resistance with aging but reduced elasticity and hence less resistance to fatigue cracking. Whilst the RAP asphalt, with its low binder content, exhibited similar TSR as the control asphalt made with additional 25% of virgin binder content. Considering the hot climate conditions in Qatar and its effect on asphalt aging, it is recommended to maintain equivalent binder content as conventional mixtures to enhance the elastic and aging properties of RAP asphalt.

4.1.2 Izghawa Maintenance of local roads – RAP BC Class B

The Izghawa maintenance of local roads was within the Ashghal Road Operation and Maintenance programme in Umm Salal area – North of Doha. The project commenced in January 2018 in three residential streets and different proportions of RAP asphalt. The asphalt reconstruction was a single layer of 70mm base course (BC, Class B) as per the QCS 2014. The road width was 7.3 m and RAP was used at different proportions of 15 %, 20%, and 40 % as follows:

- Jery Bu Awseja road – 15 % RAP: a road trial length was 406 m.
- Rawdat Al-Ajooz road – 20 % RAP: a road trial length of 406 m.
- Rawdat Shabana road – Control and 40 % RAP: Constructed with 3 sections of:
    - Control asphalt BC Class B (350 m length)
    - 40 % RAP (50m length)
    - 40 % RAP + Rejuvenator (50 m length).

The rejuvenator was supplied by INTERCHIMIVCA, Italy, and is composed of different chemical components of an antioxidant, plasticizer, rejuvenator, moisturizer, diluent and dispersant. It acts as an anti-stripping agent towards the bitumen and this allows it to "rejuvenate" efficiently the bitumen coming from RAP to produce asphalt. The dosage used in Izghawa trial was 0.12 % by weight of RAP and was added directly to the asphalt mixer with the bitumen.

The RAP material was reclaimed from an old road as shown in Figure 4-5. The RAP contained local limestone aggregate with an average binder content of 4.6 %, and the recovered binder was equivalent to pen 40/50 bitumen grade. The grading of the milled asphalt ranged between 0-19 mm and was added directly to the asphalt mixer. The RAP was not exposed to direct flame, compared to the gabbro virgin aggregate, but was heated at 80°C and fed directly into the mixer. The virgin aggregate (hot bin) was heated at relatively high temperatures of 180-190°C, to compensate for the RAP materials. The temperature of the final mix was maintained around 165°C.

Figure 4-5 Milling of old asphalt road – Izghawa project

4.1.2.1 Construction Data

During construction, loose asphalt samples were collected for Marshall testing and cores were obtained, immediately after construction, for the determination of in-place air voids and degree of compaction. A summary of the construction data is given in Table 4-4 for the control and RAP mixtures, together with the QCS specification limits. Values highlighted in "yellow" are those not complying with the QCS 2014.

The binder content results ranged between 3.5 and 4.7 %. The lowest binder content was for the control and 20 % RAP asphalt. The 40% RAP mixtures gave the highest values, with 4.7 % for the rejuvenated mixture exceeding the maximum limit of 4.4 %. Other asphalt mixtures of 15 % RAP and 40 % RAP were within the QCS 2014 specified range of 3.4 % to 4.4 %. With the exception of the RAP 20 % mixtures, all RAP mixtures possessed higher total binder content than the control mixture.

Table 4-4 Construction data – Izghawa RAP trials BC-B

Mix design parameter	QCS limits BC-B	Control	RAP 15%	RAP 20%	RAP 40%	RAP 40%+Rej
Binder Content (%)	3.4-4.4	3.5	3.8	3.5	4.4	4.7
Stability (kN)	12.0 min	13.6	14.1	14.8	16.3	16.2
Flow (mm)	2.0-4.0	2.5	2.75	2.75	2.75	2.75
Quotient (kN/mm)	5.25 min	5.4	5.1	5.4	5.9	5.9
Ret. Stability (%)	75 min	63.9	77.4	86.5	89.1	87.4
VIM (%)	4.5-8.0	8.8	9.9	9.0	5.6	4.8
VMA (%)	14 min	16.6	16.9	14.7	12.3	12.1
VFA (%)	50-75	46.9	41.1	38.6	54.6	60.2
VIM-400 blows (%)	3.4 min	5.9	6.6	7.2	4.0	3.7
Filler/Binder Ratio	0.8-1.5	1.2	1.3	2.0	1.7	1.6
Bulk density (kg/m^3)		2495	2448	2476	2518	2534
Gmm		2.744	2.726	2.728	2.675	2.671
Core in-place air voids (%)	5.0-8.0	8.0	6.8	8.1	4.8	7.7
Degree of compaction* (%)	91-95	92.0	93.3	91.9	95.3	92.3

*Calculated based on Gmm

Sieve analyses of extracted aggregates from the five trial sections are shown in Figure 4-6. The results show that all the control and RAP mixtures fall within the specified grading envelope of the QCS 2014 for BC-B. For the coarse aggregate of 9.5mm and above the grading was more towards the maximum specified limits and more towards the minimum specified limits for fine aggregate between 2.36 and 0.18mm.

The results in Table 4-4 show that the asphalt mixtures satisfied the QCS 2014 requirements of Marshall stability and flow. The stability increased with increasing the RAP content into the mixtures with the highest values achieved at 40% RAP, with the highest content of aged bitumen. The Marshall stiffness (quotient) results also show compliance the QCS 2014 requirement, with the exception of the 15% RAP mixture that gave a value of 5.1 kN/mm below the minimum specified value of 5.25 kN/mm. The retained stability is a measure of the resistance of asphalt mix to moisture-induced damage with a minimum specified value in the QCS 2014 of 75%. The RAP results at 15%, 20% and 40% satisfied the QCS requirement; whereas the control mixture gave a low value of 63.9% below the minimum specified value.

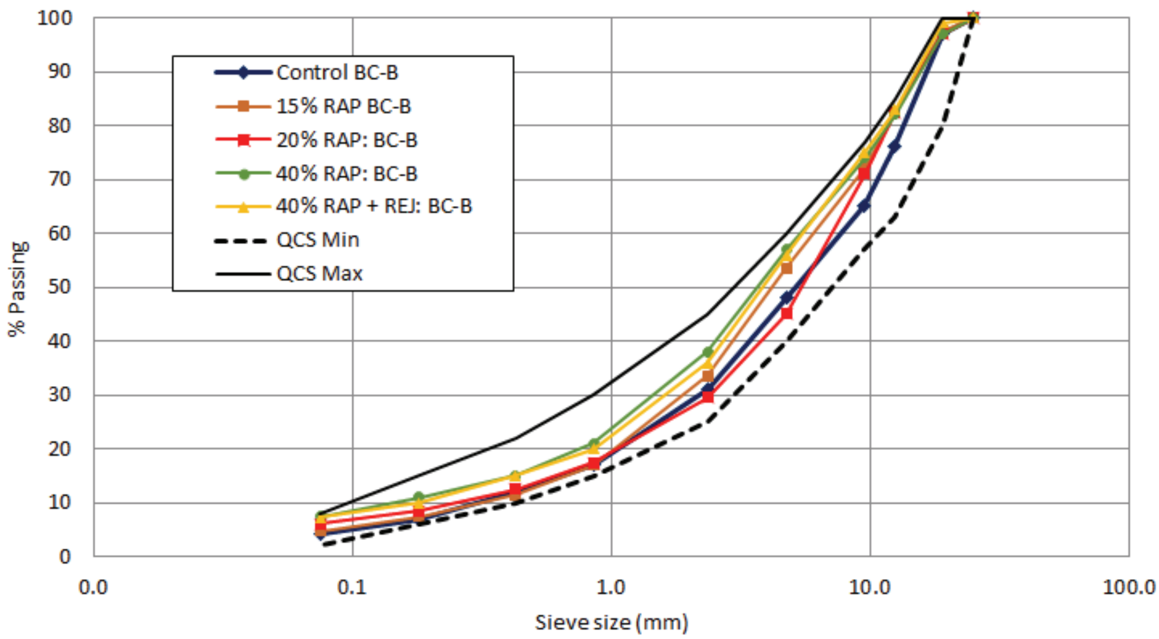

Figure 4-6 Grading of extracted aggregate – Izghawa RAP trials BC-B

The volumetric properties of the asphalt mixtures at construction are also given in Table 4-4. The air voids or voids in total mix (VTM) is a major criterion for mix design, and the QCS 2014 specifies a range of 4.5 to 8.0% for BC-B. Mixtures of control, 15% RAP and 20% RAP, with their relatively low binder contents, exhibited high values of voids content exceeding the maximum specified limit of 8.0 % in the QCS 2014. The voids content of the 40% RAP with and without rejuvenator were within the specified range. High air voids mixtures are prone to cracking and durability problems, whereas low air voids are prone to rutting and bleeding. The results of VFA (voids filled by asphalt/binder) followed the same trend as the VIM results with the control, 15% RAP and 20% RAP falling out of the specified range in the QCS 2014.

Voids in mineral aggregate (VMA) must remain high enough to achieve adequate asphalt film thickness for enhanced durability. The results in Table 4-4 show that asphalt mixtures of control, 15 % RAP and 20 % RAP satisfied the QCS requirement for VMA, whereas mixtures of

40 % RAP, with and without rejuvenator, were below the minimum specified limit of 14 %. The voids at 400 blows ranged from 3.7 % to 7.2 %, exceeding the minimum specified limit of 3.4 % in the QCS 2014. However, values for 15 % RAP and 20 % RAP were in the range of 6 % to 7 % and are considered high in relation to pavement durability and long-term performance (TRL, 1993).

During construction, the asphalt laying temperature was maintained at 140°C and site compaction was conducted using a combination of steel rollers (2 passes) followed by a pneumatic tyre roller (5 passes). Cores of 150 mm diameter were taken from the constructed pavement and tested for in-place air voids and degree of compaction. The QCS 2014 specifies in-place air voids range between 5 % and 8 %. The results in Table 4-4 show compliance of the control, 15% RAP and 40% RAP + rejuvenator mixtures with the achieved the in-place air voids requirement. The 20% RAP, which had the lowest binder content, was marginally higher than the maximum specified limit, whereas the 40% RAP that exhibited high binder content was slightly lower than the minimum specified limit. The QCS 2014 specifies a range 97 to 101.1% of the field density as determined from cores and related to the daily Marshall density. The results in Table 4-4 were calculated based on the maximum specific gravity (G_{mm}). The asphalt mixtures fell within the specified limits, with the exception of 40% RAP that gave a marginally higher value of 95.3% and exceeding the maximum limit of 95.0 %.

4.1.2.2 Performance Data – 1 Year

The performance of Izghawa site trials was assessed after 1-year in service for the different RAP mixtures and the conventional control mixture. Visually, the site trials were in good conditions with no visual defects or cracking on the surface and no obvious difference between the control and RAP asphalt. Cores of 150 mm diameter were obtained through the full asphalt layer thickness of 70mm. Three locations were selected for each trial, with three adjacent cores obtained from each location, making a total of 45 cores from the Izghawa project. The cores were initially tested for rut depth and TSR and then combined together for the determination of G_{mm}, binder extraction and recovery, and properties of recovered binder. The core logs and density measurements and properties of recovered binder were conducted in the Ashghal Centre for Research and Development, whereas the remaining testing of TSR, rut depth and G_{mm}, were carried out in an independent testing laboratory approved by Ashghal. A summary of performance results is given in Table 4-5.

Table 4-5 Average performance results – Izghawa project

Parameter	QCS 2014 limits	Control BC-B	15 % RAP	20% RAP	40% RAP	40% RAP + Rej
Density (kg/m^3)	-	2500	2535	2493	2513	2508
Gmm	-	2.717	2.743	2.709	2.672	2.673
Air voids (%)	4.5 – 8.0 %	7.7	7.3	7.7	5.7	5.9
TSR (%)	Min 60%	65	54	63	51	64
Rut depth (mm)	Max 12.5 mm	15.0	6.5	5.1	2.5	8.5

The bulk density results showed little variation between the control and RAP asphalt mixtures with values ranging between 2493 and 2535 kg/m^3. The G_{mm} values varied within the range of 2.743 and 2.672, with the lowest values for the highest RAP content. For Marshall Mix Design the QCS 2014 Section 6 Part 5 specifies the air voids for base course (Class B) to be between 4.5 % and 8 % at construction. The results in Table 4-5 are obtained after 1 year in service and all the mixtures fell within the specified limit. The control, 15 % RAP and 20 % RAP gave similar values within the range of 7.3 % and 7.7 %, whereas a lower range of 5.7 % to 5.9 % was found for the 40 % RAP and 40 % RAP + Rejuvenator mixtures.

The performance testing of TSR, to ASTM D4867 (2014), and rut depth, to AASHTO T324 (2019), were conducted on the asphalt cores from different trial sections. The Ashghal Recycling Manual (2021) specifies a minimum TSR value of 60% for unmodified binder and a maximum rut depth of 12.5 mm using the Hamburg wheel tracker test at 60°C of wet condition after 20,000 passes. The control, 20% RAP and 40 % RAP + Rejuvenator exhibited TSR values of 65 %, 63 % and 64 %, respectively, higher than the minimum specified limit of 60 %. The results of asphalt rut depth are also presented in Table 4-5. Increasing the RAP content from 0 % to 40% resulted in increased resistance to deformation as given in Table 4-5. The highest rut depth of 15 mm was found for the control mixture, which exceeded the maximum specified limit of 12.5 mm. The 15 % RAP and the 40 % RAP mixtures gave rut depth results of 6.5 mm and 2.5 mm, 57 % and 83 % lower than the control mixture, respectively. The use of rejuvenator (40% RAP + Rej) resulted in a softer binder, than other RAP mixtures with a rut depth of 8.5 mm, lower than the maximum specified limit.

Table 4-6 In-situ binder properties of asphalt samples pen 60-70 from Izghawa

Parameter	Control BC-B	15 % RAP	20% RAP	40% RAP	40% RAP + Rej
Binder content	3.7	3.7	3.6	4.3	4.2
Penetration 25°C (0.1mm)	20	23	19	21	20
Softening Point (°C)	57.7	56.9	59.4	59.0	57.2
Ductility @ 25°C (cm)	25	21	15	16	33
DSR (G*/sinδ) at min 1kPa	82.9	82.3	88.6	85.1	83.5

The binder recovery results of the RAP asphalt trials of Izghawa are given in Table 4-6. The binder content was almost the same for the control asphalt, 15 % RAP and 20 % RAP with values between 3.6 % and 3.7 %. The 40 % RAP and 40 % RAP + Rej gave higher values of 4.3 % and 4.2 %, respectively. When compared to the binder content results at construction, the control, 15 % RAP and 40 % RAP asphalt mixtures exhibited similar values after 1-year in service. However, there is a variation of 0.6 % for the 20 % RAP and 0.5 % for the 40 % RAP + Rej. The performance results after 1-year in service seem more realistic and the difference in binder content may be attributed to the reproducibility of results from different testing laboratories.

The grading results of the extracted aggregate from cores are shown in Figure 4-7. The grading results after 1-year in service were within the grading envelope, with the exception of the 20 % RAP asphalt that exhibited higher percentage of materials passing sieves of 12.5 mm and 9.5 mm. The grading results indicate the importance of controlling the consistency of RAP materials to produce mixtures complying with the required specifications.

The binder recovered from the cores after 1-year in service showed very low penetration results as shown in Table 4-6. The penetration values ranged between 19 and 23 with approximately 65 % -70 % reduction compared to the initial bitumen grade of 60/70 pen. However, the reduction in penetration was found in all mixtures, including the control mixture, with no evidence of increased hardening of the RAP mixtures. The effect of hardened bitumen on the softening point is also shown in Table 4-6 with values between 56°C and 59°C, exceeding the minimum specified limit of 46°C in the QCS 2014 at construction.

The binder ductility and DSR results also confirm the rapid hardening of the binder after 1-year. Table 4-6 show ductility values of 15 cm to 33 cm, which are much lower than the QCS 2014 minimum specified value of 100 cm for the fresh binder. Within the various asphalt mixtures, the use of 15 % RAP caused a slight reduction in binder ductility and the 40 % RAP with rejuvenator resulted in the highest ductility value of 33 cm. Nevertheless, all the values are still too low and indicate rapid hardening of the binder with increased risk of fatigue cracking within the hot climate in Qatar.

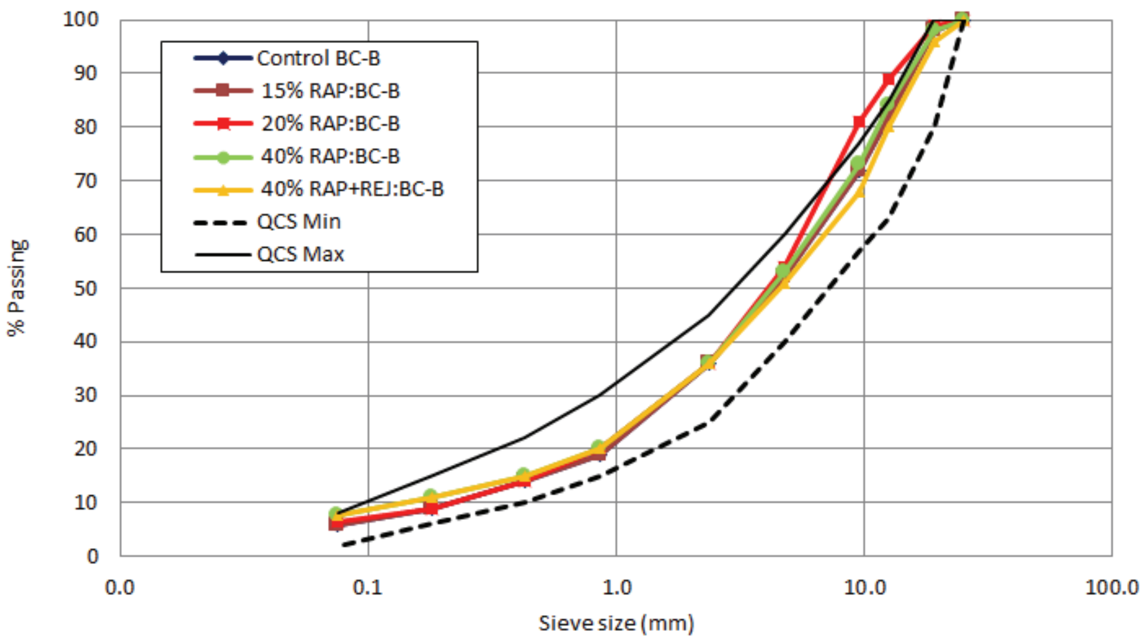

Figure 4-7 Sieve analyses of extracted aggregate from cores – Izghawa trials

The DSR testing was conducted as per AASHTHO T315 (2019) at different temperatures between 64 and 82°C, with an interval of 6°C. As per the QCS 2014, the limiting value for

G*/sinδ is 1kPa at angular frequency of 10 rad/s. The performance grade (PG) after 1-year was PG 82 for the control, 15% RAP, 40% RAP and 40% RAP + Rej, whereas a PG 88 was found for the 20% RAP. Considering the initial recovered binder from RAP aggregate of PG 72, the hardening of PG 82 and PG 88 are relatively high after 1-year in service.

The results indicate that 15 % RAP can exhibit similar performance as the control asphalt, made with 100 % imported gabbro, without modifying the asphalt mix design. The use of a rejuvenator is recommended at higher RAP contents, > 15 %, to restore the aged binder components and enhance the durability of fatigue resistance of the new mixtures.

4.2 Steel Slag Aggregate

The use of steel slag contributes to sustainable development by reducing both the use of natural aggregate, with associated energy consumption and transportation, and disposal of waste materials to landfills. Steel slag provides a strong and dense aggregate with favourable properties for use in construction (FHWA, 2016). When incorporated in hot mix asphalt (HMA), its shape and rough surface texture improve the affinity with bitumen and stripping properties, and result in high stability and resistance to rutting and fatigue cracking (Airey et al., 2004; Wu et al., 2007; Ahmedzade and Sengoz, 2015; Khodary, 2015).

Dimensional instability of the slag remains the main concern for use in construction, especially in hot climates. The increased susceptibility of slag-asphalt to long-term laboratory aging, due to the chemical composition of the slag aggregate, which acts as a catalyst for oxidative hardening of the bitumen (Airey et al., 2004). Weathering of the Qatari steel slag aggregate for 1 year was undertaken to produce aggregate with low susceptibility to expansive reactions. The properties of steel slag satisfied the aggregate requirements for used in hot mix asphalt mixtures and was successfully used to replace 20 % and 40 % of imported gabbro (Hassan et al., 2021). This section summarises the construction of road trials made with hot mix asphalt containing weathered steel slag aggregate. It also provides data on the field performance of the slag asphalt immediately after construction and after 3 years in service. It provides useful information on the long-term expansion properties of slag aggregate in hot arid climate.

4.2.1 Construction Data

A road trial was constructed in October 2016 within the premises of the Qatar Steel factory in Mesaieed. A heavily trafficked road was selected for the construction with a total length of approximately 700m, constructed with different pavement sections adjacent to each other. The old pavement was in bad condition and was removed to the subgrade level and replaced with a new construction comprising a new unbound subbase material (300 mm, 2 layers) and asphalt base course – Class A (160 mm, 2 layers). The asphalt mixtures developed with steel slag aggregate (Hassan et al., 2021) used for the road trials included:

- Control section, 100 % gabbro aggregate
- 20% steel slag, representing 50 % by weight of the coarse aggregate (5 - 20 mm)
- 40% steel slag, representing 100 % by weight of the coarse aggregate (5 - 20 mm)

During construction, loose asphalt samples were collected at the front of the paver for testing. The collected loose samples were tested for aggregate gradation, binder content, and for the preparation and testing of Marshall specimens. The combined grading was confirmed as fulfilling the QCS 2014 for all mixtures, as shown in Figure 4-8.

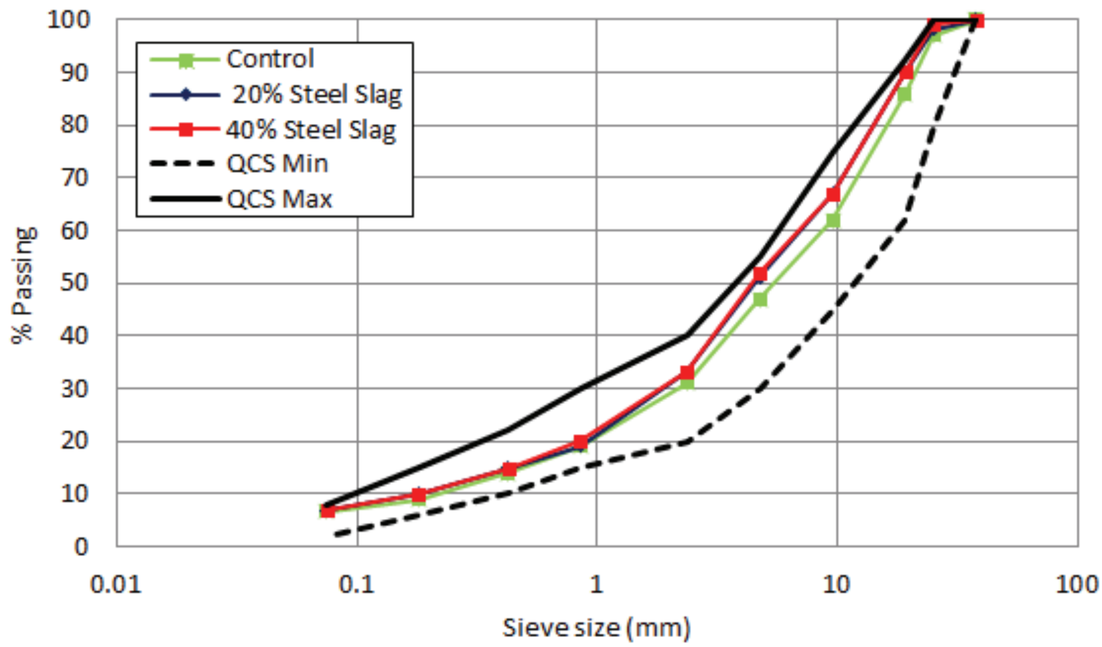

Figure 4-8 Gradation of extracted aggregate – Loose asphalt mix

The grading of the 20 % steel slag was identical to that of the 40 % steel slag. The grading of the control, 20% slag and 40% slag asphalt fell within the envelope given in the QCS 2014 for asphalt BC-Class A. During construction, no difference was noticed in mixing and laying the slag mixtures compared to the conventional asphalt control. The slag asphalt flowed easily through the paver and was compacted in the same manner as the control asphalt.

The rough surface texture and high absorption values of the slag aggregate, compared to the control gabbro, resulted in a higher binder content to achieve the same level of air voids (Hassan et al., 2021). The optimum binder content for the control mixture was 3.6 %, increasing to 3.7 % and 3.8 % for the 20 % and 40 % slag asphalt mixtures, respectively. The average Marshall results for the loose samples collected during construction are given in Table 4-7. All the asphalt mixtures fulfilled the Marshall mix design requirements, as specified in the QCS 2014 for BC-Class A. The Marshall stability was higher than the minimum specified value, with no great difference between the mixtures. Similar performances were also obtained based for Marshall flow and Quotient (stiffness). The volumetric properties of VIM, VMA and VFA satisfied the requirements of the QCS 2014 for the asphalt mixtures made with slag aggregate (20 and 40%) and the control 100% gabbro.

Samples compacted to 400 blows, using the Marshall hammer, showed air voids values for the control and 20 % slag asphalt mixtures above the QCS 2014 minimum of 3.2%, while the 40 % steel slag showed a lower value of 2.9% as highlighted in yellow in Table 4-7. In general, the Marshall results of steel slag mixtures were promising with only the 40 % slag asphalt mixture out of specification limit for voids at 400 blows.

Table 4-7 Average Marshall test results – Loose asphalt mix

Parameter		QCS limits	100% Gabbro	20% Steel Slag	40% Steel Slag
Binder Content (%)		3.2-4.4	3.6	3.7	3.8
Gmm		-	2.791	2.878	2.972
Marshall, 75 blows	Stability (kN)	9.5 min	20.8	21.8	21.0
	Flow (mm)	2-4	2.8	2.8	3.0
	Quotient (kN/mm)	4.75 min	7.6	7.8	7.1
	VIM (%)	4-8	6.3	6.7	5.8
	VMA (%)	13 min	13.1	14.5	14.1
	VFA (%)	50-70	52.8	54.6	59.3
Marshall, 400 blows	Gmb (kg/m^3)	-	2.668	2.773	2.885
	VIM (%)	3.2 min	4.4	3.7	2.9
Cores	In place air voids (%)	5.0-8.0	6.9	6.7	7.2
	Compaction level (%)	97.0-101.8	99	100	99.4

Core samples (150 mm diameter) were obtained from the laid asphalt, immediately after construction, and tested for in situ air voids and the degree of compaction (ratio between field bulk density to Marshall samples bulk density). The results are also given in Table 4-7 and show values in compliance with the QCS 2014 requirements, with no obvious trend for the different mixtures of control, 20 % slag, and 40 % slag asphalt mixtures.

4.2.2 Performance Data

The performance of the slag asphalt was assessed by visual monitoring of the road trials and testing cores at different time intervals. Visual inspections were made immediately after construction and then periodically every year up to the end of 2019. The road is heavily trafficked, exceeding 500 loaded trucks per day, bringing scrap metals and a range of raw materials to the furnaces in the steel plant. This is estimated to be equivalent to 3.4 million equivalent single axle load (ESAL)/year. The visual inspection after 3 years in service showed excellent performance of the road trials, Figure 4-9, with no visual difference between the slag and control asphalt sections. No surface defects in the form of cracks, rutting or bleeding were observed in the asphalt sections.

Cores were collected in January 2020, after 3 years in service, and tested for bulk density (G_{mb}) to ASTM D2726 (2013), indirect tensile test (IDT) to ASTM 4867 (2014), moisture damage

AASHTO T283 (2014), and maximum theoretical density (G_{mm}) to ASTM D2041 (2019). A summary of the test results is given in Table 4-8.

Figure 4-9 Visual condition of the pavement trials after 3 years in service

The in-situ voids in the total mix (VIM) of the asphalt cores, taken immediately after construction and after three years, are shown in Figure 4-10. The VTM results at construction were very similar for the control and 40 % slag, with a slightly lower value of 6.6 % for the 20 % slag. After three years in service, the slag mixtures exhibited lower reduction in air voids compared to the control asphalt. The VIM for the control mixture reduced from 6.9 % at construction to 3.7 % after three years, a reduction of 86 %. The reduction of slag mixtures was 40 % for 20 % slag and 61 % for the 40 % slag, indicating improved resistance to deformation under increased traffic loading. Figure 4-11 presents the dry indirect tensile strength of the asphalt cores at construction and after 3 years. All the asphalt mixtures showed increase in the tensile strength with time, probably due to the aging of the bitumen. A slight increase in the IDT is noticed with increasing the slag content, which could be attributed to improved bond characteristics between the slag aggregate and bitumen.

Bitumen was extracted from the asphalt cores following the procedure described in ASTM D2172 (2017), Method A. The bitumen was recovered from the solvent using the rotary evaporator as per ASTM D5404 (2017). The recovered bitumen was tested for penetration to ASTM D5 (2019), Softening Point to ASTM D36 (2014), ductility to ASTM D113 (2017), and complex modulus and phase angle (δ) to AASHTO T315 (2019). Results of the recovered bitumen are presented in Table 4-8, together with the results of original bitumen and after aging in the rolling thin film oven (RTFO), ASTM D2872 (2019), as per references.

Table 4-8 Properties of asphalt cores and recovered bitumen after 3 years in service

Parameter		100% Gabbro	20% Steel Slag	40% Steel Slag	Original bitumen	RTFO bitumen
Cores	Gmb (kg/m^3)	2638	2722	2837		
	Gmm	2.747	2.866	2.977		
	VIM (%)	3.7	4.7	4.4		
	IDT dry (kP)	1283	1376	1477		
	TSR (%)	96	95	96		
Recovered binder	Penetration @ 25°C (0.1mm)	20	20	23	64	54
	Softening Point (°C)	58	59	56	48	54
	Ductility @ 25°C (cm)	44	45	69	150	110
	DSR (G*/sinδ) temp at 10 rad/s (°C)	83.7	84.9	79.9	1.19 @64°C	2.31 @ 64°C

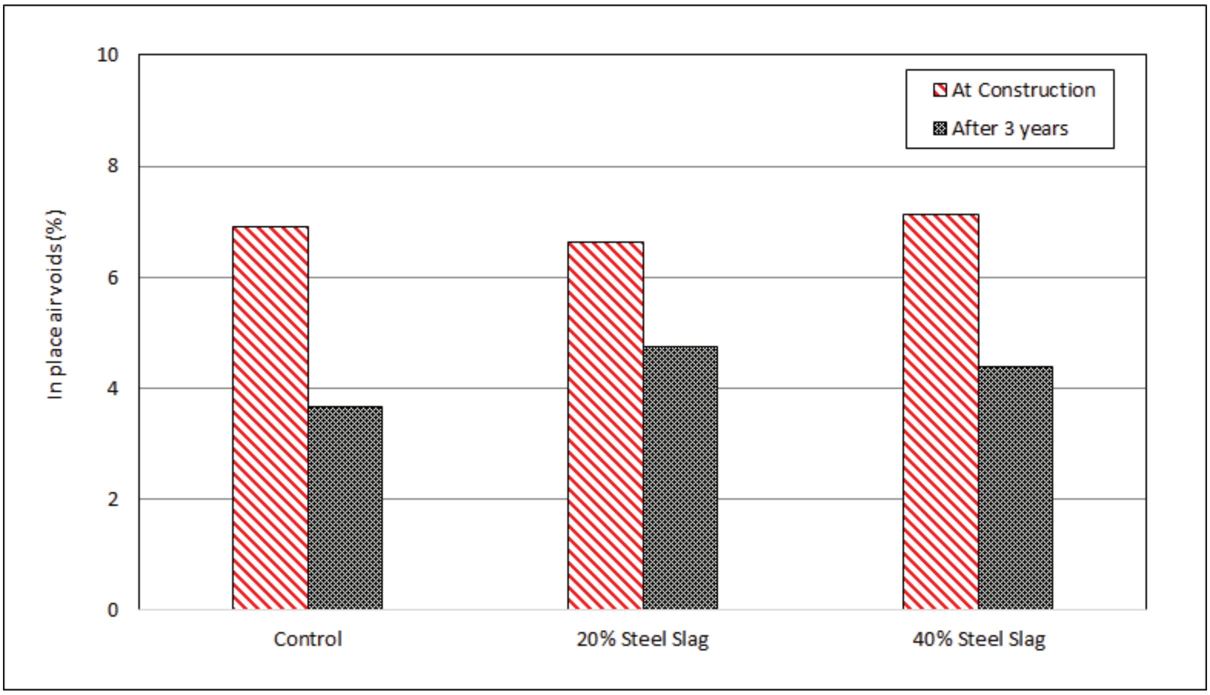

Figure 4-10 In-place air voids at construction and after 3 years in service

The fresh bitumen used for the road trials was pen 60/70 binder, equivalent to Performance Grade PG 64-10. Hardening of the bitumen binder takes place from the time of asphalt mixing. The penetration results of the recovered binder after three years in service show identical values of 20 mm for the control and 20 % slag, with a slightly higher value of 23 mm for the 40 % slag. The penetration results indicate a rapid aging of asphalt in the hot environment, but with no evidence of increased hardening for the slag asphalt up to 40% replacement.

The results of softening point and ductility show a similar trend to the penetration, of very similar values for the control and 20 % slag mixtures. However, less aging more improvement was noticed from the 40 % slag mixture with a ductility value of 69 cm, indicating a lower aging rate of the bitumen. Dynamic shear rheometer (DSR) provides additional information relating to the stiffness behaviour of bitumen over a range of temperatures and reflects the true grade of recovered bitumen. The results in Figure 4-12 and Table 4-8 clearly show a softer recovered bitumen for the 40% slag asphalt, compared to the control and 20% slag mixtures. The 40% slag showed the lowest level of aging, when comparing the change of complex modulus (G*) / sin δ (phase angle) with temperature.

In general, the properties of recovered binder indicate significant binder aging for all mixtures due to the hot climate in Qatar, in agreement with Sirin et al. (2017). However, there is no evidence that the steel slag aggregate, as processed in this investigation, would change the aging behaviour compared to conventional gabbro aggregate. The results obtained in this study provide confidence the wider use of steel slag aggregate in HMA.

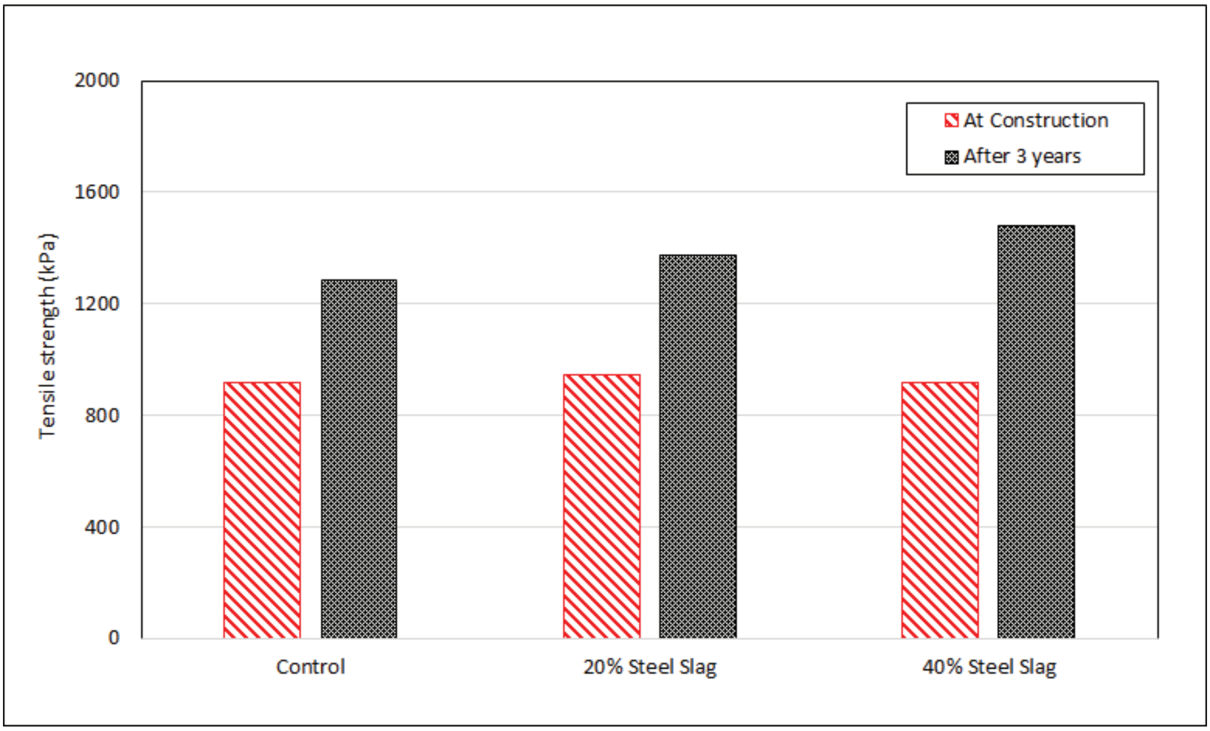

Figure 4-11 Dry indirect tensile strength

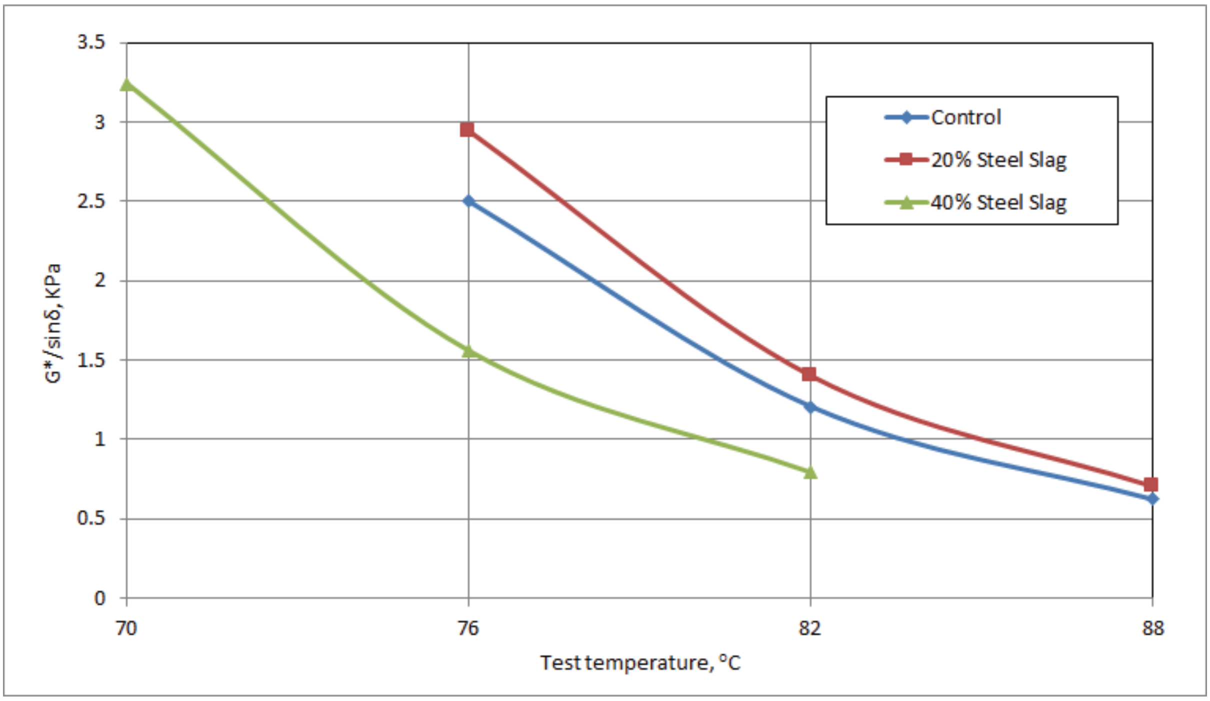

Figure 4-12 DSR (G*/sinδ) at 10 rad/s for the control and slag mixtures

4.3 Crumb Rubber

The growing number of waste tyres in Qatar has become a major environmental concern. When tyres catch fire, they burn with intense heat and produce toxic smoke that can cause serious health problems. The use of crumb rubber as an additive in hot mix asphalt (HMA) mixture contributes to sustainable development and is considered within the NDS-2 target and the Ashghal Recycling Manual (2021). This section summarises the properties of crumb rubber modified binder (CRMB) in comparison to a conventional bitumen of 60/70 penetration grade. It presents site data on the performance of CRMB asphalt up to 1 year in service.

4.3.1 Binder properties

The properties of CRMB are compared to a control 60/70 penetration grade bitumen that is commonly used in Qatar. Table 4-9 presents the main characteristics of CRMB binder used in the study. Crumb rubber (CR) is currently produced locally in Qatar and is available in large quantities. The CR used in the study was derived from truck tyres, and was in compliance with the requirements of the QCS 2014 and the Ashghal Recycling Manual (2021). The grading of CR was passing sieve No. 30 (0.60 mm) and was mixed with bitumen at elevated temperature of 180 - 190 °C. The CR content was 12% by weight of bitumen, within the specified range of 10 to 25 %.

The addition of CR has been shown to increase the penetration, softening point, and viscosity of the bitumen. The results in Table 4-9 show that adding CR to the binder increased its viscosity at 135 °C from 0.45 Pa.s to 2.35 Pa.s. The higher viscosity would require higher mixing and compaction temperature to achieve the desired workability of the mixture. The addition of CR to the bitumen enhanced its high temperature characteristics. The high temperature dynamic shear (G*/Sin δ) reached 2.89 kPa at 76°C compared to 1.43 kPa at 64°C for the control 60/70 penetration grade binder. The increased stiffness of CR will be expected to provide improved deformation and fatigue resistance in hot weather.

Table 4-9 Binder properties of CRMB and 60/70 pen bitumen

Test Parameters	Standard	CRMB	Control (60/70)	QCS 2014 limits
Original binder				
Flash Point temperature (°C)	AASHTO T48	304	302	230 °C min
Rotational Viscosity @135 °C	AASHTO T316	2.63	0.45	3.0 Pa.s max
DSR r, G*/sinδ, @ 64 °C for 60/70 & 76C °C for CRMB at 10 rad/s, kPa	AASHTO T315/ ASTM D7175	2.89	1.43	1.0 kPa min
RTFO Residue				
DSR r, G*/sinδ, @ 64 °C for 60/70 & 76 °C for CRMB at 10 rad/s, kPa	AASHTO T315/ ASTM D7175	3.88	3.54	2.2 kPa min
Mass Loss, Maximum Percent	AASHTO T240	0.084%	0.15	1 % max
J_{nr} 3.2 kPa^{-1}, (@64 °C for 60/70 & @76 °C for CRMB)	AASHTO T350/ ASTM D7405	0.27	2.79	1 kPa^{-1}Max
Recovery R3.2 @ (@64 °C for 60/70 & @76 °C for CRMB)		80.51	0.332	Report
J_{nr} diff, %, (@64 °C for 60/70 & @76 °C for CRMB)		1371.22	7.33	Report
PAV Residue				
PAV Aging Temperature, (°C)	AASHTO R28	110	110	110 °C
Dynamic shear, G*sinδ @ 37 °C, at 10 rad/s, KPa	AASHTO T315/ ASTM D7175	810	4410	5000 max
Creep Stiffness,(S) MPa at (@-12 °C for 60/70 & @0 °C for CRMB), MPa	AASHTO T313	35.45	170.5	300 max
m-value (@-12 °C for 60/70 & @0 °C for CRMB)	AASHTO T313	0.397	0.319	0.30 min

The rolling thin film oven (RTFO) test measures the effect of heat and air on a moving film of hot mix asphalt binder, simulating short-term aging that occurs during production and paving operations. After aging the binder in the RTFO test, the CRMB had G*/Sin δ of 3.88 kPa at 76 °C compared to 3.54 for 60/70 penetration grade binder at 64 °C, indicating another enhancement in rutting resistance at high temperature. The selected test temperature is based on the expected binder grade.

The pressure aging vessel (PAV) provides simulated long term aged asphalt binder for physical property testing. Asphalt binder is exposed to heat and pressure to simulate in-service aging over a 7 to 10 year period. The result of the PAV aged CRMB, G*/Sin δ was only 880 kPa compared to 4400 kPa for the control 60/70 pen grade binder, indicating significantly less aging than the control. Whilst the original and RTFO CRMB exhibited stiffer characteristics than the control 60/70 pen bitumen, it was not aged to the same level of the 60/70 pen after the PAV testing. The effect of retarding binder aging for the CRMB over long term is of great importance to the rapidly aging asphalt pavement in hot countries, such as Qatar and the Gulf region.

Based on the results presented in Table 4-9, the CRMP is classified as PG 76 E-10 in accordance with AASHTO M332, i.e. a stiff binder, compared to the control 60/70 binder, which was classified as PG 64 H-22.

4.3.2 Mix Design

The use of CRMB is currently limited to asphalt wearing courses in local roads, whereas polymer modified binder (PMB) is used as the wearing course for primary roads and highways. The CRMB mix was designed as wearing course following the Superpave mix design requirements according to the QCS 2014. Details of the CRMB mix design are given in Table 4-10, and the grading is graphically presented in Figure 4-13.

Table 4-10 Mix Design of CRMB – Superpave QCS 2014

Test Parameters		CRMB Mix Design	QCS 2014 (Superpave, 19 mm NMAS)
Binder content, %	ASTM D2172	4.4	JMF value ±0.40
Dust/binder ratio	ASTM D6307	1.1	0.8-1.6
Bulk specific gravity, G_{mb}	ASTM D2726	2.605	-
Density, gm/cm^3		2.607	-
Max specific gravity, G_{mm}		2.716	-
Voids in total mix, VIM %	ASTM D2041	4.0	4%
Voids in mineral aggregate (VMA), %	ASTM D2041	13.8	min 13
Voids Filled with Asphalt (VFA), %	ASTM D5821	71.1	65 to 75
Tensile Strength Ratio (TSR),%	ASTM D4867	98.0	min 80%

The CRMB grading fell within the grading envelope complied specified for the 19 mm nominal maximum aggregate size (NMAS) in the QCS 2014. The grading of the CRMB is relatively coarse in the fine aggregate range, containing 41 % passing 4.75 mm. The grading of the fine aggregate also coincided with the minimum grading levels at sieve sizes of 4.75 mm to 0.18 mm.

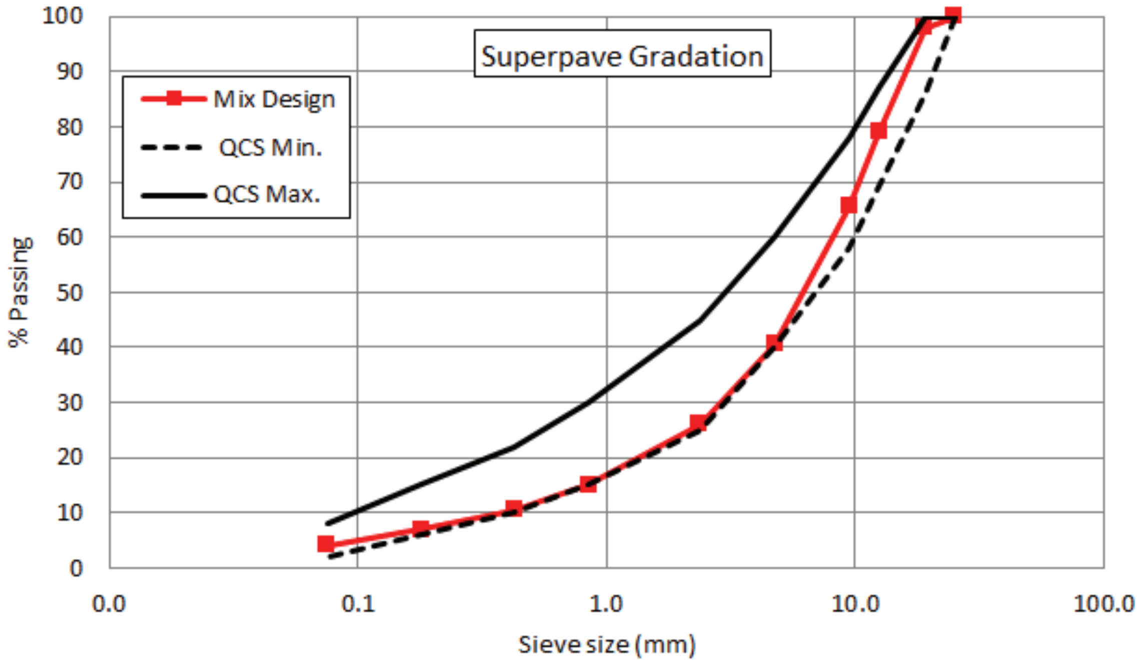

Figure 4-13 Grading of the CRMB mix design

The CRMB asphalt exhibited excellent resistance to moisture susceptibility with a tensile strength ratio (TSR) of 98 %, much higher than the minimum specified value of 80 % in the QCS 2014. The high TSR can be attributed to the improved bond of the CRMB with aggregate and also to the low values of voids in total mix (VTM) and voids in mineral aggregate (VMA).

4.3.3 Site Performance

The CRMB was used in the construction of a road section of Al-Bustan Street in November 2018, Figure 4-14. The construction was limited to a section of CRMB binder, approximately 200 m length, to assess its compliance with the QCS 2014 requirements. The thickness of the CRMB wearing course was 50 mm. During construction, loose mix samples were collected to check the conformance of produced mix to the mix design and specifications. Cores were also taken immediately after construction to assess the compaction level and in-place voids content. The results of site data at construction are summarised in Table 4-11. Core samples were also collection after 2 years of service and were subjected to the testing of bulk density (G_{mb}) to ASTM D2726 (2013), maximum theoretical density (G_{mm}) to ASTM D2041 (2019), indirect tensile test (IDT) to ASTM 4867 (2014), moisture damage to AASHTO T283 (2014), and rut depth using the Hamburg Wheel-Track Testing to AASHTO T324 (2019). The performance results after 2 years are also presented in Table 4-11.

Figure 4-14 Construction of CRMB road section – Al-Bustan Street

The grading curves of the CRMB mixtures at construction and after 2 years in service are shown in Figure 4-15, together with the specified limits in the QCS 2014. Similar to the mix design, the site data showed acceptable grading for the coarse aggregate > 4.75 mm, but coarse grading for the fine aggregate passing 4.75 mm. In fact, the grading of the CRMB mixture after 2 years failed the grading requirements at sieve sizes 4.75 mm and 2.36 mm, giving lower values than the minimum specified. The grading of asphalt mixtures can be adjusted by improving the quality production at the plant.

Table 4-11 shows the CRMB mix properties of the fresh samples collected during construction. For comparison, the mix properties were compared to Marshall mix design requirements given in the QCS 2014. The air voids after 400 blows was 4.5 %, higher than the minimum specified limit of 4.0 %. The 400 blows test is a measure of the voids content at maximum compaction, as an indication of the mix's resistance to permanent deformation (rutting). The air voids after 400 blows of the CRMB mix was higher than the specified limit, indicating enhanced rutting resistance. The Marshall stability of the CRMB mix was also higher than the minimum specified value of the QCS 2014. The volumetric properties of the CRMB at construction are also within the specified limits of the QCS 2014.

Core testing at construction showed an average in-place voids of 6.5%, within the QCS 2014 specified range of 5 % to 8 %. The average field density varied from 2495 to 2523 kg/m^3, representing 98.7 % to 99.8 % of achieved Marshall density (2528 kg/m^3), and within the QCS 2014 specified range of 98 % to 101.8 %.

Table 4-11 CRMB Mix performance at construction and after 2 years in service

Test Parameters		Construction	At 2 years	QCS 2014 limits	
				Min	Max
Binder content, %	ASTM D2172	4.0	3.9	3.4	4.4
Filler/Binder ratio	ASTM D6307	1.01	1.13	0.75	1.35
Bulk specific gravity, G_{mb}	ASTM D2726	2.536	2.543	-	
Bulk density, kg/m^3		2528	2536	-	
Maximum specific gravity, G_{mm}		2.705	2.687	-	
Air voids, Va, %	ASTM D2041	6.3	-	5	8
Voids in mineral aggregate (VMA), %	ASTM D2041	15.8	-	14	
Voids Filled with Asphalt (VFA), %	ASTM D5821	60.2	-	50	75
Stability (kN)	ASTM D6927	12.9	-	11.5	
Flow (mm)	ASTM D6927	2.5	-	2	4
Marshall Quotient (kN/mm)	ASTM D6927	5.14	-	Min 5.25	
Retained Stability, %	ASTM D6927	_	_	75	
Voids at 400 Blows per face, %	ASTM D2041	4.7	-	4.0	
Core test results					
In-place air voids, %		6.5	6.0	5	8
Degree of Compaction, %		99.3	-	98	101.8
Rut depth (mm) at 60 °C, Wet, 20,000 passes, mm				6.2	12.5 max
Tensile Strength Ratio, %				91	75 min

The performance results of the CRMB after 2years in service, Table 4-11, show air voids of the collected cores of 6.0 %, slightly lower than the 6.5 % at construction and within the QCS 2014 specified range of 5.0 % to 8.0 %.5.1%. The air void of asphalt mixtures is expected to reduce with time due to traffic loadings. The slight reduction in voids after 2 years reflects the good resistance of the CRMB to permanent deformation.

Two performance tests are specified in the QCS 2014 and the Ashghal Recycling Manual for assessing the performance of CRMB mixtures of tensile strength ratio (TSR) and rut depth. The TSR of the CRMB asphalt was 91 % after 2 years in service, and indicates clearly the high resistance of the CRMB mixture to moisture damage and aging.

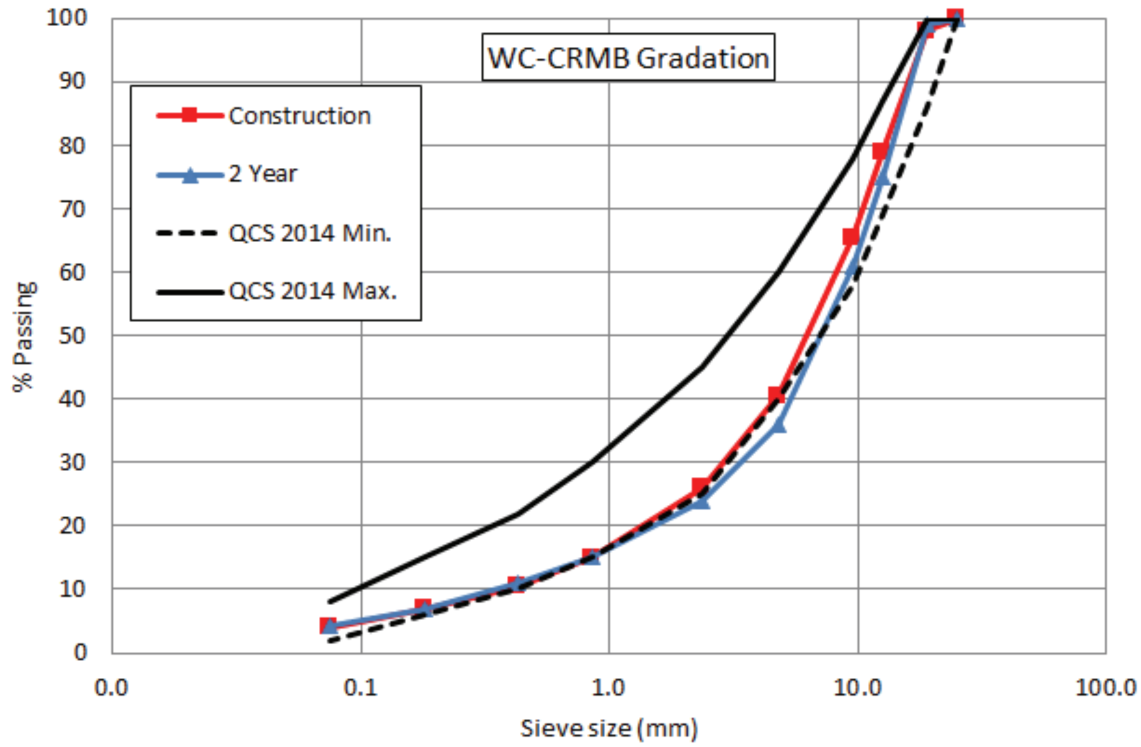

Figure 4-15 Grading of the CRMB mixtures at construction and after 2 years in service

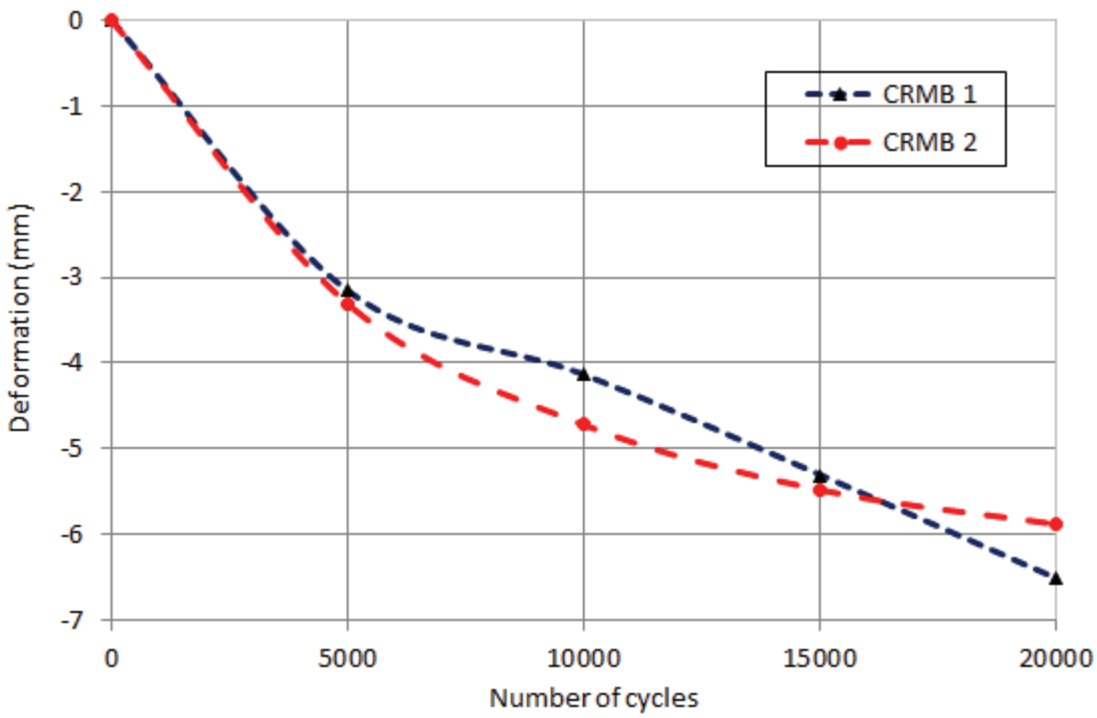

Figure 4-16 Rut depth of CRMB cores after 2 years in service

The rut depth test was conducted as per the Humberg Wheel Tracking (HWT) test to AASHTO T324 (2019) to assess mix resistance to rutting and potential stripping. Collected cores were tested at 60°C, submerged in water (wet condition). The Ashghal Recycling Manual (2019) specifies a maximum rut depth of 12.5 mm after 20,000 passes. The results are presented in Figure 4-16 for the 2 set of cores tested in the laboratory. The average rut depth was 6.2 mm, Table 4-11, half of the maximum specified limit in the Ashghal Recycling Manual and indicates good resistance to rutting and permanent deformation after 2 years in service.

In general, the CRMB was found to greatly enhance the properties of binder aging with time, and the CRMB asphalt complied with the requirements of the QCS 2014 and the Ashghal Recycling Manual.

4.4 Summary

Recycled aggregate of RAP and steel slag aggregate were used to partially replace imported gabbro in the production of hot mix asphalt, and CR to partially replace the bitumen binder in CRMB mixture. Field data were used to assess the performance of asphalt made with recycled materials and to compare to conventional asphalt made with imported gabbro/binder and national specifications of the QCS 2014 and Ashghal Recycled Manual (Ashghal, 2021).

Good practice in the inclusion of RAP in hot mix asphalt was achieved through the fractioning and re-blending of aggregate of different size fractions. At 15 % RAP content, RAP was cold-fed directly into the asphalt mixture. At a higher RAP content, it is recommended to preheat the RAP aggregate to improve the mix consistency. Controlling the temperature of the mix ingredients is essential for the consistent production of RAP mixtures.

RAP asphalt was used to replace from 15 % up to 40 % by weight of imported gabbro. The RAP aggregate satisfied the requirement of the QCS 2014 for use as aggregate in hot mix asphalt. With the high RAP content of 40 %, it is essential to use a rejuvenator to improve the recovery of aged bitumen and the workability of the mixture. Field data confirmed the Ashghal Recycling Manual (2021) requirement of modifying the asphalt mix design when the RAP content is ≥ 30 %. The RAP asphalt showed similar performance to the conventional asphalt in satisfying the Marshall requirements. The specified performance requirements of TSR and rut depth could be achieved in situ with the use of RAP, with reduced rut depth and increased resistance to deformation for higher RAP content. A few data fell outside the specified limits from both the control and RAP mixtures, but the overall performance was similar.

The current practice of weathering the steel slag aggregate produced compliant aggregate with low susceptibility to expansive reactions. The properties of steel slag satisfied the aggregate requirements for use in hot mix asphalt mixtures, with higher binder content for increased slag content to achieve similar voids content to the control. Despite the similar results of in-situ voids content and IDT of the slag and gabbro asphalt immediately after construction, the slag asphalt exhibited lower reduction in voids and increased IDT after 3 years in service. The results confirm the benefits of slag aggregate in improving the bond characteristics with bitumen and resistance to pavement deformation.

The properties of the recovered binder indicated significant aging in service in the hot climate of Qatar. Great reduction occurred in the penetration grade and binder ductility with increased softening point and high-grade temperature of the recovered binder. However, the binder aging was observed in both asphalt mixtures made with conventional and recycled aggregate. There is no evidence of adverse effect of the RAP or slag aggregate on the binder ageing compared to the gabbro.

The main advantage of CRMB was in retarding the binder aging with time and enhancing the strength and durability properties of asphalt. For the PAV aged CRMB, the G*/Sin δ was only 880 kPa, compared to 4410 kPa for the control 60/70 pen grade bitumen. The low value of the CRMB indicates improved elasticity and enhanced aging properties over the long-term. The CRMB mixture complied with QCS 2014 and Ashghal Recycling Manual (2021) requirements. The mixture was designed following the Superpave specification, and performance was checked against the Marshall mix design criteria. The CRMB mixture fulfilled the specification requirements, with field data indicating good compaction on site, low air voids and enhanced resistance to moisture and permanent deformation. All asphalt parameters related to the strength of the material are boosted with the CRMB modification, including the Marshall stability, Marshall flow, Marshall stiffness, TSR, and rut depth.

The site trials presented in this chapter provide confidence in the use of RAP and steel slag aggregate and CRMB modification in HMA. As local recycled and by-product materials, they satisfy the aggregate and binder requirements and exhibit similar performance to imported gabbro. The RAP, slag, CR could be converted from waste, with potential impact on land use and the surrounding environment, into high value construction products to improve the aggregate supply chain and asphalt properties in Qatar.

5 Recycling in Concrete

Concrete is the most widely used construction material and the second most consumed material on earth, after water (Gagg, 2014). With its versatility, concrete can uptake large quantities and different types of local and recycled materials into various applications of ready mix and precast concrete. Recycled aggregate has the potential for use in highest value engineering products as partial replacement of primary aggregate in structural and non-structural concrete. This Chapter covers the performance of EW and Wadi gravel aggregate in structural concrete, as well as the performance of CDW, IBA and RCA in concrete blocks. A case study on the implementation of recycled aggregate in a concrete block factory is also presented.

5.1 EW and Crushed Rock Fines in Structural Concrete

Three building trials were constructed at Ashghal-Najma site in June 2013 (Hassan et al., 2015; Hassan et al., 2016). The site is located in a heavily built-up area in the capital, Doha, within 1 km of the coast. The trials were made with C40 structural concrete, which achieves cube strength of at least 40 MPa at 28 days water curing, and concrete blocks with the details given in Table 5-1. The site construction commenced in summer time, where average daytime temperature exceeded 40°C. Hassan et al. (2014) reported the early results of the performance of building trials up to 1-year.

Table 5-1 Use of recycled and secondary aggregates in building trials

Application	Building 1	Building 2	Building 3
C40 concrete	50% EW: 50% gabbro 100% washed sand	Control: 100% gabbro 100% washed sand)	100% gabbro 60% CRF (replacing sand), 10% cement reduction
Concrete blocks	50% CDW (replacing gabbro)	Control (100% gabbro and 100% washed sand)	20% IBA (replacing Gabbro)

The building design consisted of three similar rooms each measuring 2.5m by 2.5m by 4.0 m that consisted of ground beams, slab on grade, columns, roof beams and roof slab. Additional concrete beams were constructed adjacent to the building trials for monitoring performance in service. Erection of the concrete structural elements of the rooms was finalised by the end of June 2013.

The building trials were periodically inspected up to the age of 5 years. Figure 5-1 shows the building trials immediately after construction, and Figure 5-2 after 5 years in service. The structural concrete of Building 1 was made with the 50% EW (left), Control (middle) and 60% CRF (right). Similarly, the concrete blocks were made with the 50% CDW (left), Control (middle) and 20% IBA (right).

Figure 5-1 EW and CRF building trials immediately after construction

Figure 5-2 EW and CRF building trials after 5 years in service

The buildings were left exposed without the application of a mortar rendering or paints that could provide additional protection to the concrete. Such exposure enabled accurate visual assessment of the performance of concrete elements made with different recycled and alternative aggregates. The structural concrete elements of slabs, columns, and beams exhibited excellent performance with no signs of deterioration or cracking observed in any of the building at any age up to 5 years. The inspection showed identical performance of the 3 buildings with no obvious differences between them. Overall, the 3 buildings were in good conditions with no apparent structural or non-structural damage in the concrete elements and blocks. Continuous monitoring is planned to provide a longer-term performance data.

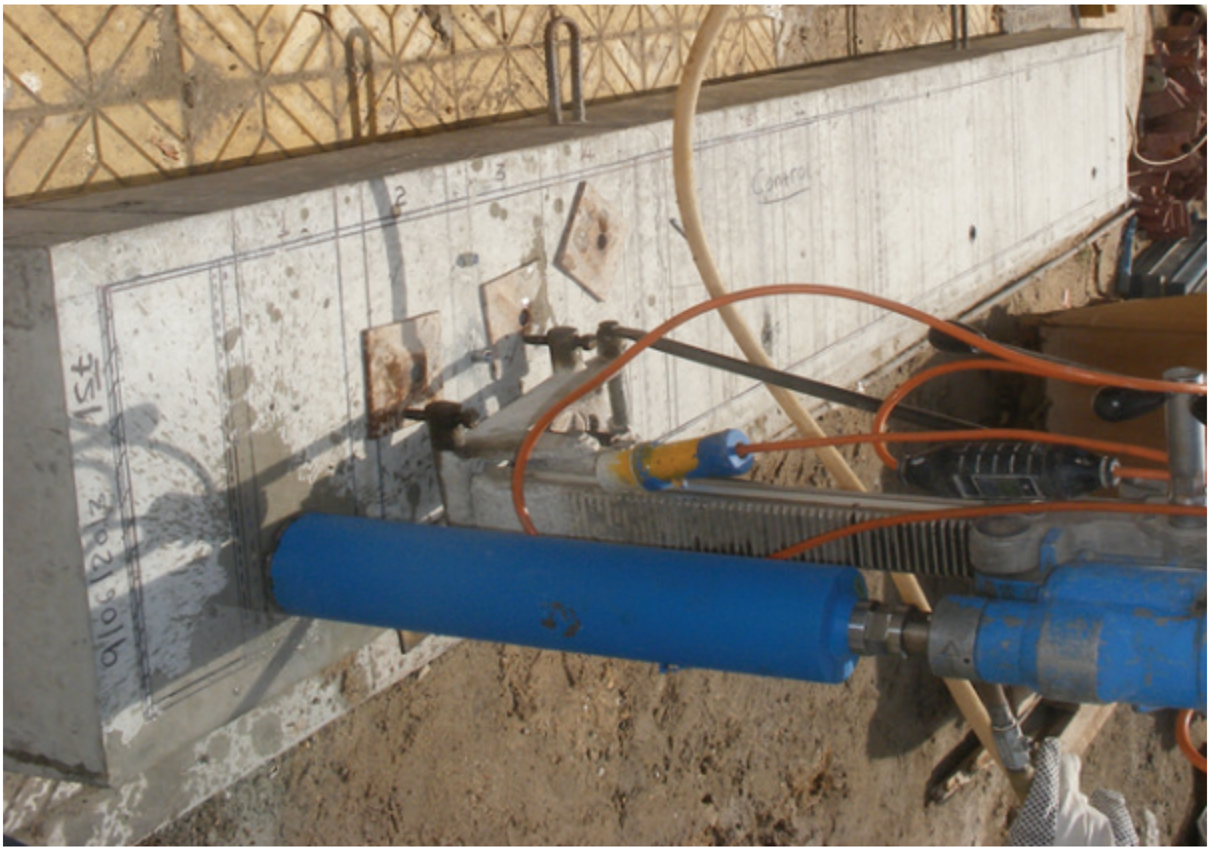

Figure 5-3 Testing beam with marks and initial coring at 28 days

Figure 5-4 Coring of the testing beams at 5 years

In addition to the buildings, concrete beams with the dimensions of 200 x 500 x 4000 mm were cast on site for coring and assessing performance at different ages, while maintaining the buildings intact. One beam was cast for each of the structural concrete mixtures, Table 5-1, and marked on the surface to avoid coring through the steel reinforcement, as shown in Figure 5-3. The beams were exposed to the same exposure environment as the building trials and were cored at different ages for testing (Figure 5-4). The coring and testing of the concrete cores were carried out by an independent testing house approved by Ashghal.

5.1.1 Performance testing and results

The C40 concrete used for the construction of the buildings was composed of cement: coarse aggregate: fine aggregate: water in the weight ratio of 1: 3.27: 2.05: 0.44, respectively with a total cement content of 370 kg/m^3. The control concrete mixture was made with imported gabbro and local washed sand aggregate, and was used for the construction of Building 2. Excavation waste (EW) was used to replace 50% by weight of the imported gabbro in Building 1, whereas Building 3 was made by replacing 60% of local washed sand with imported crushed rock fines (CRF) of limestone aggregate. The selection of the CRF was made to reduce reliance on diminishing sources of sand deposits in Qatar. All the mixtures were designed to have the same water/cement ratio of 0.44, and the superplasticiser dosage was adjusted to achieve the same workability.

The materials used for the production of C40 concrete, properties, and compliance with the QCS 2014 requirements are reported elsewhere (Hassan et al., 2013). The EW aggregate satisfied the QCS 2014 requirements, except the chloride content. The water absorption of the EW was 2.3 %, slightly higher than the specified value of 2.0% for natural aggregate but within the relaxed specified value of 3% for recycled aggregate. The acid soluble chloride of the EW was 0.11, exceeding the maximum specified limit of 0.03%.

Cores were extracted from the testing beams at the ages of 28 days, 1 year and 5 years. The cores were tested for compressive strength, water absorption and rapid chloride permeability (RCP). Three core samples were used for each test at any tested age and the average values are reported.

5.1.1.1 Compressive strength

The compressive strength testing was conducted as per BS EN 12504-1 (2009) on cores of 100 mm diameter and 100 mm height. The core samples were prepared in accordance with BS EN 12390-3 Annex A (2009) by capping the flat surfaces with the sulphur mixture method. The core compressive strength results are presented in Figure 5-5 for the 3 building at testing ages of 28 days, 1 year and 5 years.

The C40 concrete mixtures were designed as C40, i.e. to achieve a cube compressive strength of 40 MPa after 28 days of water curing. Core strength is generally lower than cube strength mainly due to drilling disturbance of the core and inferior site curing compared to water curing for cubes (Neville, 2011; Yaqub and Javed, 2006). The results in Figure 5 5 show that both the control and 50% EW concrete mixtures gave a similar strength of 33 MPa at 28 days, and the 60% CRF achieved a higher strength of 41 MPa. Despite the hot weather exposure in Qatar, the compressive strength of concrete continued to develop with age. At the age of 1 year, all the mixtures exceeded 40 MPa, with the 60% CRF exhibiting the highest compressive strength of 53 MPa. At 5 years, the 60% CRF reached 70 MPa, whereas the control and EW concrete mixtures gave 60 MPa and 57 MPa, respectively. The strength results are relatively high for C40 concrete and indicate that recycled materials can be successfully used to achieve and exceed the desired concrete strength in field.

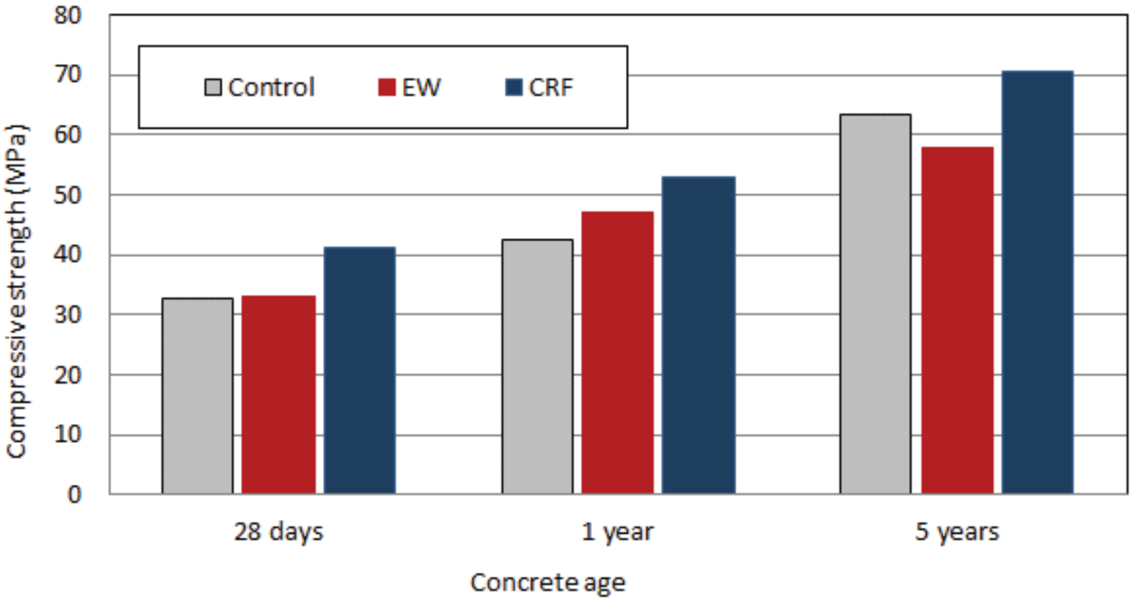

Figure 5-5 Core compressive strength up to 5 years

The considerable increase in strength after 28 days indicates continuous improvement of the concrete properties despite the harsh exposure environment of Qatar. Previous work on the long term mechanical properties of recycled aggregate concrete showed high strength gain after 5 years is mainly due to the improvement in bonding between the cement matrix and the recycled aggregate (Kou and Poon, 2008). The porous nature of the recycled aggregate could have contributed to the strength development due to internal curing and improved aggregate interface slowly over time.

5.1.1.2 Water absorption

The water absorption test was conducted as per the QCS 2014 in accordance with BS 1881-122 (2011) on concrete cores of 50 mm diameter and 75 mm height. The QCS 2014, Section 5 Part 6, recommends a range of 2 – 4% for a durable concrete.

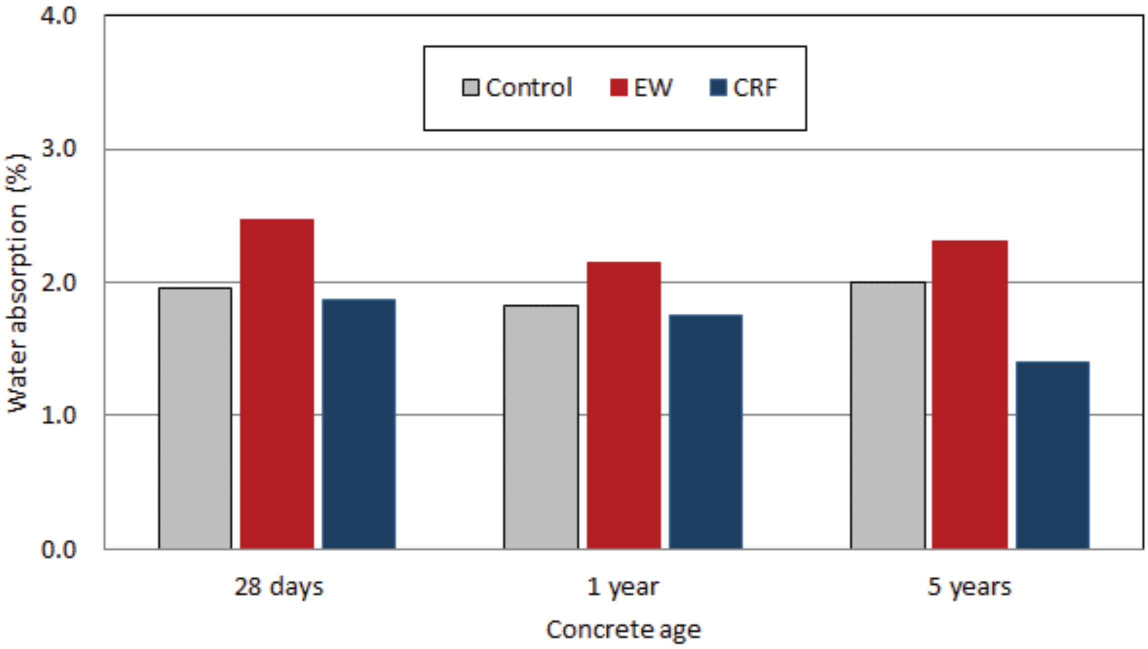

Figure 5-6 Core water absorption up to5 years

The results in Figure 5-6 show that the lowest absorption value of 1.4% was obtained for the 60% CRF concrete after 5 years in service. The low water absorption could be attributed to the fine particles of the CRF that improve the packing and densification of concrete. The more porous nature of excavation waste, compared to imported gabbro, resulted in the highest average absorption between 2.0% and 2.5% for the EW concrete at all tested ages, but still within the ranged recommended by the QCS 2014 for durable concrete. The control concrete showed intermediate values of 2.0%. In general, the average water absorption values for the 3 building trials were within the lower range of QCS 2014 recommended values for durable concrete.

5.1.1.3 Rapid chloride permeability

The QCS 2014 recommends the RCP test as per ASTM C1202 (2012) for assessing the concrete durability under an external applied force of electrical voltage. The recommended range for durable concrete is between 500 to 4000 total charge passed, in Coulombs.

The results in Figure 5-7 show values within the range of 3400 to 4600 Coulombs, within the higher range for durable concrete. Similar to the compressive strength and water absorption results, the 60% CRF concrete exhibited the best performance whereas the Control and 50% EW concretes showed similar performance.

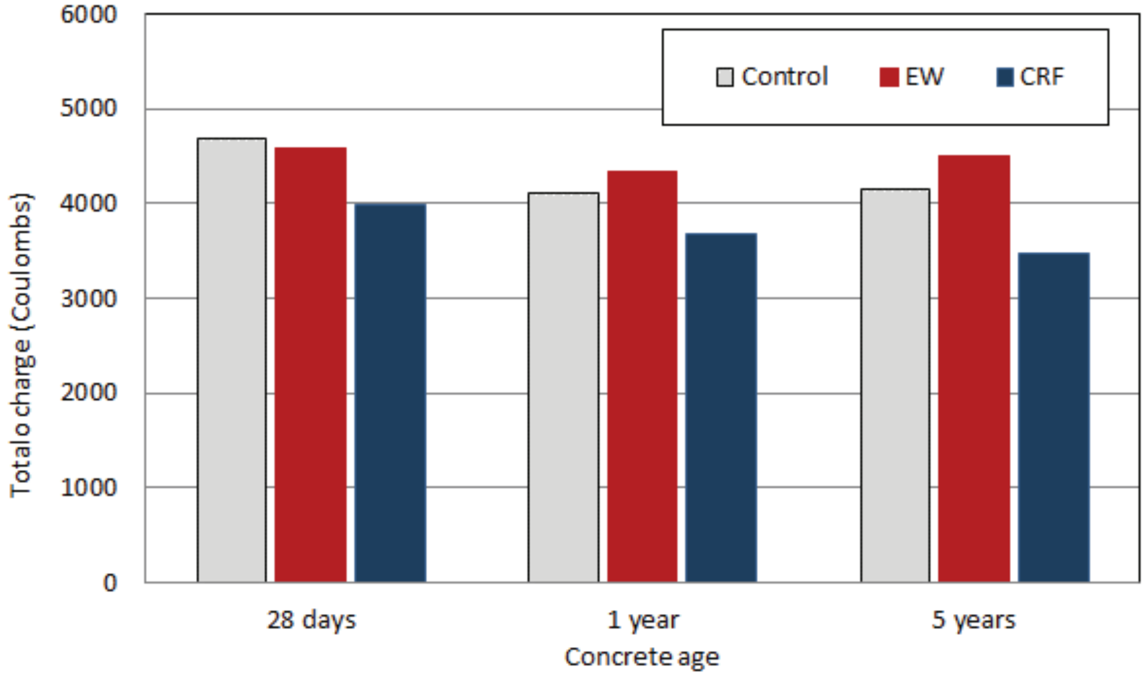

Figure 5-7 Core chloride permeability up to5 years

5.1.2 Discussion of results

Overall, the 3 buildings were in good condition with identical performance and no obvious visual differences between the concrete made with recycled/alternative materials and conventional aggregates. No evidence of cracking, spalling, or reinforcement corrosion was observed after 5 years in service.

The core compressive strength showed significant improvement with age. The 60% CRF exhibited the highest compressive strength with average values exceeding 40 MPa at 28 days and 70 MPa at 5 years. The control and 50% EW concrete showed similar strength development with average values around 33 MPa at 28 days, and 60 MPa at 5 years. A considerable increase of core strength from the age of 28 days to 5 years was achieved, despite the harsh exposure environment in Qatar. The porous nature of recycled aggregate results in high water absorption, and could have contributed to the slow release of water over time. Further work is required to investigate this in more detail.

The QCS 2014: Section 5: Part 6 provides optional values for assessing the durability performance of concrete in terms of water absorption, water permeability, RCP and chloride migration. Water absorption and RCP tests were conducted in this investigation for monitoring performance. The water absorption results revealed low values of 1.4 to 2.5% for the 3 mixtures at different ages. The lowest values were found for the 60% CRF concrete, with higher values for the control and 50% EW. A similar trend was obtained from the RCP results, with the lowest permeability values for the 60% CRF. The 50% EW concrete gave slightly higher values than the control concrete, probably due to the higher EW aggregate levels of chloride content than the maximum specified in the QCS 2014 (Hassan et al., 2013).

The QCS 2014 currently limits the use of recycled aggregate in structural concrete to 20%, by weight of aggregate, provided the materials satisfy the aggregate requirements listed in Section 5: Part 2. The QCS 2014 also allows a relaxation of the aggregate absorption to 3%, compared to 2% for natural aggregate. The current specification provided in the QCS 2014 for structural concrete seems adequate and does not prohibit the wider implementation of recycled aggregates in practice. However, there is a need to consider the durability requirements for concrete cores obtained from real structures/buildings in service. The development and implementation of field durability requirements, based on locally available materials and specified exposure conditions, would contribute to extending the service life of concrete structures.

The use of recycled materials in the concrete blocks in this trial is described in Section 5.3.

5.2 Wadi Gravel in Structural Concrete

Deposits of Wadi gravel are available in Qatar and the region, but have not been widely utilised as aggregate for concrete, mainly due to the possibility of internal sulfate attack, plus the perceived risk of alkali aggregate reactivity (AAR). The use of local Wadi gravel contributes to enhanced sustainability by replacing expensive imported gabbro. As discussed in Section 3.4, the material is produced in large quantities as a by-product from the sand washing process and requires intensive, multistage processing before use in concrete. Three trial buildings were constructed in June 2016 with the mix composition shown in Table 5-2. Wadi gravel aggregate was used to replace 50% and 100% of the gabbro coarse aggregate in the C40 structural concrete.

Table 5-2 Mix compositions – Wadi gravel trial building mixtures

Material	100% Gabbro	50% Wadi gravel	100% Wadi gravel
Portland cement, kg/m^3	340	340	340
Water, l/m^3	143	143	143
Gabbro, kg/m^3	1197	598	-
Wadi gravel, kg/m^3	-	553	1106
Washed sand, kg/m^3	835	835	835
Super plasticiser, l/m^3	5.90	5.30	4.60

The Wadi gravel was obtained from the Mekaines site, south-west of Doha, and processed to satisfy the QCS 2014 requirements for use as coarse aggregate in concrete. The washed sand complied with the QCS 2014 requirements, with the exception of sulfate content. The acid-soluble sulfate was 0.6 %, exceeding the maximum permissible limit of 0.4 %. The mixing water was maintained at a constant w/c ratio of 0.42 for all mixtures, and the amount of superplasticiser was adjusted to achieve a target slump of 200 mm (±20) at the production unit, and to maintain 100 mm minimum on arrival at site, measured in accordance with BS EN

12350-2. The materials supply and properties of the aggregate materials are presented elsewhere (Hassan et al., 2020b).

The results in Table 5-2 shows that Wadi gravel reduces the superplasticiser dosage required to achieve the same slump as the 100% gabbro concrete. The improved workability is attributed to the smooth surface and more rounded particles of Wadi gravel, compared to gabbro aggregate.

5.2.1 Alkali Aggregate Reaction (AAR)

A comprehensive testing programme was conducted to investigate the AAR of Wadi gravel, which comprised petrographic examination; accelerated screening tests; and longer-term expansion tests. Details of the testing programme and results are reported by Sims et al. (2020). The results of the long-term expansion tests are summarised below.

The long-term tests were conducted on the 3 concrete mixtures in Table 5-2, using the RILEM AAR-4.1 (2015) and BS 812:123 (1999) test methods. In addition to the Wadi gravel and gabbro aggregates, a reference aggregate of Spratt's silicified limestone aggregate was chosen to represent a known alkali-silica reactive aggregate. The BS 812:123 concrete prism test takes a relatively long time (52 weeks), by comparison with the accelerated AAR-4.1 test (20 weeks) but is considered probably to be more realistic at representing typical behaviour of aggregate materials used in the field. Storage conditions varied between the two tests. RILEM AAR-4.1 concrete prisms were exposed to 60 °C temperatures at as close as possible to 100 % relative humidity (RH), whereas BS 812-123 concrete prisms were exposed to humidity > 96 % RH at 38 °C.

Figure 5-8 presents the 15 weeks expansion of different concrete mixtures made with different proportions of Wadi gravel aggregate in the RILEM AAR-4.1 test. The interpretation guidance presented in RILEM AAR-0 (2016) allows tentative classification against a criterion of 0.03 % expansion at 15 weeks age. The 100% Wadi gravel was slightly higher than the suggested 0.03 % criterion, with 0.04 % at 15 weeks. Results for the 50% Wadi gravel were encouraging, with expansion reduced to 0.015 % at 15 weeks, which is identical to the expansion of the 100% gabbro concrete. The mixture containing the reactive Spratt's aggregate appreciably exceeded the criterion with the measured expansion of 0.1%, falling within the range (0.06 to 0.22 %) of published studies using similar techniques detailed in RILEM AAR-0 (2016). The significant expansion of the Spratt's aggregate mix confirmed that the methodology, conditions and equipment used produced expansion in a reactive aggregate.

Results of the BS 812:123 expansion results are presented in Figure 5-9. The criteria for assessment given for BS 812:123, within BRE Digest 330-2 (2004), are based on the expansion values after 12 months exposure. Non-expansive classification is for expansion values ≤ 0.05 %, probably non-expansive for >0.05 % and ≤0.10 %, possibly expansive for >0.10 and ≤0.20 %, and expansive for > 0.20 %.

In contrast to the AAR-4.1 tests, the measured BS 812-123 prism expansions for all of the Wadi gravel mixtures, including 100 % Wadi gravel, fell into the non-expansive aggregate classification. This classification suggests no significant expansive behaviour and a low reactivity type for the Wadi gravel. The mixture containing imported gabbro consistently reduced expansion by 20-50 %, compared with the 100% Wadi gravel mixture. The 50% Wadi gravel mixture produced similar expansions to the 100% gabbro concrete throughout the testing. The reference Spratt's aggregate recorded an expected expansive trend that achieved approximately 0.175 % expansion after 52 weeks.

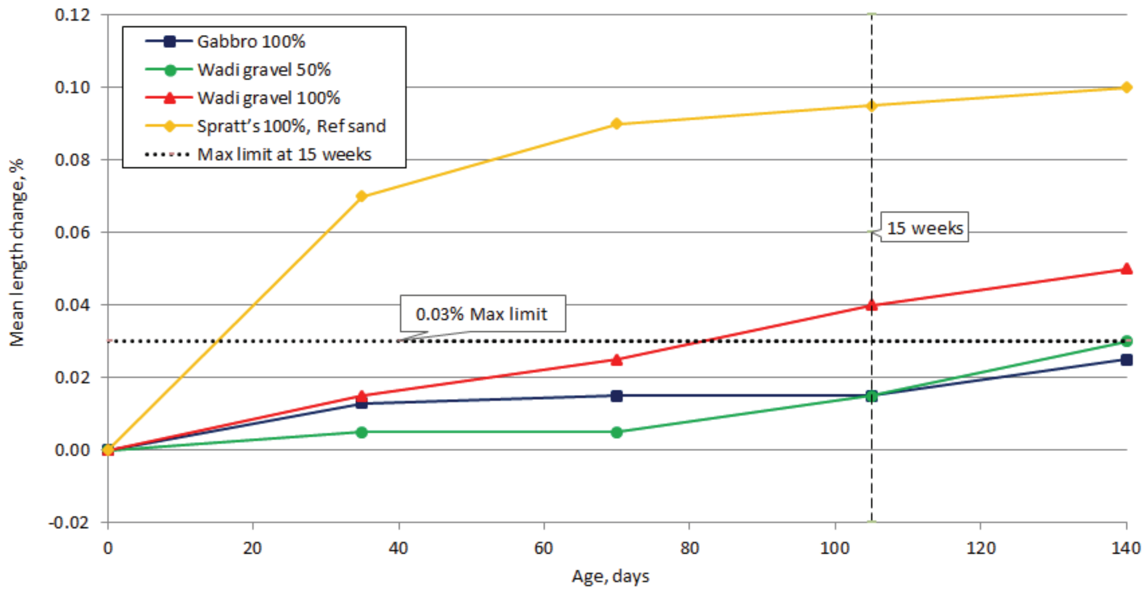

Figure 5-8 RILEM AAR-4.1 expansion of concrete prisms

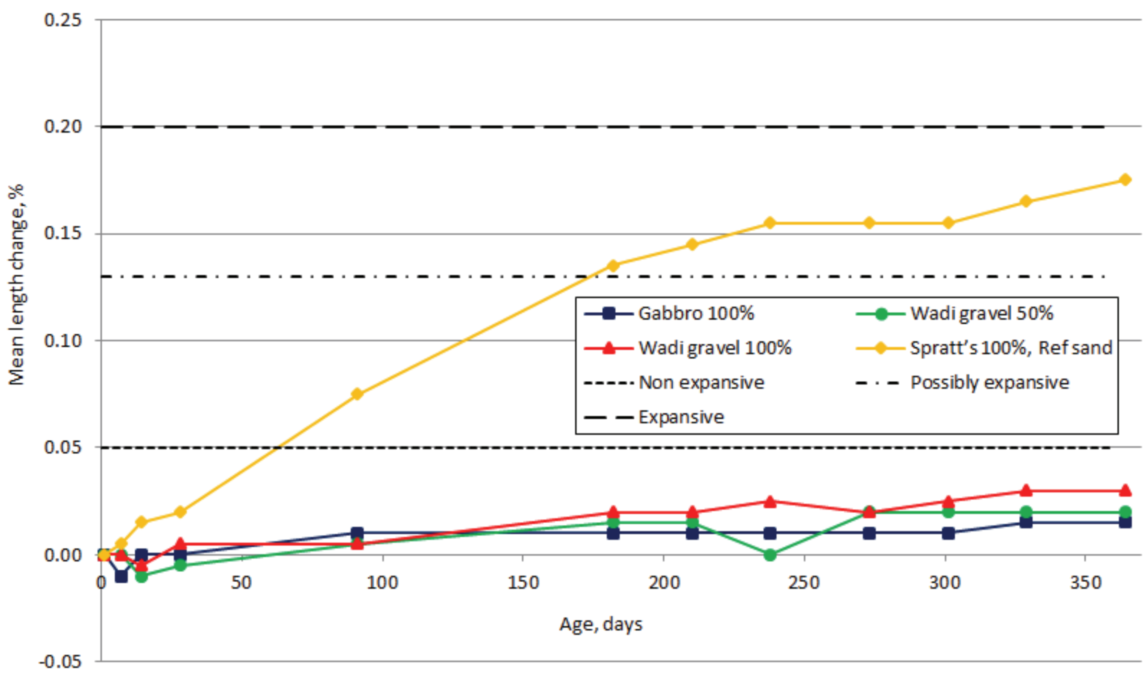

Figure 5-9 BS 812-123:1999 expansion of concrete prisms

The degree of AAR within the BS 812-123 prisms was notably lower than those within RILEM AAR-4.1 prisms of the same mixtures. As laboratory testing is not always adequate to assess the real performance of the materials in service, site trials were constructed with the same mixtures given in Table 5-2.

5.2.2 Building trials

Details of the construction and monitoring of the trial buildings up to one year are given in Hassan et al. (2020b). Three trial buildings were constructed at the Mekaines site, each with the cross section of 4.0 m x 4.0 m and one storey height of 3.85m as shown in Figure 5-10 . Each building was constructed with one of the mixtures given in Table 5-2. The construction of the three buildings was conducted in parallel with one truck for each concrete mix delivered on the same day of casting. Four structural elements were cast for each building to include foundations, ground and neck beams, columns and a control beam, and roof beams and slabs

Figure 5-10 Trial buildings, 6 months after construction: control (100%) gabbro on left; 50% Wadi gravel in centre; 100% Wadi gravel on right.

Additional beams, with dimensions of 200 mm x 500 mm x 4000 mm, were cast from the same batches used for the concrete columns and stored separately behind each building as shown in Figure 5-11. The additional beams were partially buried within the fill material around the buildings and were used for coring and testing the different concrete mixtures at different ages. At the age of testing, the beams were removed from the ground for coring and then reinstalled again for long-term monitoring. The purpose is to represent aggressive ground conditions and excessive heat near the ground surface. Precast concrete blocks, block paving and kerbstone were also made of 100% Wadi gravel and used for the construction of the building trials (Hassan et al., 2020b).

Figure 5-11 Additional beam cast for coring and long-term monitoring behind buildings.

Construction took place in the summer of June 2016, with an average air temperature in the range of 40°C to 50°C. The QCS 2014 requires that the temperature of concrete on delivery shall not exceed 32°C. This was achieved using chilled water for mixing concrete and pre-cooling the truck-drum prior to loading the fresh concrete. Testing of concrete slump, BS EN 12350-2 (2009), was conducted on arrival at site, approximately 75 min drive from the plant.

Figure 5-12 shows the site monitoring of concrete temperature and slump. As part of controlling the quality of ready-mix concrete used for different batches, cubes (150mm sides) were prepared from each batch and cured in a water tank at 20°C (±2). The cubes were tested for compressive strength at the ages of 7 and 28 days, in accordance with BS EN 12390-3, and the results are given in Table 5-3. Three cubes were used for each test and the average value was reported.

Figure 5-12 Measurements of concrete temperature (left) and slump (right) on site

The slump and compressive strength testing were used to assess the variation of concrete batches delivered to site. A target slump of 100mm minimum was set on arrival at site to enable easy pumping and compacting of the concrete mixtures. The slump values ranged from 150 to 220mm, with the majority of results being between 180 and 200mm. The slump results for the delivered concrete were generally higher than the desired target of 100mm.

The cube compressive strengths at 7 and 28 days are also given in Table 5-3. At 28 days, the mixtures exceeded the desired strength of C40 concrete and achieved values in excess of 50 MPa. The 100% gabbro concrete exhibited the highest strength of 58.4 MPa at 28 days, and the lowest of 53.0 MPa was obtained for the 100% Wadi gravel concrete. In fact, the mixtures achieved the target C40 after 7 days in cube tests, with average values of 46.9 MPa for the 100% gabbro, 46.2 for the 50% Wadi gravel, and a slightly lower average of 43.8 MPa for the 100% Wadi gravel. The variation of compressive strength results for the different batches ranged between 6% and 11%, indicating a good quality of concrete production.

Table 5-3 Slump (mm) and compressive strength (MPa) results of concrete batches

Concrete	100% Gabbro			50% Wadi gravel			100% Wadi gravel		
	Slump	7d	28d	Slump	7d	28d	Slump	7d	28d
Foundations	200	53.3	65.3	190	50.9	62.1	180	46.9	57.1
Ground beams	210	40.8	55.9	220	41.9	53.7	200	40.1	50.8
Columns/control beams	190	45.4	54.9	200	45.5	51.9	200	43.2	50.8
Roof slabs	190	48.2	57.6	180	46.6	54.8	150	45.1	53.1
Average	-	46.9	58.4	-	46.2	55.6	-	43.8	53.0
CV%	-	11.1	8.1	-	8.0	8.1	-	6.6%	5.6

5.2.3 *Performance Results*

The performance of Wadi gravel concrete was assessed by extracting cores from the additional beams and testing for compressive strength, water absorption, and petrographic analyses. The core testing commenced at the age of 28 days and further cores were taken after 1 year and 4 years in service.

5.2.3.1 Moisture and Salt Content

High salt concentration in soil may cause serious problems for reinforced concrete structures. Soil samples were collected from the excavated materials (limestone) for the building trials and tested for chloride and sulfate content as per BS 1377-3 (1990) (currently BS 1377-3: 2018). For earth works related to buildings, the QCS 2014 specifies maximum values of acid soluble chloride not exceeding 2%, and 3% for acid soluble sulfate. The soil testing indicated sulfate content of 2.58%, which is relatively high, but within the maximum permitted level. Much lower chloride content of 0.04% was measured in the surrounding soil. Concrete cores were extracted after 4 years from the test beams. Cores were tested for wet density, moisture content, chloride content and sulfate content, and the results are presented in Table 5-4.

Table 5-4 Density, moisture content and salt contents at 4 years

Material	100% Gabbro	50% Wadi gravel	100% Wadi gravel
Density, kg/m^3	2347	2310	2250
Moisture content, %	3.7	3.8	3.3
Acid-soluble chlorides, % Cl-	0.01	0.01	0.01
Acid-soluble sulfate, % SO_3	0.61	0.83	1.12

The gabbro aggregate, with its high particle density, gave the highest concrete density of 2347 kg/m^3. Substituting the gabbro with 100% Wadi gravel reduced the concrete density to 2250 kg/m^3. The 50% Wadi gravel concrete gave an intermediate value of 2310 kg/m^3. The moisture content ranged between 3.3% and 3.8% for the different concrete mixtures. The amounts of acid-soluble chloride measured were identical and negligible. The sulfate content was much higher, with the highest value of 1.12% for the 100% Wadi gravel, and the lowest of 0.61 for the 100% gabbro.

5.2.3.2 Compressive strength and water absorption

The core compressive strength results are presented graphically in Figure 5-13. Similar to the original cube results, all the mixtures achieved the target C40 strength at 28 days. The 100% gabbro concrete exhibited the highest strength of 45.2 MPa, with slightly lower average values of 41.7 MPa and 41.3 MPa for the 50% and 100% Wadi gravel concretes, respectively. Strength development continued with age up to 4 years in service to reach 57.6 MPa, 53.1 MPa and 52.2 MPa for the 100% gabbro, 50% Wadi gravel, and the 100% Wadi gravel, respectively.

The water absorption results are presented in Figure 5-14. All the mixtures showed low water absorption values within the range of 1% to 2% at the different ages up to 4 years in service. The absorption results are lower than the range recommended in the QCS 2014 of 2% - 4% for durable concrete. The absorption results followed the same trend as the strength results, with slightly lower absorption results of the gabbro concrete compared with the Wadi gravel concrete at 28 days and after 4 years. After 1 year, the values were almost identical for all three mixtures.

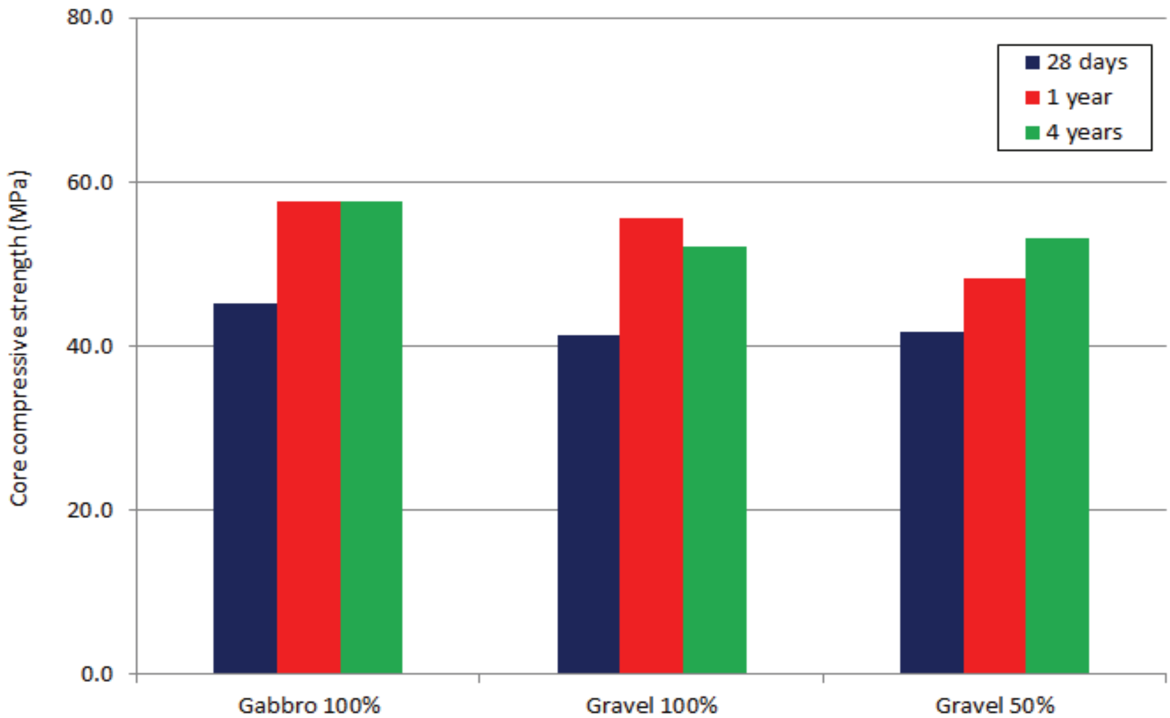

Figure 5-13 Core compressive strength of Wadi gravel and gabbro concrete mixtures.

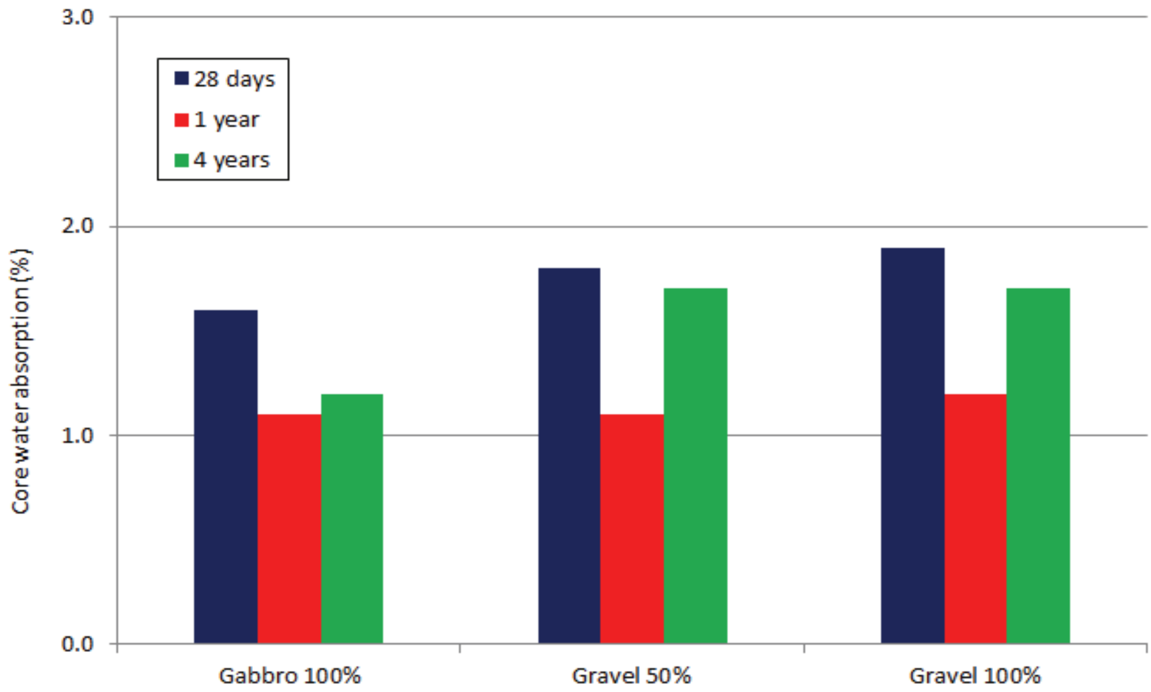

Figure 5-14 Core water absorption of Wadi gravel and gabbro concrete mixtures.

5.2.3.3 Petrographic examination of cores after 4 years

A summary of the concrete petrography test results is given in Table 5-5. All the mixtures showed dense structure with low air voids. The 100% gabbro and 50% Wadi gravel concretes gave the same range of 2.0% to 3.0% air voids, with a higher range of 3.0% to 4.0% for the 100% Wadi gravel concrete. An example of the dense structure of the 50% Wadi gravel concrete is shown in Figure 5-15.

Table 5-5 Summary of petrographic examination of concrete cores after 4 years

Parameter	100% Gabbro	50% Wadi gravel	100% Wadi gravel
Mix quality	Good compaction	Good compaction	Good compaction
Air voidage, %	2.0 – 3.0	2.0 – 3.0	3.0 – 4.0
ASR	No evidence	No evidence	No evidence
Cracking/Microcracking	No evidence	No evidence	No evidence
Deposits	Trace ettringite	Trace ettringite	Trace ettringite

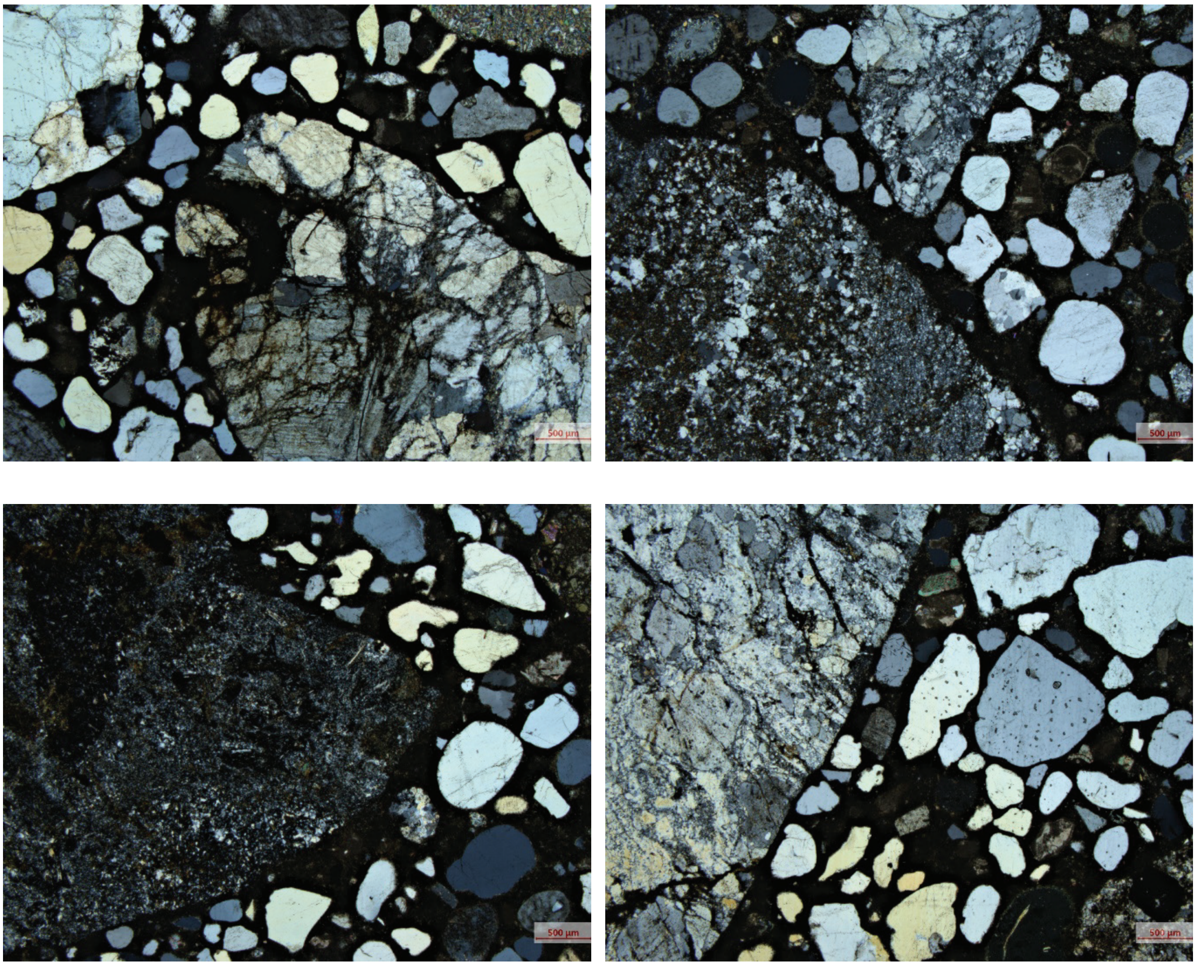

Figure 5-15 Granite rock – 50% Wadi gravel (top left), Quartzite rock – 50% Wadi gravel (top right), Rhyolite rock – 50% Wadi gravel (bottom left), and Quartzite rock – 100% Wadi gravel (bottom right)

None of the concrete mixtures showed any evidence or ASR or other significant causes of deterioration after 4 years; in particular there were no ASR reaction sites or products, such as silica gel, and no evidence of any micro-cracking associated with aggregate-binder interfaces. Images in Figure 5-15 show different rock constituent types of Wadi gravel with good aggregate packing and no signs of deleterious reactions. The concretes appeared generally sound with only minor evidence of leaching remobilising sulfate, giving rise to secondary ettringite deposits that were too limited to be indicative of damaging sulfate attack. The petrographic examination after 4 years supports the BS 812-123 finding of low alkali-silica reactivity of Wadi gravel.

5.2.4 Discussion of results

The use of Wadi gravel in Qatar is still rather limited, mainly due to the perceived risk of AAR and sulfate attack, with lack of long-term performance data to provide confidence in use. Petrographic examinations have been conducted on the hardened concrete mixtures after 4 years in service to assess potential ASR, and to clarify the different expansion behaviours for the different concrete prism tests. The results indicated sound concrete with no observed cracking or microcracking, and no evidence of distress or deterioration from ASR or sulfate attack. The 4-year petrographic results of the hardened concrete support the results obtained from the BS 812-123 expansion test and indicate that the Wadi gravel could be classified as a non-expansive aggregate. Based on the results obtained in this study, the BS 812-123 method is considered ultimately more representative of performance in practice than the accelerated RILEM AAR-4.1 method.

Figure 5-16 Trial buildings, 4 years after construction: control (100%) gabbro on left; 50% Wadi gravel in centre; 100% Wadi gravel on right.

The trial buildings were visually inspected periodically up to 4 years in service. The 3 buildings looked generally identical, with no obvious differences between them, Figure 5-16. The climate in Qatar is generally hot and humid during summer, with some strong storms and heavy rains in winter. Despite these harsh weather conditions, the buildings remained in good condition, with no visual signs of deterioration. No structural damage was apparent.

Core samples were obtained from the test beams, stored behind the building trials. The core strength achieved the target C40 concrete at 28 days. Strength development continued, with the availability of moisture within the pore structure of concrete, as confirmed by the moisture content results. The water absorption results were lower than 2% for the different mixtures at all tested ages up to 4 years. The QCS 2014 recommends a range of 2 - 4% water absorption as an indication of durable concrete. The absorption results obtained in this study for the Wadi gravel and gabbro aggregates were lower than the minimum level recommended, and hence would be expected to provide high resistance to the ingress of harmful substances into concrete.

The trial beams were exposed to the most aggressive environment within the trials. They were partially buried in a soil with a relatively high sulfate content and also exposed to the diurnal heat cycles at the surface. The trial beams have also been more at risk of deterioration, owing to periodic exposure to moisture in the soil during rainy periods. In this inland site, the groundwater table is well below the surface, but in coastal areas foundation concrete would also be exposed to potential capillary rise of salts from ground water. The availability of moisture and heat would potentially accelerate the deterioration mechanisms of sulfate attack and ASR. The tight pore structure and low absorption values have contributed to mitigate the risk of sulfate attack of concrete.

Petrographic examination of hardened concrete after 4 years only detected only traces of white sulfate deposits (ettringite) lining the air voids of concrete, with no evidence of other distress or deterioration due to sulfate attack. On-going testing is planned for the building trials and partially buried beams to assess longer-term performance and correlated to laboratory accelerated testing.

Wadi gravel offers a quality aggregate for use in concrete and is available locally in Qatar and other parts of the Gulf region. When the material is processed properly to meet with the QCS 2014 requirements, particularly sulfate content, it has the potential to replace up to 100% of imported gabbro in structural concrete applications. This has important implications for the use of Wadi gravel in concrete, as it is easier – and cheaper – to make concrete with one aggregate rather than a blend of two or more types of aggregate, such as the 50:50 blend with gabbro used in this study. Site testing after 4 years in service showed similar performance to the conventional gabbro concrete. The results obtained in this study also support the finding of the BS 812-123 test for Wadi gravel to be classified as having low reactivity in relation to AAR and confirms that the BS 812-123 test is more representative of the behaviour of concrete in the field than the RILEM AAR 4.1 concrete prism test.

5.3 Concrete Blocks

CDW (mixed) and IBA were used to partially replace gabbro as coarse aggregate for the production of concrete blocks in the trial buildings at the Ashghal-Najma site in Doha (Section 5.1). Hollow blocks were made in the dimensions of 400 x 200 x 200 mm for use as non-load bearing walls. Three mixtures were used in the building trials as shown in Table 5-1 and Figure 5-1, to include CDW 50% (Building 1), control (Building 2), and IBA 20% (Building 3). The control mixture was composed of cement: coarse aggregate: fine aggregate: water in the weight ratio of 1: 4.67: 3.83: 0.35, with a total cement content of 300 kg/m^3. Additional concrete blocks were made during construction and stored adjacent to the building trials as shown in Figure 5-17. The additional blocks were tested for compressive strength and water absorption at 28 days and 5 years of age.

Figure 5-17 Concrete blocks with recycled materials used for testing

The QCS 2014 specification for concrete blocks, Section 13, Part 4, is based on BS 6073-2 (2008), and specifies strength and water absorption requirements for the non-load bearing blocks. The average compressive strength, for 3 tested blocks, shall be equal to or greater than 7.0 MPa, with the lowest individual value not less than 5.6 MPa. For the full water absorption, measured in accordance with CML 9-97, the average value shall not exceed 7 %, with no individual block greater than 7.5 %.

The QCS 2014 allows the use of recycled aggregates to replace up to 50% of the aggregate in concrete blocks when the average compressive strength is equal to or greater than 7 MPa, and up to 100% replacement for average strength less than 7 MPa. The limits for acid soluble chloride and sulfate are 0.2 and 0.8%, respectively. Whilst the CDW and IBA met the chloride content requirement, the CDW gave a higher value of 1.56% acid soluble sulfate and hence the decision of 50% replacement rather than 100% CDW was made (Hassan et al., 2020a).

Three concrete blocks were tested at 28 days and 5 years, and the average results are presented in Figure 5-18 and Figure 5-19 for the compressive strength and water absorption respectively. The results show that the concrete blocks used for the construction of the building trials satisfied both the compressive strength and water absorption requirements of the QCS 2014. The average compressive strength values ranged between 11.0 MPa and 15.0 MPa, much higher the specified 7 MPa. All the blocks showed improved strength with age.

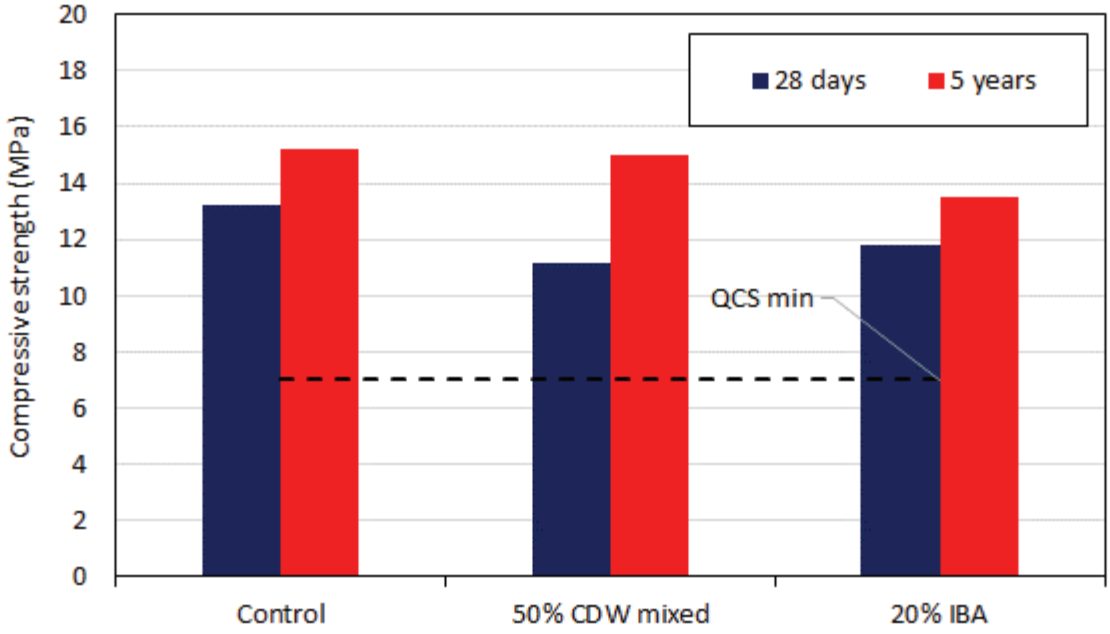

Figure 5-18 Compressive strength of concrete blocks

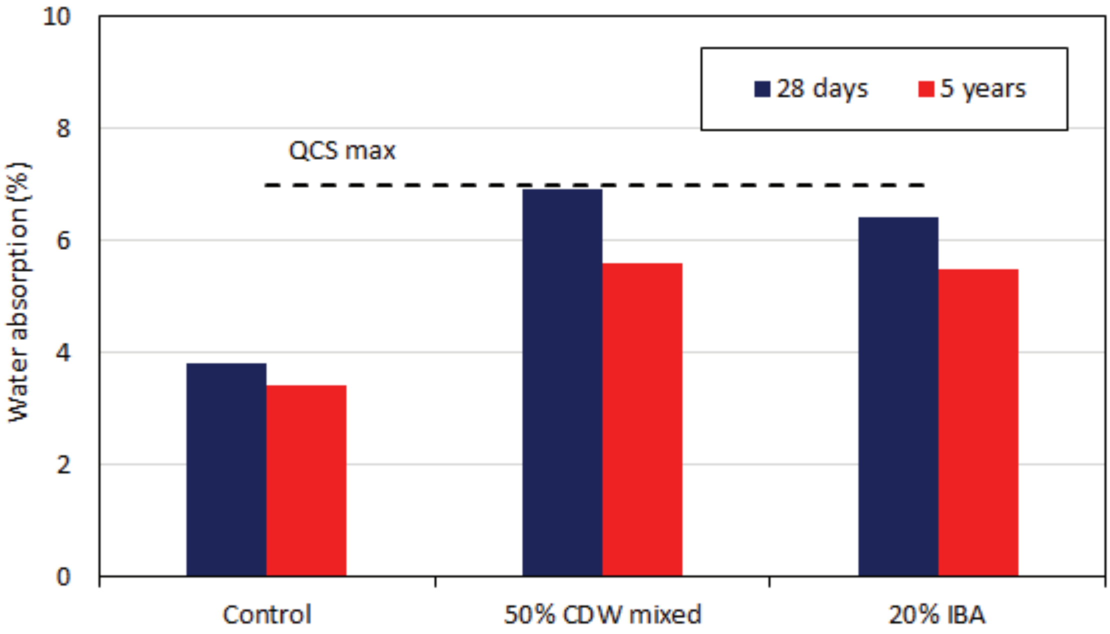

Figure 5-19 Water absorption of concrete blocks

The water absorption results showed average values between 3.5% and 6.9%, with the control blocks exhibiting the lowest water absorption values. Similar to the compressive strength results, the absorption results improved with age for all blocks. All the results were lower than the maximum specified value of 7% water absorption. In general, the results show that both CDW and IBA can partially replace imported gabbro aggregate with almost similar performance to the control blocks, and in compliance with the QCS 2014 requirements for non-load bearing walls.

5.4 Case Study – Concrete Block Factory

The recycling initiatives undertaken by the government and key stakeholders, together with the availability of the recycling specification and a supply of quality recycled aggregate have encouraged the industry to implement recycling. FBA Ready Mix is one of the concrete suppliers who took the lead in implementing the use of recycled aggregate in concrete blocks. The block factory is located in Doha-Industrial Area, and currently produces approximately 60,000 blocks per day.

The coarse aggregate used for the production of the concrete blocks is sourced from local and recycled materials. The coarse aggregate comprised mixed CDW and Wadi gravel, both of the same size of 5.0 mm to 10.0 mm. The washed sand and Portland cement were also sourced locally. The percentage of CDW used is 40% by weight of the block. The mixed CDW was supplied by QPMC, and the material is shown in Figure 5-20, and the block production followed the conventional method as shown in Figure 5-21, with no changes in equipment used or curing methods.

Figure 5-20 Mixed CDW used for the production of concrete blocks

Figure 5-21 Production of concrete blocks with recycled aggregate

The production of concrete blocks with recycled aggregate commenced in summer 2020. Data on compressive strength and water absorption are provided by FBA for the period of September 2020 to February 2021. The monthly average results are presented in Figure 5-22 and Figure 5-23 for compressive strength and water absorption, respectively. The concrete blocks made with recycled aggregate exhibited lower compressive strength and higher water absorption than the control blocks made with primary aggregates. However, all the results were within the specified limits in the QCS 2014. It is also important for the ingredient materials, including recycled aggregate, to comply with the requirements of the QCS 2014.

In addition to the environmental benefits of using recycled materials, there is a cost saving associated with the use of recycled aggregate. It was confirmed by FBA team that the price of concrete blocks made with recycled aggregate is 10% lower than the price of the conventional concrete blocks. The price reduction is mainly attributed to the reduced cost of recycled materials compared to expensive imported aggregate.

The environmental and economic benefits obtained from implementing recycling in the FBA concrete blocks has encouraged the team to widen the use of recycled aggregate in other precast concrete products. Trial mixtures were developed for the production of paving blocks and kerbstone with recycled aggregate up to 40% by weight of imported gabbro. The results of the precast concrete products made with recycled materials were in compliance with the

QCS 2014 requirements. An implementation plan has already been developed by the FBA team to the full-scale production of paving blocks and kerbstone with recycled aggregate.

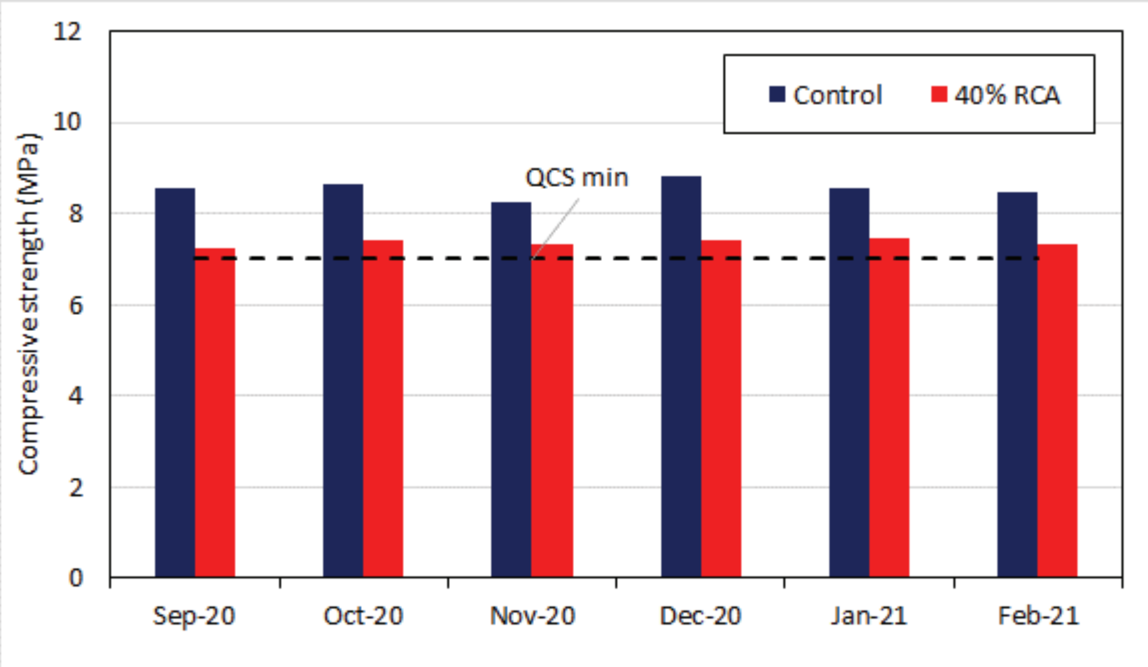

Figure 5-22 Compressive strength of concrete blocks – FBA

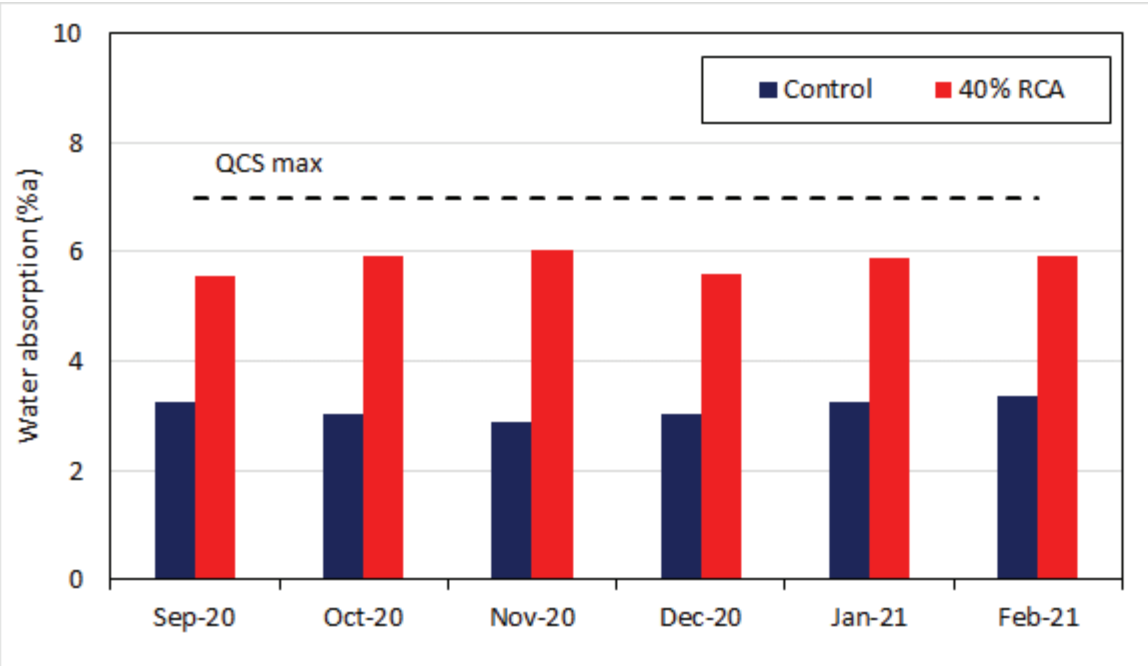

Figure 5-23 Water absorption of concrete blocks – FBA

5.5 Summary

EW and CRF were used to partially replace imported gabbro and washed sand, respectively, in structural C40 concrete. Visual inspection of the 3 buildings indicated identical performance of the different concrete mixtures with no obvious cracks, spalling or reinforcement corrosion up to 5 years in service.

The core compressive strength after 5 years achieved values of 60 to 70 MPa, with the highest value for the CRF concrete. These values are considerably higher than the designed strength of 40 MPa (C40 concrete), and confirm continuous strength developed within the hot exposure environment in Qatar. Durability tests of water absorption and RCP showed similar trends as the compressive strength results, with the CRF exhibiting the highest durability compared to the control and EW concretes. The results obtained from monitoring the buildings support the QCS 2014 limitation of 20% of recycled aggregate in structural concrete for durability issues, and up to 100% in concrete blocks and non-structural concrete applications.

Wadi gravel was also used as coarse aggregate in structural C40 concrete, to replace 50% and 100% of imported gabbro. Site data up to 4 years in service indicated similar performance of the Wadi gravel concrete to the conventional gabbro concrete, when the Wadi gravel aggregate was processed to comply with the QCS 2014 requirements, especially sulfate content. Use of Wadi gravel was easily implemented in the ready-mix plant for the production of structural concrete. At the same w/c, Wadi gravel concrete reduced the superplasticiser dosage to achieve the same workability as the gabbro concrete. The target C40 concrete compressive strength was achieved after 28 days, and strength continued to develop with age to over 50 MPa after 4 years.

The risk of potential AAR of Wadi gravel was assessed using a comprehensive laboratory investigation and site cores. For the laboratory concrete prism methods, Wadi gravel was classified as potentially reactive in the RILEM AAR-4.1 and of low reactivity in the BS 812-123 test. The BS 812-123 interpretation was confirmed by petrographic examination of the hardened concrete after 4 years in service, as no signs of AAR or cracking were detected in the Wadi gravel concrete.

The test beams, used for the assessment of site performance of Wadi gravel concrete, were exposed to the most aggressive environment within the trials. They were partially buried and surrounded by a relatively high sulfate soil and exposed to heat cycles on the surface and potential moisture from rainy periods and capillary rise. Despite the aggressive exposure environment, the Wadi gravel concrete exhibited sound performance, similar to that of gabbro concrete, with no observed cracking or defects on the buildings, and no evidence of distress or deterioration from ASR or sulfate attack within the concrete microstructure.

The results obtained for the use of recycled materials in structural concrete indicate the importance of durability assessment, in addition to strength properties, and long-term monitoring for judging the performance of new materials and products in construction. Strength is known to be a bulk property, whereas most deterioration mechanisms in Qatar and the region, are more related to the ability of concrete to resist the aggressive surrounding environments; such as extreme heat and humidity, saline environment and ground conditions. Durability assessment is therefore essential in addition to the conventional strength testing.

Concrete blocks and non-structural concrete provide a wider market for the uptake of recycled materials, as up to 100% recycled aggregate could be used. Non-load bearing walls are the most widely used in the concrete block industry. The results provided at construction and after 5 years in service indicated full compliance with the QCS 2014 for strength and absorption requirements, with no adverse effect with age. The results provide more confidence for the industry to implement the use of recycled aggregate with economic and environment benefits.

A case study is presented on the FBA as one of the leading concrete block factories who implemented recycled aggregate into their production. Performance data over 6 months indicated compliance with the strength and water absorption requirements of the QCS 2014. The use of recycled aggregate resulted in 10% cost reduction, due to the cheaper recycled materials compared to conventional aggregate. Further recycling implementation is planned by FBA for the use of recycled aggregate in new precast products of paving blocks and kerbstone. The FBA case study is encouraging for other factories in Qatar to implement recycling, with the provided government support and facilities to supply recycled aggregate at regulated quality and prices for successful implementation.

6 Recycling in Base and Subbase Materials

Road base is the layer directly beneath the asphalt course layers and above the subbase or subgrade layer. It consists of compacted selected materials and can be made of bound or unbound granular materials. It is considered as the main structural layer of pavement construction, with the function of spreading the surface loads and reduce the stresses on the lower layers, thereby ensuring that the bearing capacity of the subgrade is not exceeded. Road subbase is the first layer in pavement construction and acts as a platform for the construction of upper pavement layers and protection of the subgrade material. It is generally made of compacted granular materials with improved properties and quality compared to the subgrade. Subbase is made of similar materials, with slightly lower specification requirements, and is used to further spread the load from traffic and reduce stress on the subgrade.

This Section presents site data on the performance of recycled and local materials used in base and subbase applications, and their compliance with the QCS 2014 requirements. The performance was assessed in comparison to conventional construction materials, to provide confidence for the wider use of recycled aggregate in construction.

6.1 Unbound Subbase Materials

Local limestone has been successfully used as unbound pavement layers in Qatar for many years. Due to the varying clay type and content, the material was traditionally blended with dune sand to improve its properties and ensure compliance with the QCS 2014 requirements, especially plasticity and sand equivalent. The shortage of dune sand in Qatar and government restrictions on it use, have initiated the need to identify alternative materials for the sustainable supply to road construction projects. The use of recycled materials in unbound subbase applications was demonstrated by the project team in 2014 (Hassan et al., 2015) with the construction of road trials with different types of recycled aggregate materials. The performance of subbase materials after 4 years in service is presented below.

6.1.1 Road Construction Data

The access road to the Rawdat Rashid Recycling site was selected for the site trials. It covers a length of approximately 500m with heavy traffic loading, in the range of 500-1000 lorries/day. The old access road suffered from extensive deformation and potholes and was removed and replaced with a new access road in October 2014. Details of the construction data were reported previously (Hassan et al., 2015; Reid et al., 2016) and are summarised below. The subbase construction consisted of 3 sections, Figure 6.1, each of 120 m length and comprising:

- Section 1: EW subbase
- Section 2: RCA subbase
- Section 3: a control section made of EW + 20% dune sand

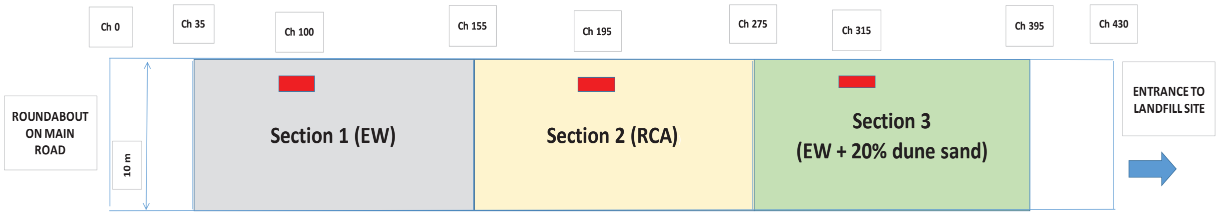

Figure 6-1 Layout of the subbase trial sections; red boxes represent sections tested after 4 years

After removing the existing road and exposing the natural subgrade of limestone, the construction was made in different layers. The new pavement construction consisted of 2 subbase layers, 150mm each, with an asphalt overlay of 80mm. The recycled subbase materials, sections 1 and 2, were constructed with EW and RCA materials, produced from the Rawdat Rashid Recycling site. Section 3 represented the traditional subbase construction of EW blended with dune sand.

During construction, site testing was conducted on the top of compacted subbase layers, and loose samples were collected for laboratory testing. Field-testing of in-situ density, surface modulus and a trafficking trial were carried out on the top of subbase layer 2. The in-situ density was determined using the sand replacement test to BS EN 1997-2 (2007) and the trafficking trial according to the procedure described in the UK Specification for Highway Works – Series 800 (Highways England, 2016). Table 6-1 presents the results of in-situ density and rut depth after trafficking.

Table 6-1 In-situ density and rut depths after trafficking

Subbase	Laboratory		In-situ density (layer 2)			Rut depth (mm)	
	MDD (g/cm^3)	OMC (%)	Dry density (g/cm^3)	MC (%)	Relative compaction (%)	Average	Maximum
EW	2.18	7.1	2.07	5.8	95	7.5	11.0
RCA	2.09	9.2	1.87	8.2	89	7.4	11.0
Control	2.32	5.0	2.12	4.9	91	0.4	6.0
QCS 2014	2.05	± 2%	-	-	100%	-	-

The QCS 2014 specified a maximum dry density (MDD) of minimum 2.05 g/cm^3 for unbound subbases, with in place moisture content ± 2% of the optimum moisture content (OMC) and a relative compaction of 100% of the MDD. The results in Table 6-1 show the 3 subbase materials satisfied the laboratory MDD, but the field dry density was lower than 100% of the laboratory values. The dry density is dependent on the moisture content, and the hot environment in Qatar caused rapid drying of the materials after compaction as reflected in the field moisture content being on the lower side of the OMC. However, the laid subbase materials visually appeared well compacted. The trafficking trial provided a further assessment of the subbase materials after being subjected to 1000 equivalent standard axles. The average rut depth was less than 10mm for each subbase section, well below the maximum specified limit of 30mm in the UK Specification for Highway Works.

6.1.2 Performance at 4 Years

To assess the performance of subbase materials after 4 years in service, the asphalt overlay was removed to expose the subbase surface. For each road section, an area of 900 x 1600 mm was exposed from the subbase, highlighted in red in

Figure 6-1 Layout of the subbase trial sections; red boxes represent sections tested after 4 years

. The asphalt overlay was initially cut into small slabs using a diamond saw, loosened at the edges using a vibrating hammer, and lifted to provide an undisturbed subbase surface. A thin layer of dune sand was sprayed on top of the exposed subbase to provide an even surface for the surface modulus field testing. The dune sand was then cleaned and the exposed subbase was loosened using a pick axe and a spade and the loose materials were collected in sealed bags for laboratory testing, Figure 6-2. The RCA subbase, section 2 of the road trials, was found to have hardened after 4 years in service and was therefore treated as a bound subbase and cores were extracted for testing as shown in Figure 6-3.

Visual assessment of the road trials was made immediately after construction in November 2014 and periodically every year to October 2018. The access road was heavy trafficked with loaded trucks bringing the construction waste into the landfill site and mostly loaded trucks leaving the site with processed recycled materials. The visual inspection showed excellent performance of the road trials in service. No surface defects in the form of cracks, deformation or bleeding were observed on the asphalt overlay, with identical performance between the different subbase materials made with recycled materials (EW and RCA) compared to the control section.

Testing of the subbase materials was carried out during construction and after 4 years in service. The testing programme was divided into unbound subbase (EW and control) and bound subbase for the RCA subbase. The unbound subbase materials were tested for grading, plasticity, sand equivalent, and other physical and mechanical properties, whereas the RCA subbase cores were tested for compressive strength, moisture content and density.

6.1.2.1 Unbound Subbase Materials

As the QCS 2014 was issued in December 2014, the grading of the subbase materials at construction was made to the requirements of QCS 2010 Class B specification. At construction, 3 samples were tested for each subbase materials and the average grading curves are shown in Figure 5 4. All the samples complied with the QCS 2010 Class B grading envelope except the EW subbase, which was marginally coarser between 2 and 5mm. The effect of adding dune sand on the grading of the control subbase significantly increased the percentage passing at 0.6mm, but the material remained within the grading limits. The dune sand is almost a single size material with its grading within the narrow range of 0.15 mm and 0.6 mm, hence this affects the grading of subbase material.

Figure 6-2 Exposed subbase after 4 years in service – EW material

Figure 6-3 Exposed subbase after 4 years in service – RCA material

After 4 years in service, the extracted unbound subbase materials (EW and control) were tested for sieve analysis as per the QCS 2014 requirements, and the results are shown in Figure 6-5. The QCS 2014 provides a narrower grading envelope than the QCS 2010 Class B subbase, mainly at the minimum specified limit whereas the maximum limit is almost the same for both specifications.

The grading curve for each subbase material represents the average of 3 tested samples. The EW and control showed significantly finer grading than at construction at all sieve sizes. The EW subbase, with its initial coarser grading at construction, remained within the QCS 2014 grading envelope with the fine particles of 0.6-0.075 mm towards the higher specified limits. However, the control subbase exceeded the maximum limit between 2 mm and 0.25 mm, associated with the dune sand addition. The different grading of the unbound materials after 4 years could be attributed to the effect of trafficking, breaking the weak subbase particles into finer materials. It could also be due to the method of extracting the unbound materials, by cutting, vibrating and removing of the asphalt overlay, causing breakdown of the weak limestone particles.

The unbound subbase materials were also tested for liquid limit, plastic limit and plasticity index in accordance with ASTM D4318 (2017), and sand equivalent as per ASTM D2419 (2014). Table 6-2 shows the results of the subbase materials together with the QCS 2014 specified limits. The results show that none of the subbase materials satisfied all the 3 criteria at construction. The EW subbase failed the QCS 2014 requirements of liquid limit, plasticity index and sand equivalent. The RCA subbase failed the liquid limit but satisfied the plasticity index and sand equivalent requirements. The control subbase passed the liquid limit and plasticity index but failed the sand equivalent.

After 4 years in service, the EW subbase showed slight changes in the liquid and plastic limits but a significant increase in the sand equivalent to exceed the minimum limit specified in the QCS 2014. A slight increase in the sand equivalent was also observed for the control subbase.

Table 6-2 Index tests on the subbase materials at construction and after 4 years in service

Test / Subbase	At construction			After 4 years			QCS 2014 limits
	EW	RCA	Control	EW	RCA	Control	
Liquid limit (%)	47	47	25	47	-	NP	25 max
Plastic limit (%)	26	NP	NP	27	-	NP	-
Plasticity index (%)	21	NP	NP	20	-	NP	6 max
Sand equivalent	13	34	17	36	-	21	25 min

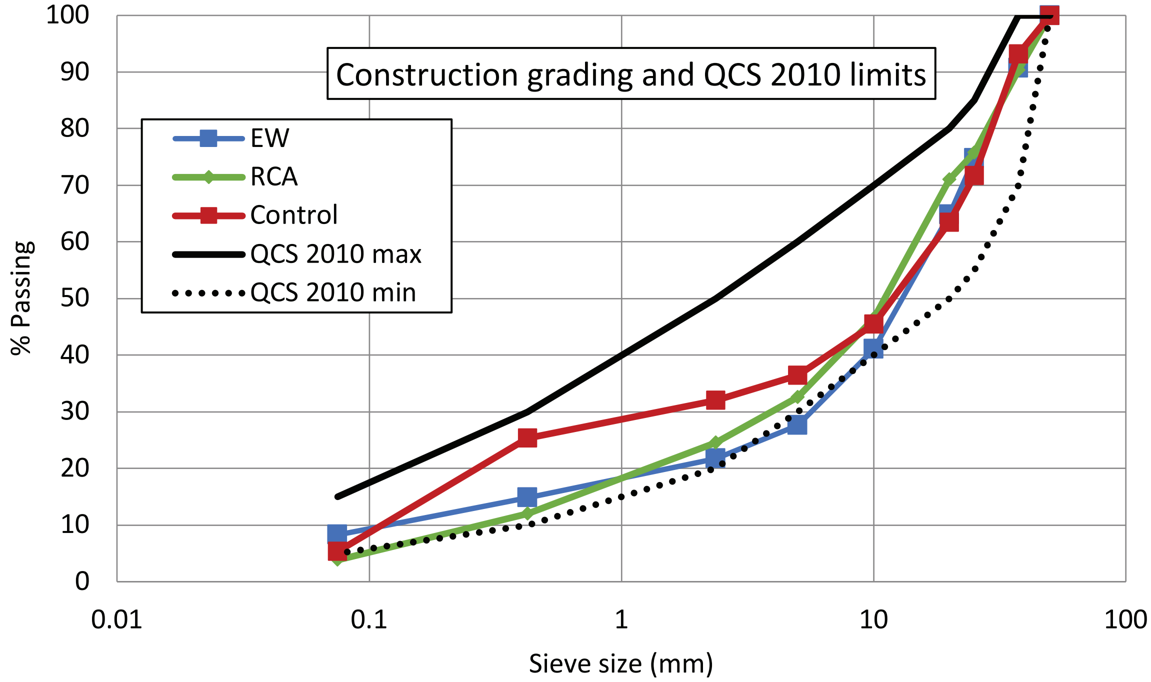

Figure 6-4 Grading of the subbase materials at construction (QCS 2010)

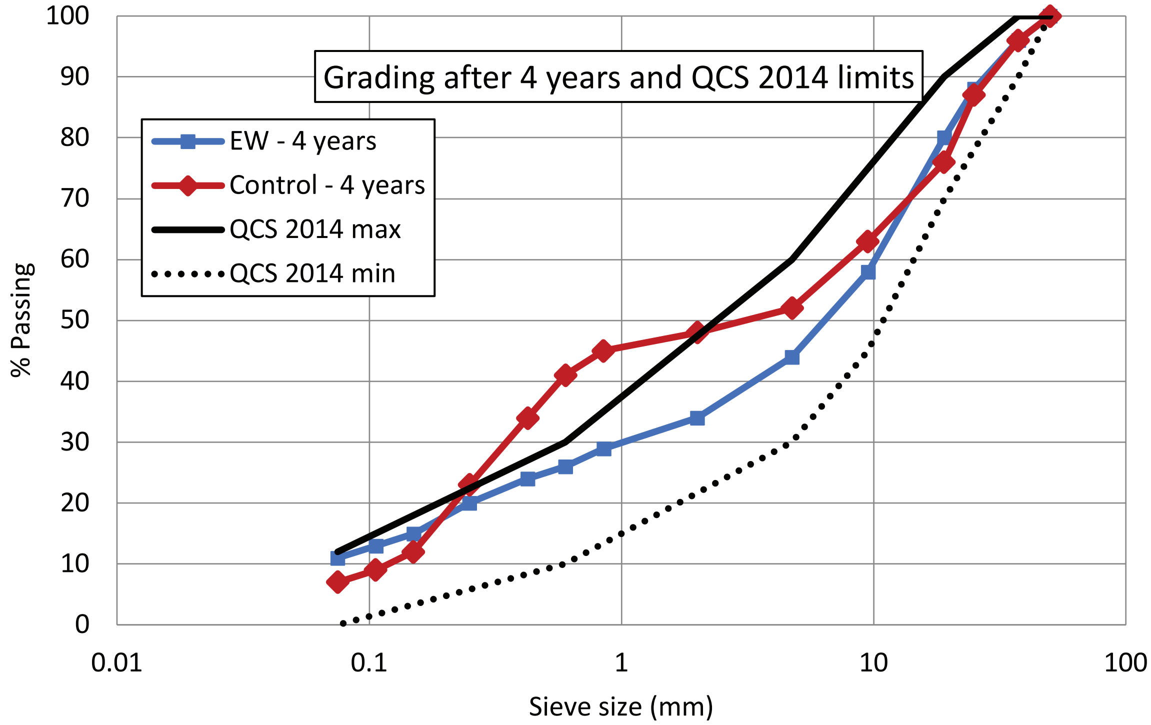

Figure 6-5 Grading of the subbase materials after 4 years (QCS 2014)

The results of Los Angeles Abrasion (ASTM C131, 2014), soundness (ASTM C88, 2013) after 5 cycles in magnesium sulfate solution, soaked California Bearing Ratio – CBR (ASTM D1883, 2016), and swell (ASTM D1883, 2016) are given in Table 6-3. All the subbase materials comfortably satisfied the requirements of the QCS 2014.

Table 6-3 Physical and mechanical properties of subbase materials

Test / Subbase	At construction			After 4 years			QCS 2014 limits
	EW	RCA	Control	EW	RCA	Control	
LA abrasion (%)	30	30	28	27	-	27	40 max
Soundness (%)	16.6	2.3	10.6	7.0	-	5.4	20 max-
Soaked CBR (%)	190	145	260	265	-	164	70 min
Swell (%)	0.16	0.17	0.13	0.20	-	0.80	1 max

The surface modulus of the subbase materials was measured using a light weight deflectometer (LWD), as per ASTM E2583 (2015). Six tests were carried out in each subbase section on the top of subbase layer 2 at construction and after 4 years in service. At construction, the measurements were conducted after compaction, before laying the asphalt overlay, at approximately 20m intervals. After 4 years, the measurements were conducted on the exposed subbase surface (900 x 1600 mm). The average and minimum modulus values are given in Table 6-4, together with the Foundation Classes of the UK pavement design as given in the Interim Advice Note (IAN) 73/06 (Highways England, 2009).

Table 6-4 LWD values for subbase materials at construction and after 4 years in service

Age	Subbase	Average dynamic deflection modulus Evd (MN/mm^2)	Minimum dynamic deflection modulus Evd (MN/mm^2)
At construction	EW	107	70
	RCA	109	87
	Control	105	90
After 4 years in service	EW	101	58
	RCA	205	151
	Control	81	63
Foundation Class 1 (UK guidance)		40	25
Foundation Class 2 (UK guidance)		80	50
Foundation Class 3 (UK guidance)		200	150

The LWD values at construction showed no significant difference between the 3 subbase sections with average values ranging between 105 to 109 MN/mm^2. All the 3 subbase materials would be a Class 2 Foundation, suitable for traffic loading up to 80 million standard axles. The exposed subbase after 4 years gave slightly lower values for the unbound materials of 101 MN/mm^2 for the EW and 81 MN/mm^2 for the control subbase. The RCA subbase exhibited the highest surface modulus, double the EW and control subbase materials, and would be a Class 3 bound subbase with an average surface modulus exceeding 200 MN/mm^2.

6.1.2.2 RCA Subbase Material

Cores (150mm diameter and 150mm height) were extracted from the hardened RCA subbase, section 2 of the site trials. The cores were sealed in plastic bags and tested in the laboratory for compressive strength, density and moisture content. The irregularities at the core ends were minimised by sawing the cores to produce flat perpendicular surfaces. Unbounded metal caps were used for the compressive strength testing as per ASTM C1231 (2015), Figure 6-6. Three cores were tested for compressive strength in "as-received" conditions, and the crushed cores were dried in an oven at 105±5 °C for the moisture content determination. Another set of three cores were used for the density measurement, weight in air and water, and soaked in water for 7 days at 24±5 °C. The saturated-surface dry cores were tested for compressive strength for the determination of retained strength as per the QCS 2014.

Figure 6-6 Compressive strength testing of the RCA subbase core

Table 6-5 RCA core results of strength, density and moisture content

	Compressive Strength (MPa)		Retained strength (%)	Density (kg/m^3)	Moisture content (%)
	As received	After soaking			
Core 1	2.1	2.0		2131	1.97
Core 2	2.4	2.5		2149	2.01
Core 3	2.5	-		2092	2.31
Average	2.3	2.2	96 %	2124	2.1

The core results of compressive strength, density and moisture content are given in Table 6-5. The average "as-received" core strength of the RCA subbase was 2.3 MPa. For the soaked strength, one core was excluded as it became short after sawing. The average soaked strength of the remaining two cores was 2.2 MPa. The retained compressive strength, measured as the ratio of soaked to as-received strength, was 96% and exceeded the minimum specified value of 80% in the QCS 2014. The high retained strength indicates high durability of the RCA subbase material for the ingress of water into the pavement. The average density and moisture content results were 2,124 kg/m^3 and 2.1%, respectively. The presence of moisture within the RCA subbase material allowed self-hardening of unhydrated cement in the RCA particles.

6.1.3 Discussion

EW, RCA and EW + 20% dune sand subbase materials were trialled in a field investigation on the access road to Rawdat Rashid Recycling site. The performance of recycled materials in unbound subbase was assessed at construction and after trafficking for 4 years. The assessment was made by comparing the in-service performance with construction data and the Qatar Construction specifications (QCS 2014) and was based on at least similar performance to the adjacent conventional subbase made with 20% dune sand. Visual inspection revealed excellent performance with no surface defects or cracking of the asphalt overlay, and no obvious differences between the 3 subbase sections.

Recycled materials satisfied the maximum dry density of the QCS 2014 but failed to achieve the field density of 100% of the maximum dry density achieved in the laboratory. Consideration should be given to the hot environment in Qatar and its effect on the rapid drying of materials in-situ, making it hard to achieve laboratory values of MDD. The subbase materials exhibited excellent performance in the trafficking trial with only minor development of rutting after loading of 1000 ESALs. The average surface modulus results exceeded 80 MN/mm^2, with no significant difference between the 3 subbase sections at construction and after 4 years in service. The surface modulus is a function of the foundation stiffness and thickness and the results indicate satisfactory performance under high traffic loading as per the UK Specification for Highway Works.

The grading curves of the subbase materials at construction fell within the grading envelope of the QCS 2010 Class B, except the EW subbase. After 4 years of trafficking, the unbound subbase materials of EW and control showed finer grading at all sieve sizes. The results may indicate the breakdown of the unbound particles under the effect of traffic loadings but could be also attributed to the extraction method of the unbound subbase material and the variability of materials. It is also important to consider the limitation of the exposed subbase surface compared to the full size of the trials.

The main parameters that appeared to fail the QCS 2014 requirements are the index properties of liquid limit, plastic limit and sand equivalent. None of the unbound subbase materials satisfied all the three requirements at construction or after 4 years in service. There is no doubt the use of dune sand improves the index properties of subbase materials, but the current restriction on its use will necessitate the use of alternative materials, such as recycled materials.

EW and local limestone materials are often contaminated with clay particles, widely disseminated throughout the limestone, and it is not possible to separate the clay from the limestone entirely. The clays are highly plastic, so even small amounts of contamination will lead to material failing the current limits for liquid limit, plasticity index and sand equivalent. These index properties are less significant to the pavement performance where the unbound materials are not subjected to water. In a hot and arid environment, such as in Qatar, the unbound materials are generally placed in dry conditions and covered by impermeable asphalt overlay. TRL Overseas Road Note 31 (TRL, 1993) recommended plasticity characteristics for granular subbases in arid and semi-arid climates; the liquid limit should be less than 55% and the plasticity index less than 20%. There could be potential to revise the QCS requirements where the unbound materials are placed in a dry environment above the ground water level.

The RCA subbase offered a superior performance with strength gain over time. The RCA material was placed as unbound material and met with all the QCS 2014 requirements with the except of liquid limit and field density, lower than 100% of the maximum dry density. However, the material hardened with time to become a bound subbase and achieved average values of surface modulus exceeding 200 MN/mm^2 and compressive strength of 2.3 MPa. The hardening of the RCA materials is due to the unreacted cement particles in the presence of water (Hassan et al., 2004), as evident from the available moisture content. The weak strength developed by the RCA subbase provides an excellent support to the overlaying pavement with reduced risk of reflection cracking.

6.2 Cement Bound Materials

The use of cement bound materials (CBMs) for road construction in Qatar is relatively new. CBM substrate provides a relatively strong and durable pavement layer, with uniform load distribution to the underlying foundation. However, consideration should be given to the rapid setting time, strength development, crack development and potential reflection cracks, especially in hot environment such as Qatar. Higher strength CBM results in increased stiffness, with greater tendency for wide cracks that could reflect through the asphalt overlay (FEHRL, 2009; Hassan et al., 2008). Due to the recent use of CBM in Qatar, laboratory mixtures were initially developed in the laboratory with the use of recycled materials then site trials were conducted to assess their performance in service.

6.2.1 Laboratory Development of CBMs

The QCS 2014 Section 6: Part 6 classifies CBMs based on their 7-day compressive strength (CBM 1 to CBM 4) with grading, strength and durability requirements. Laboratory mixtures of CBM 1, CBM 2, CBM 3, and CBM 4 were developed with the aim of utilising 100% recycled and local materials, comprising 75% local limestone and 25% RCA. Details of the CBM mix designs and properties are given in Table 6-6. The Portland cement was supplied by the Qatar National Cement Company (QNCC) and complies with the requirements of the QCS 2014 and BS EN 197-1 (2011), minimum grade of 42.5. The coarse aggregate consisted of 75% local limestone, obtained from Sand and Rocks Crusher, and 25% RCA, supplied by Beton concrete. Washed sand from QNCC was used as fine aggregate. The amount of mixing water ranged from 110 to 120 l/m^3, and a superplasticiser based on synthetic polymer was used in the range of 0.6 to 3.75 l/m^3 with a higher dosage for a higher strength CBM mixture.

Table 6-6 Mix design of the CBM materials

Material/Mix	CBM 1	CBM 2	CBM 3	CBM 4
Portland cement (kg/m^3)	80	120	150	190
Local limestone, 0-40mm (kg/m^3)	1100	1070	1080	1090
RCA, 5-20mm (kg/m^3)	400	410	400	385
Washed sand (kg/m^3)	690	710	690	650
Water (litre/m^3)	120	110	110	115
Chemical admixture (litre/m^3)	0.6	1.1	2.4	3.75
Fresh density (kg/m^3)	2302	2300	2331	2386

The grading curves of CBM 1 and CBM 2 are shown in Figure 6-7 and Figure 6-8 shows the grading of CBM 3 and CBM 4. The grading envelope provided in the QCS 2014 for each CBM type is also presented in Figure 6-7and Figure 6-8. CBM 1 and CBM 2 showed identical grading, which fall within the specified grading envelope in the QCS 2014. Similarly, the grading of CBM 3 and CBM 4 were identical and fit within the mid-range of the specified envelope. The QCS 2014 provides a wider grading range for the low strength CBM 1 and CBM 2, compared to the relatively high strength of CBM 3 and CBM 4, and would allow a range of local and recycled materials for use.

The aggregate materials were mixed initially with 50% of the mixing water before adding the cement, remaining mixing water and superplasticiser. Figure 6-9 shows the mixing of CBM material. Upon mixing, the materials were compacted into cube moulds using a vibrating hammer and the surface was levelled using a metal rod, Figure 6-10. It was noticed during mixing that CBM 1 was not holding together due to the relatively low cement content to coat all aggregate particles. Increasing the cement content would improve the consistency of the CBM mixture, but will increase the strength and the tendency of wide transverse cracks that may affect the performance of CBM in service.

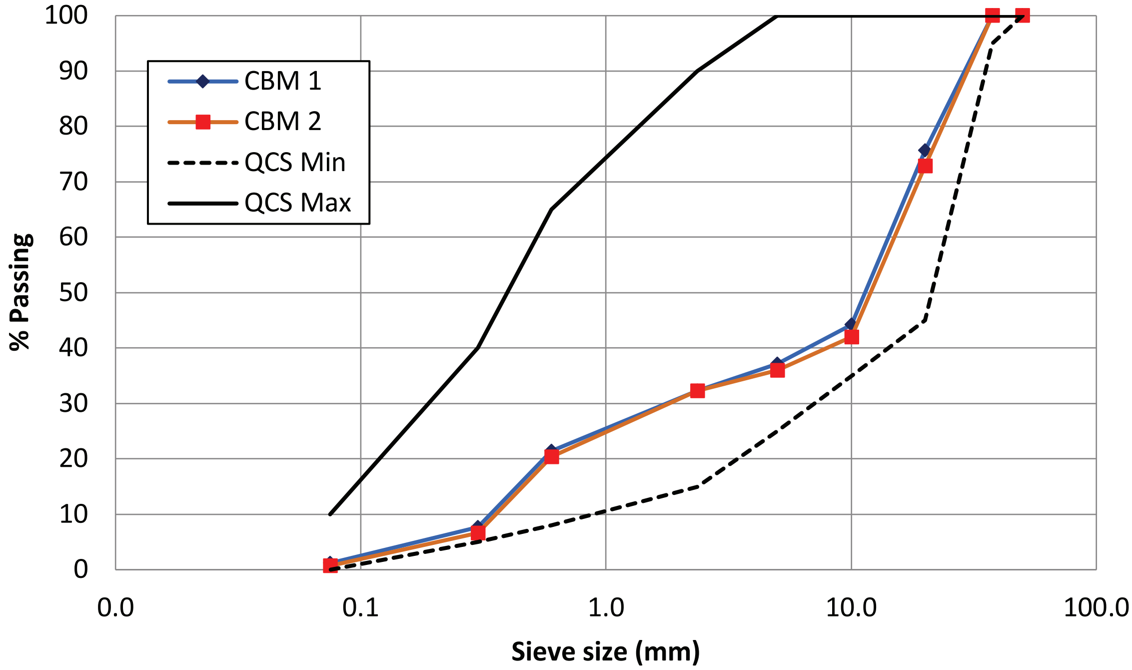

Figure 6-7 Grading curves of CBM1 and CBM2, together with QCS 2014 envelope

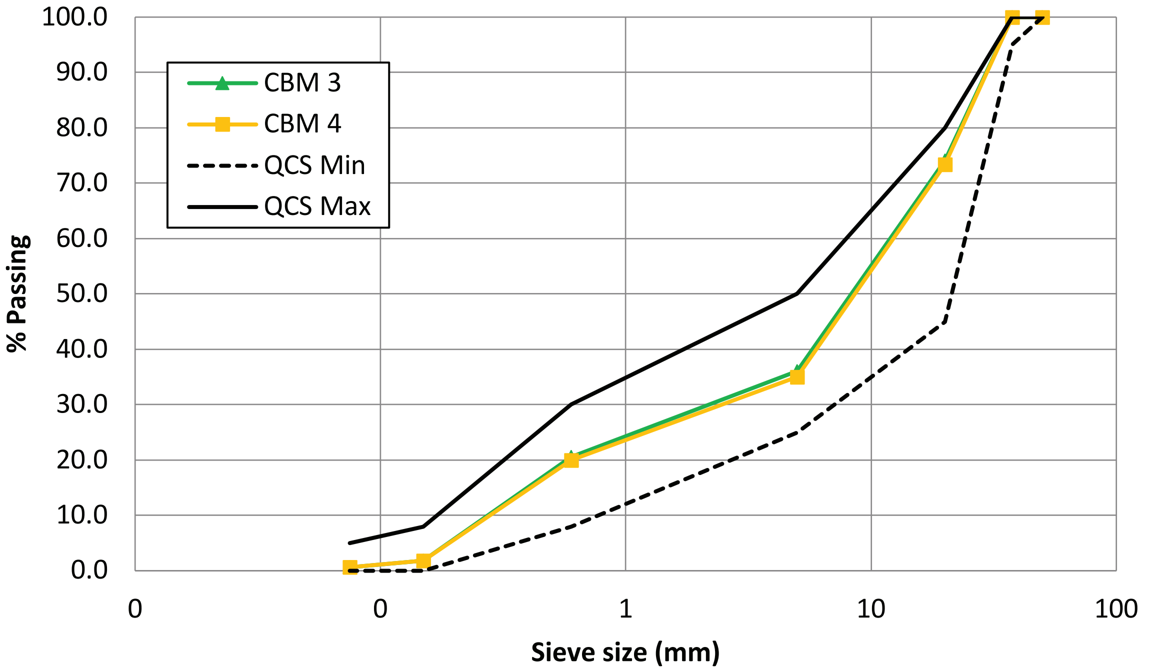

Figure 6-8 Grading curves of CBM3 and CBM4, together with QCS 2014 envelope

Figure 6-9 Preparation of the CBM mixtures

Figure 6-10 CBM compaction (left) and surface levelling (right)

After mixing, the fresh CBM material was poured into cube moulds with 150 mm sides. The material was compacted and levelled as shown in Figure 6-10. Compaction was made in two layers using a vibrating hummer and following the procedure described in BS EN 13286-51 (2004). The levelled surfaces of the cubes were covered with wet hessian and polyethylene sheets overnight. On the following day, the cubes were removed from moulds and cured in sealed plastic bags until required for testing at 3, 7, and 28 days. Fifteen cubes were prepared for each mix, with 3 tested for each test type, and the average values are reported in Table 6-7. The fresh density was determined by weighing the cube moulds before and after filling with CBM materials. The values ranged from 2300 to 2386 kg/m^3, with increased density for a higher strength CBM material. The retained strength was determined from the ratio of the average compressive strength after 7 days of immersion in water to the average control strength.

Table 6-7 CBM average density, strength and durability properties

Material/Mix	CBM 1	CBM 2	CBM 3	CBM 4
Fresh density (kg/m^3)	2302	2300	2331	2386
3 days compressive strength (MPa)	3.51	5.87	8.72	11.30
7 days compressive strength (MPa)	5.67	8.27	12.71	19.60
28 days compressive strength (MPa)	7.29	10.34	16.30	25.43
Retained strength (%)	97%	95%	96%	93%
QCS 2014: Min average 7-d strength (MPa)	4.5	7.0	10.0	15.0
QCS 2014 Min individual, MPa	2.5	4.5	6.5	10.0

The cubes were tested for compressive strength as per BS EN 12390-3 (2019). The QCS 2014 specifies a minimum average 7-day compressive strength for the various CBM mixtures. Table 6-7 shows that the average 7-d strength for all CBM mixtures exceeded the minimum specified values. The QCS 2014 also specifies a minimum individual value for each CBM type, and all the developed CBMs satisfied the minimum strength requirements of the QCS 2014.

Durability of CBM materials is generally assessed by exposing to water and measuring the compressive strength after immersion. The CBM ingredients need to satisfy the QCS 2014 Section 5 for Concrete, including aggregate and cementitious binders. The QCS 2014 sets a minimum retained strength of 80%, as determined from the ratio of the average compressive strength after immersion in water to the average control strength. The results in Table 6-7 show retained strength values ranging between 93 to 97% for the development CBM mixtures, far exceeding the minimum specified limit. In general, the strength and durability results obtained from the laboratory development show that local and recycled materials could be effectively used for the production of CBM materials with full compliance with the QCS 2014 requirements.

6.2.2 *CBM Site Trial*

The RCA-CBM 3 mix design, developed in Section 6.2.1, was applied in a full-scale construction project of an access road to the Katara Metro Station. The access road to the station is made with paving blocks, laid on a bed of sand and CBM 3 as the main base layer. Figure 6-11 shows the constructed CBM 3 and the overlay with sand bed and paving blocks. The CBM 3 used in the Katara Metro Project was supplied by ReadyMix Qatar, with the details described in Table 6-6.

Figure 6-11 CBM 3 overlaid with sand and paving blocks – Katara Metro Station

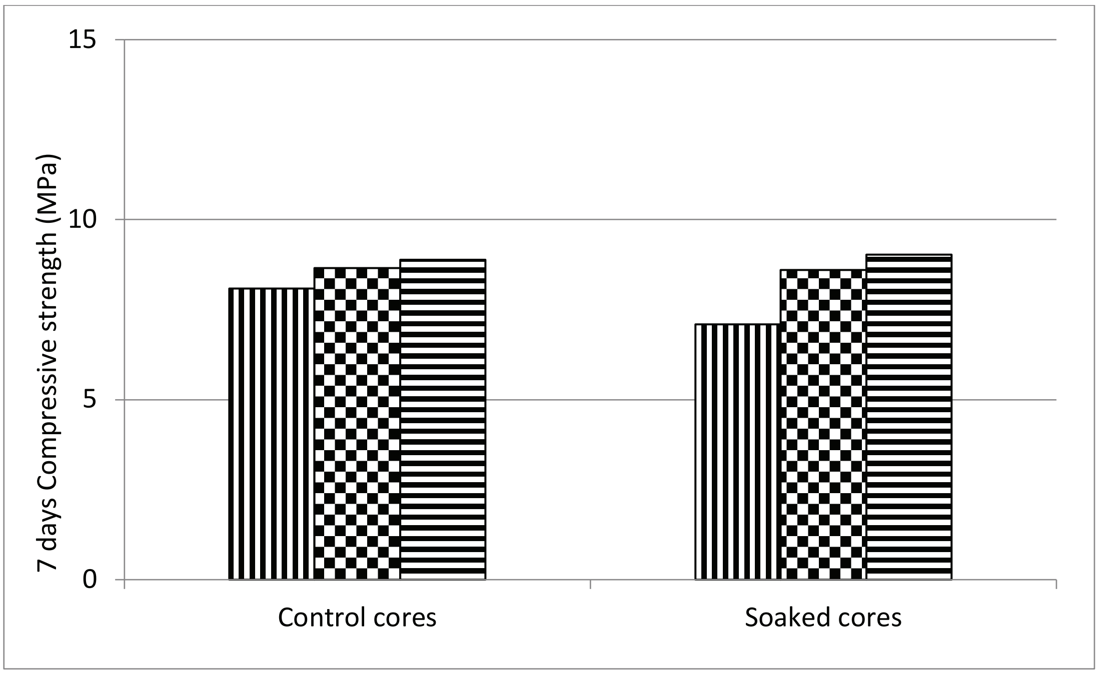

Figure 6-12 CBM 3 core strength, Katara Metro Station

Cores of 150 mm diameter and 150 mm height were taken from the constructed CBM at 7 days after construction and tested for compressive strength and retained strength. The results are given in graphically presented in Figure 6-12.

Three cores were tested for each test. For the control strength, the core compressive strength varied from 8.1 MPa to 8.9 MPa, with an average value of 8.5 MPa. Each individual core exceeded the minimum QCS 2014 requirement of 6.5 MPa, however, the average core 7-days compressive strength was lower than the minimum specified of 10.0 MPa. It is important to note that the QCS 2014 specification is referred to cube strength, and core strength is expected to be approximately 75% of the cube strength (Neville, 2011). The retained strength, after 7 days soaking, was 96% and greater than the minimum specified value of 80%.

6.2.3 CBM Site Data

While the QCS 2014 specifies minimum average and minimum individual compressive strength values at the age of 7 days, project specifications tend to deviate from the QCS and specify a maximum value for the CBM strength. This is mainly due to the concern of reflection cracking within the hot weather in Qatar.

The Ashghal Quality and Safety Department (QSD) provided site data for CBM materials constructed in various Ashghal projects at the age of 7 days. Data were obtained from 10 projects with over 750 strength results and reported by Hassan et al. (2020c) and summarised in Table 6-8. Loose CBM materials were collected during construction, compacted on site into cubes (150mm), and tested for compressive strength at the age of 7 days.

Table 6-8 Site data of various CBM projects – Average 7-day strength

CBM Type	CBM
Average compressive strength, MPa	4.5
Min compressive strength, MPa	0.7
Max compressive strength, MPa	12.7
Project specified Minimum strength, MPa	3.0
Project specified Maximum strength, MPa	7.0

Site data for the different CBM projects showed a wide variation of the 7-day compressive strength. The average 7-day compressive strength was 4.5 MPa, well within the specified range of 3.0 to 7.0 MPa. However, the minimum 7-day strength was 0.7 MPa, much lower than the minimum specified for the project, and the maximum was 12.7 MPa exceeding the maximum specified strength. The CBM results indicate the difficulty of achieving a consistent strength for the specified low strength CBM.

6.2.4 Discussion

The laboratory development of CBMs demonstrated the potential use of 100% local and recycled aggregate materials. CBMs were made with coarse aggregate of 25% RCA and 75% local limestone, and the developed mixtures satisfied the QSC 2014 strength and retained strength requirements, indicating good durability and resistance to water damage. During the laboratory development, it was noticed the low cement content of 3% in CBM 1 was not adequate to coat all the aggregate particles. At a cement content of 5%, CBM 2 and above, the mixture looked more homogeneous with adequate binder content. Site data also indicated the inconsistent compressive strength, especially for CBMs with low strength (low cement content).

CBM layers are expected to crack after construction due to shrinkage and thermal movements, and the intensity of cracks are expected to increase in hot environments, such as in Qatar. The QCS 2014 specifies that after compaction and immediately before overlaying, the CBM surface shall be well closed and free from movement, cracks, loose materials, ruts, or other defects. It also specifies that all defected areas shall be removed, to the full thickness, and replaced with a new CBM layer.

Figure 6-13 Induced CBM cracks and filling the grooves

While low strength CBMs are generally used to minimise the risk of reflection cracks in the asphalt overlay, they may not provide consistent strength and uniform support across the pavement length. To overcome the issue of reflective cracking, the UK Specification for Highway Works (Highways England, 2016), Volume 1, Series 800 specifies induced cracks for all HBMs that are expected to reach a compressive strength of 10 MPa at 7 days. Transverse cracks are induced in the fresh CBM/HBM by grooving the layer between half and 2/3 its thickness and filling the grooves with a bitumen emulsion before final compaction as shown in Figure 6-13. The transverse cracks will not prevent the CBM from shrinkage and thermal movements but will accommodate such movements and minimise their effect of reflection cracking. The technology is relatively cheap, has been successfully used in the UK, and potential for implementation in Qatar and the region.

Another factor contributing to the inconsistent strength of CBM is the setting time of Portland cement and inadequate curing on site. The QCS 2014 specifies that laying and compaction of the CBM shall be made within 2 hours from mixing the cement with water, and a minimum curing period of 7 days immediately after compaction. The hot weather in Qatar could greatly accelerate the rapid hardening of cement and evaporation of mixing water, and hence influence the strength and cracking of CBMs.

Cement replacement materials, such as fly ash (FA) and ground granulated blast-furnace slag (GGBS), provide alternatives to Portland cement with improved performance and reduced impact on the environment. The use of FA and GGBS as partial replacements for cement increases the setting time of the binder due to slow-hardening and provides with more homogeneous mixtures with consistent strength and support to the pavement structure (Hassan et al., 2008a). The binder content in FA and GGBS bound materials is generally higher than of CBM, and therefore a more consistent mix is generally produced (Hassan et al., 2008a).

There is no doubt that the use of CBMs in construction will enhance its structural capacity and durability towards more sustainable construction. CBM acts as the main structural layer within the semi-rigid pavement with an asphalt overlay. The combination of a bound structural layer and an asphalt surfacing has great potential to provide long-life pavements with minimum maintenance. However, the variability of CBM has to be reduced and quality improved if it is to achieve this potential.

6.3 Summary

The performance of recycled materials in pavement subbase was determined by excavating the asphalt overlay after 4 years in service and comparing field and laboratory results with construction data and the QCS 2014. The road trial proved to be successful, with the subbase materials made of recycled materials of EW and RCA performing at least similar or better than the control subbase made with conventional materials. Visual inspection showed no signs of surface defects or cracking of the asphalt overlay with no difference in appearance between the 3 subbase sections.

A finer grading was found for the unbound subbase after trafficking for 4 years, with the control section made with dune sand falling out of the QCS 2014 specified grading envelope. The subbase materials comfortably met with the key subbase parameters of Los Angeles abrasion, soundness, soaked CBR and swell, with initial satisfactory resistance to rutting and surface modulus under very high traffic loading. However, the unbound subbases did not meet with all the index properties of liquid limit, plasticity index, and sand equivalent, which could be of less significance in the arid climate of Qatar where the material is not subjected to water.

An excellent performance was achieved from the RCA subbase, with the material initially laid as unbound material and hardening with time to provide support to the pavement structure. A further set of construction trials is proposed to investigate the potential use of RCA fines to replace dune sand to enable the wider utilisation of recycled and local materials in construction towards more sustainability in Qatar.

CBM and other hydraulically bound materials are the main structural layers in semi-rigid pavements, with potential for extending the service life and sustainability of road pavements. CBM 1 to CBM 4 mixtures developed in the laboratory complied with the strength and durability requirements of the QCS 2014. The average retained strength values exceeded 90%, indicating good durability and resistance to water damage. The mixtures were made with 100 % local materials, including 75 % limestone aggregate, 25 % RCA and Portland cement. The developed CBM 3 was used in the construction of an access road to the Katara Metro Station, and the site data confirmed the laboratory results for satisfactory performance and compliance with the QCS 2014 requirements.

A review of project specifications indicated the addition of a maximum limit on the strength requirement of CBM to minimise the risk of reflection cracking. Project specified values for the average 7-day compressive strength are generally between 3.0 MPa minimum and 7.0 MPa maximum. Site data indicated a high variability strength results, mainly due to the low content of Portland cement. To improve the performance of CBMs in Qatar, recommendations are made for the use of cement replacement materials and to adopt the UK specification of induced cracks into the fresh CBM materials. The effective use of CBM materials in Qatar will enhance the pavement service life and the uptake of a wide range of recycled and local materials. It is also important to ensure there is adequate quality control of the construction of CBM in the hot climate of Qatar to ensure the materials are properly mixed, placed and compacted while they are at optimum moisture content.

7 Recycling in Pipe Bedding

Pipe bedding is one of the aggregate applications considered in the Ashghal Recycling Manual (2021) for the use of 100% recycled materials in duct, pipe and cable bedding and surround materials. However, the use of recycled aggregate in pipe bedding and drainage applications in Qatar is still rather limited. This Chapter reviews the pipe bedding requirements, as specified in the QCS 2014 and Kahramaa Specifications, and compares them to the UK specifications. The recent requirement made by the Ashghal Drainage Networks and Designs Department for limiting the use of imported gabbro in wet utilities are also discussed within the context of locally available natural and recycled aggregate materials. Laboratory testing was conducted to assess the compliance of EW and RCA aggregates for use in pipe bedding. A site trial was constructed to demonstrate the potential use of local Wadi gravel, to replace imported gabbro, in a trench soakaway. Recommendations are made for updating the national specifications for pipe bedding and increasing the usage of local materials.

7.1 Requirements in Pipe Bedding Materials

The rapidly developing infrastructure in Qatar has generated an enormous demand for pipe bedding to support all the cables, drains, pipes and services associated with new roads, housing, education, health, retail, leisure and other facilities being constructed. While the quantities may be relatively small compared to the requirements for other unbound applications such as subbase, subgrade and general fill, pipe bedding is a vitally important application for the functioning of all the new developments.

Pipe bedding is an essential component in every "open cut" pipeline installation, with the primary function to transfer loads between the pipe and the surrounding soil. Pipe bedding must provide a stable base below the pipe. The material must be clean and free from clayey fines, lumps of clay or other friable materials that could break down during placing and compaction. It must be able to flow freely into the trench and be adequately compacted. The particles must be strong enough to support the pipe or duct without crushing, and the pipe bedding should not contain levels of sulfates, chlorides or other salts that could cause corrosion of the pipes and ducts.

While other unbound applications such as subbase generally require a broad range of particle sizes and can be spread and compacted in layers in the open, pipe bedding requires very tightly controlled single-size grading related to the diameter of the pipe or duct that is being supported. The selected materials are used for different utilities such as 0-5 mm for medium voltage cables, IT ducts and street lights, 0-10 mm for potable water lines, and 10-20 mm for drainage.

The requirements of pipe bedding, particularly the grading, mean that a lot of processing is needed to obtain satisfactory materials from many of the local materials in Qatar. In some cases, blending with other materials may be necessary to achieve compliance with QCS 2014.

7.1.1 QCS 2014 Pipe bedding requirements

Detailed requirements are given for pipe bedding directly associated with road drainage, in:

- Section 6: Road Works: Part 17: Road drainage

- Section 8: Drainage: Part 3: Earthworks

The requirements are similar in both sections, but the grading varies slightly between bedding for rigid and flexible pipes (Section 8: Part 3) and surround material for soakaways (Section 6: Part 17). It is recommended to combine the requirements in a single section of the QCS 2014 to improve the overall consistency of the requirements and avoid repetition of text.

The aggregate requirements are given in terms of grading and other properties related to the cleanliness of the materials, mechanical and chemical properties, and durability as discussed below.

7.1.1.1 Grading

Grading envelopes are provided in the QCS 2014 for coarse/all-in aggregate (aggregate with a maximum particle size greater than 5 mm). The grading for surround material for trench soakaways is given in Section 6.17.9.5 Single size coarse aggregate. The grading envelopes for pipe bedding for rigid and flexible drainage pipes are given in Section 8.3.2.1 Pipe bedding. The QCS 2014 grading requirements are reproduced in Table 7-1.

Table 7-1 Grading requirements for pipes bedding and granular materials (% passing)

Sieve size, mm	Granular Material	Rigid pipes			Flexible pipes	
		<300	300-800	>800	<300	≥300
37.5	100	-	-	-	-	-
25	-	-	-	100		
20	60-90	-	100	90-100		
14	5-30	90-100	80-100	50-80	-	90-100
10	2-10	50-85	60-85	40-70	50-85	50-85
5	0-2	10-40	20-55	25-60	10-40	0-10
2.36	-	0-10	10-30	10-40	0-10	0-10
0.3	-	-	0-10	0-15	-	-

The gradings are all slightly different and partly related to the diameter of pipe to be supported. The gradings are coarser the larger the pipe diameter, but there are also differences between gradings for flexible and rigid pipes of the same diameter. The coarsest grading, with the lowest fines content, is for surround to trench soakaways. This material has to be clean and highly permeable to allow the water to flow rapidly away from the pipe.

For flexible pipes, no grading limit is provided in the QS 2014 for pipes (<300mm) at sieve size 14mm, and the grading limits for sieve sizes 5 and 2.35mm are identical of 0-10mm. It would have been expected to provide a wider grading range for the larger sieve size of 5mm.

7.1.1.2 Other Requirements – QCS 2014 6.17

Other requirements for single size coarse aggregates for trench soakaways are given in the QCS 2014 Section 6.17.9.5.3 and Table 17.4, reproduced below in Table 7-2.

Table 7-2 Requirements for granular material (Table 17.4 of QCS 2014)

Item No.	Requirements	Test Method	Permissible Limits
1	Grading	BS EN 933-1	Table 17.3
2	Clay lumps and friable particles	ASTM C142	1% Max.
3	Lightweight Pieces	ASTM C123	0.5% Max.
4	Water Absorption (SDD)	ASTM C128/127	2.0% Max.
5	Shell Content	BS EN 933-7	3% Max.
6	Soundness (5 cycles by $MgSO_4$)	ASTM C88	15% Max.
7	Loss by Los Angeles Abrasion	ASTM C131/C535	30% Max.

In addition, the granular material shall be clean, durable, sharp-angled fragments roughly cubical or pyramidal in shape, of un-weathered rock of uniform quality and meet the grading limits. The materials source shall be approved by the Engineer based upon the properties of the materials in accordance with the testing requirements given in Table 7-2. No reactive carbonate rock or sources with indication of local ground water contamination shall be used.

Cleanliness is covered by the grading in the QCS 2014 Table 17.3 and the requirements for clay lumps and friable pieces and lightweight pieces. No limiting value is specified for fines (silt and clay finer than 0.075 mm). This is done for fine aggregate in the Kahramaa specification (Section 7.1.2), and for pipe bedding in the UK Specification for Highway Works (Section 7.1.3). It is suggested that the limiting values for coarse aggregate for use in normal concrete in the Section 5 Concrete: Part 2 Aggregates Table 2.1 of the QCS 2014 would also be suitable for pipe bedding.

The QCS 2014 specifies limiting values for clay lumps and friable pieces and lightweight pieces and shell content. The limiting value for clay lumps and friable particles is 1%, 0.5% for lightweight pieces, and 3% for shell content. The values specified for lightweight pieces and shell content are identical to those specified in the QCS 2014 for Aggregate use in concrete (Section 5: Part 2). However, the clay lumps and friable material is half that for aggregate for concrete, 1 % as opposed to 2 %.

Particle strength and durability are covered by Loss by the Los Angeles Abrasion, Soundness and Water Absorption tests. The values given in Table 7-2 are the same as those for coarse aggregate in concrete in Section 5 Concrete: Part 2 Aggregates. The concrete specification (Section 5.02) allows higher values of water absorption for recycled aggregate; 3% for structural concrete and 4% for non-structural concrete are permitted for EW, RCA, CDW. These higher values recognise that these materials have higher values of water absorption, but can still provide suitable aggregate for concrete. It would be appropriate to apply these higher values to pipe bedding using recycled aggregates for the same reasons.

The values for Loss by Los Angeles Abrasion and Soundness for pipe bedding in Table 7-2 are the same as those for coarse aggregate for concrete in Section 5.02 and for road base in Section 6.04. However, slightly lower values of 40% for Los Angeles and 20% for Soundness are given for subbase in Section 6.04 Table 4.2.

The introductory text also describes aggregate as “sharp-angled fragments roughly cubical or pyramidal in shape”. These characteristics are usually measured by parameters such as flakiness index and elongation index. The QCS 2014 Table 2.1 in Section 5.02 includes a limiting value for Flakiness Index of 35%, and this could usefully be applied to pipe bedding and included in Table 17.4. Table 4.2 in Section 6.04 uses ASTM D4791 test for Flat and Elongated Particles to control particle shape, with maximum values of 10% for road base and 15% for subbase. This test may be more appropriate for pipe bedding, which is also an unbound material.

The QCS 214: Table 17.4 does not include any limiting values for Sand Equivalent, Liquid Limit or Plasticity Index. These are not appropriate for coarse aggregate for an unbound application such as pipe bedding. The limiting values for lightweight pieces, clay lumps and friable particles, plus tight control on the grading and the quantity of fines, will ensure the aggregate is suitable for purpose.

Table 17.4 does not include any limiting values for sulfate or chloride for pipe bedding. The Kahramaa specification provides limiting values for acid-soluble chloride and sulfate for fine aggregate. The QCS 2014 Section 5.02 Table 2.1 also includes limiting values for both fine and coarse aggregate for use in concrete. The risk of corrosion of the pipes from sulfate or chloride salts in the pipe bedding has to be considered. The risk may be low when the pipe bedding is dry, but water readily finds its way into permeable materials such as pipe bedding during heavy rainfall events, and on these occasions sulfate and chloride salts could be readily mobilised and could potentially attack concrete or metal pipes. However, the risk also depends on what measures are taken to protect the pipes, particularly metal pipes, to prevent corrosion. The Kahramaa Specification, Section 8 Corrosion Protection, describes extensive measures that should be taken to protect pipes against corrosion, which would also protect against low levels of salts in the pipe bedding.

The limiting values for sulfate and chloride given for fine aggregate in the Kahramaa specification are therefore probably the most appropriate to use for coarse aggregate in the QCS Table 17.4. These are maximum sulfate content (SO_3) of 0.4% and maximum chloride content of 0.10%. The type of sulfate is not specified, but is assumed to be acid-soluble sulfate, as this parameter is used for sulfate throughout the QCS 2014.

7.1.1.3 Other requirements – QCS 2014 8.03

The QCS 2014 Section 8: Drainage, Part 2: Earthworks, use almost identical text as Section 6: Part 17 to describe the permitted materials for pipe bedding. “Pipe bedding shall consist of granular material and shall be free of organic and deleterious matter and shall consist of strong durable crushed un-weathered rock or stones having roughly cubical or pyramidal shaped fragments, graded and tested from a source approved by the Engineer. No reactive carbonate rock or sources with indication of local groundwater contamination shall be used." The grading requirements as per Section 7.1.1.1.

7.1.1.4 French Drains – QCS 2014 8.02

For French drains, the QCS 2014 Section 8, Part 2 specifies that pipe bedding and backfill shall be in accordance with Section 6, Part 14, Clause 14.9.5. There is no Clause 14.9.5 in the QCS 2014, presumably this refers to an earlier version.

A further requirement is that the total loss factor for the granular material used in French drains using the 10-minute rotational test shall not exceed 10%. The loss factor is the Central Materials Laboratory (CML, 1997) standard method of test for the 10-minute rotational test for aggregate – Immersed Rotational Test. This was a test developed for assessing earthworks suitability and was included in the QCS 2010 Section 6.03 Earthworks in the previous (2010) version of the QCS. It has not been used in the QCS 2014, so it is recommended to replace by an equivalent one such as Loss by Los Angeles Abrasion or the micro-Deval as per BS EN 1097-1 (2011).

The QCS 2014 also specifies that chloride and sulfate levels for bedding materials shall conform to BS EN 10319.

7.1.1.5 Limitations on Material Type – Drainage Networks Design Department Requirements

In addition to the requirements for grading and material properties, the QCS 2014 includes limitations on material type for pipe bedding in Sections 6.17 and 8.02 as follows: "No reactive carbonate rock or sources with indication of local groundwater contamination shall be used."

This text is amplified in a memo from the Ashghal Drainage Networks Design Department to the Road Projects Department of Ashghal dated 19th April 2016 and headed "Test for Carbonate Rocks and Revision of Drawings" (Ashghal Memo, 2016). The memo refers to the wording above and expands on it by stating, "Carbonate rocks should not be used as a single size aggregate material for Pipe Bedding". The memo specifies two test methods for determining the carbonate content of the rocks:

- X-Ray Diffraction (XRD) – Calcite and Dolomite;
- Carbonate content test (ASTM D4373-14).

If the carbonate content is more than 50% the material should not be used as a single size aggregate for pipe bedding. If the carbonate content is less than 50% then the material should be tested in accordance with QCS 2014, Section 6, Part 17, Table 17.3 and 17.4, as described in the previous sections. Tests should also be carried out for:

- Acid soluble chloride content;
- Acid soluble sulfate content;
- Organic matter;
- Flakiness index.

The Ashghal memorandum of 2016 was replaced with another memorandum on 4th June 2018 (Ashghal Memo, 2018). The Memo is headed "QA000- Drainage works- Backfill gabbro" and states "Material (either single sized or graded) which is used for pipe bedding around wet utilities (excluding TSE), must include gabbro hardstone aggregates. In the case of filtration and percolation systems such as French drains, soakaway and ground water lowering systems gabbro hardstone aggregate shall be used throughout the whole filtration/percolation medium it is designed for, regardless of the current level of ground water identified on site".

The Ashghal memo clearly restricts the use of local aggregate (natural or recycled) and conflicts with the Ashghal Recycling Manual for the wider use of recycled aggregate in construction. Excluding local limestone from use as pipe bedding and replacing it with imported gabbro would add considerably to the cost. It also adds to the environmental cost, as the transport of gabbro to Qatar generates large quantities of greenhouse gases, which would be avoided if locally available limestone or recycled materials was used.

From the text used - "reactive carbonate rock or sources with indication of local groundwater contamination" – the issue has to do with reaction between carbonate rock and groundwater. The majority of Qatar's land surface comprises chalky limestone and dolomites which are susceptible to dissolving and eroding in water. Large areas of Qatar are low-lying, with groundwater close to ground level, and trenches for larger diameter pipes may reach below the water table, at least for part of the year. The groundwater is likely to have high chloride and sulfate content, and possibly also other salts, which may interact with the pipe bedding and/or the pipe material, particularly where this is steel, iron or concrete.

Carbonate rocks are more susceptible to dissolving in groundwater with high sulfate content due to the formation of gypsum, which could clog up the drains overtime. Cripps et al. (2019) reported gypsum formation, as precipitated mineral, in limestone drainage blankets in Carsington Dam due to acidic leachate with high sulfate content from the surrounding black shale fill material used for the construction of the dam. Deposits of gypsum were also found agglomerated to the particles of Wadi gravel obtained as oversize materials from the sand washing plants in Qatar (Hassan et al., 2020b).

Groundwater movement could cause the fragmentation of weak bedding aggregate, resulting in increased fine content and blockage of the pipe/drainage system. Stuyt et al. (2005) recommended that the use of limestone aggregate must be avoided in subsurface land drainage systems, because a high percentage of lime in the granular material could be a source of incrustation. In wet conditions, the precipitation of calcium carbonate and calcium sulfate may occur from weak limestone aggregate, forming hard and crystalline deposits that are likely to build up comparatively slowly with adverse effects on flow after a long time.

The Ashghal Memo (2018) excludes the use of other local and recycled materials of non-carbonate rocks such as Wadi gravel and steel slag aggregate. A case study is presented in Section 7.3 on the use of local Wadi gravel in pipe bedding, as an alternative to imported gabbro.

7.1.2 Kahramaa Specifications

The Kahramaa General Specification for Main Laying Contracts, dated April 2005, provides detailed requirements for pipe bedding material in Section 5 Backfilling Trenches, Clause 5.1

Imported Granular Material and Selected Excavation Material. The relevant text is reproduced below:

- Imported granular material shall comprise either of natural dune sand or crushed clean hard limestone or be a mixture of these. The sand and/or crushed limestone shall be obtained from an approved source.
- Granular material shall contain no excessive quantities of dust, soft or flaky particles, shells, congealed lumps, nodules of soft clay, shell, alkali or other contamination likely to affect adversely the compaction of the material or to cause damage to pipes.
- The sulphate content (as SO_3) of the material shall not exceed 0.4% by weight and the Chlorides (as CI) shall not exceed 0.10% by weight.
- Prior to commencement and during progress of works the Contractor shall provide Kahramaa with samples of the proposed granular material to be used in the works, along with their soil test results and shall obtain his written approval for its use. This sample will be retained by Kahramaa for comparison with deliveries to the site during the works.
- The grading of fine aggregate when determined by the method described in BS 812 shall lie within the respective limits specified within Table 7-3.

Table 7-3 Grading limits for fine aggregate pipe bedding (Kahramaa, 2005)

BS Sieve Size (mm)	Percentage passing by Weight (%)	
	Normal Sand	Crushed Rock
4.76	95 – 100	90 – 100
2.4	75 – 95	60 – 90
1.2	45 – 85	40 – 80
0.6	25 – 60	20 – 50
0.3	5 – 30	5 – 30
0.15	0 - 10	0 - 15

- The total quantity of fine dust through No. 22 mesh sieve in fine aggregate derived by crushing rock, shall be determined by the method described in BS 812 paragraph 14 and shall not exceed 8% by weight.
- The total quantity of clay and silt in natural sand shall not exceed 4% by weight when determined by the field setting test described in BS 812 paragraph 15.

The Kahramaa specification covers fine aggregate, 0-5 mm, whereas the QCS 2014 covers coarse and all-in aggregate, where the maximum particle size is greater than 5 mm. There are no references to different gradings to be used depending on the pipe diameter. The pipes, cables and service ducts covered by the Kahramaa Specification will generally be quite small in diameter, seldom greater than 150 mm, and can be adequately seated on a 0-5 mm bedding material, often at quite shallow depth. The Kahramaa Specification includes crushed limestone as one of the permissible materials for pipe bedding, so clearly they do not have concerns about the use of local aggregate and carbonate rocks as pipe bedding.

The Kahramaa Specification provides clear grading envelopes for the two permitted materials, dune sand and crushed limestone. It also provides limiting values for the fines (< 0.063 mm, silt and clay-sized particles) content of 8 % for crushed rock and 4 % for natural sand. The higher limiting value for crushed rock is because fines generated by crushing rock are likely to be dominantly silt-sized, whereas in the natural sand there is likely to be a higher proportion of potentially harmful clay-sized particles. A similar distinction is made in the UK Specification for Highway Works (Section 7.1.3).

Specific limiting values for sulfate and chloride are given, though no test methods are specified. The Kahramaa Specification included detailed requirements for corrosion protection measures to be applied to all types of buried pipes, so the limiting values for sulfate and chloride in pipe bedding in the Kahramaa Specification can probably be assumed to be adequate to cope with the conditions likely to be encountered.

There is general text around the same issues as for pipe bedding in the QCS 2014 – cleanliness, presence of clay lumps or friable particles, lightweight particles or other contamination "likely to affect adversely the compaction of the material or to cause damage to pipes". It is suggested that these general comments be replaced by specific limiting values for the relevant parameters used for coarse aggregate in Table 17.4 of Section 6 of the QCS 2014. Limiting values for Loss by Los Angeles Abrasion and Soundness are not required for fine aggregate. The test methods for grading and fines content are out of date and should be replaced by the methods used in the QCS 2014.

7.1.3 UK Specification for Highway Works

In the UK Specification for Highway Works (SHW), pipe bedding is covered under Series 500 Drainage and Service Ducts (Highways England, 2020). The grading of the pipe bedding varies with the pipe diameter, as in the QCS 2014. There are limiting values for fines content, with different values for pipe bedding derived from natural aggregate of 1.5% and 4% for crushed rock and recycled aggregate. For fine aggregate and all-in aggregate, the maximum values of fines content are relaxed to 3% for natural aggregate and 10% for crushed rock and recycled aggregate. Natural aggregate, recycled aggregate and recycled concrete aggregate are permitted for coarse aggregate, but if recycled aggregate or recycled concrete aggregate are used the composition must be tested and contain no more than 1% other materials. This could be covered by the requirements for clay lumps and friable particles and lightweight pieces in the QCS 2014, to save introducing a new composition test to the QCS.

There is a requirement for a maximum Loss by Los Angeles Abrasion of 50% for particle strength, which is the same as the value for unbound subbase. There is a general limiting value for water-soluble sulfate of 0.2% for pipe bedding, when tested in accordance with BS EN 1744-1 (2009). No limiting value is given for acid-soluble sulfate or chloride. Chlorides are not common in UK soils and rocks, so limiting values are not normally given. Limiting values for water-soluble sulfate, total sulfur and pH are given for pipe bedding placed adjacent to buried concrete or structural metallic items. The values for backfill to metallic structural items are very stringent.

7.2 Recycled and Local Aggregates for Pipe Bedding

Recycled aggregate of EW and RCA were assessed for compliance with national specifications for use in pipe bedding applications. The materials were processed following the procedure described in Chapter 3 to meet general specifications for use as aggregate for concrete, subbase and pipe bedding applications. The selection of EW and RCA was made because the materials provide relatively clean aggregates, compared to other recycled types of construction and demolition waste, and are available in relatively large quantities in Qatar.

The physical, mechanical and durability testing of the recycled materials were conducted at the Ashghal Centre for Research & Development, whereas the chemical testing was carried out at an Ashghal-approved testing house. The carbonate content was conducted on the granular aggregate (single size of 14 to 20 mm) of coarse aggregate, and the fine aggregate (passing 5 mm).

7.2.1 Rigid Pipes

Rigid pipes, such as concrete, clay-ware, and iron, are relatively strong and the majority of the structural strength from the embedment is inherent in the pipe itself. This allows a choice from a range of bedding materials. The QCS 2014 grading limits for pipe bedding for rigid pipes are given for different pipe diameters of less than 300mm, 300-800mm, and greater than 800mm in diameter. EW and RCA aggregates were tested for sieve analyses and the grading results are given in Table 7-4, together with the QCS 2014 grading envelopes.

Table 7-4 Grading of EW and RCA aggregate for rigid pipe bedding

Sieve size, mm	Pipes < 300mm			300 to 800 mm			Pipes > 800 mm		
	EW	RCA	QCS	EW	RCA	QCS	EW	RCA	QCS
25	100	100	-	100	100	-	100	100	100
20	100	99	-	98	99	100	100	97	90-100
14	88	90	90-100	80	87	80-100	72	63	50-80
10	73	78	50-85	56	73	60-85	47	47	40-70
5	13	10	10-40	21	22	20-55	22	26	25-60
2.36	6	2	0-10	12	15	10-30	11	18	10-40
0.300	4	1	-	5	4	0-10	5	4	0-15
0.075	3.1	0.9	-	2.1	1.6	-	4.3	1.9	-

The QCS 2014 specifies different grading curves for different sizes of rigid pipes, with a smaller maximum aggregate size and narrower envelopes for smaller pipe diameter. The grading results are illustrated in Figure 7-1, Figure 7-2, and Figure 7-3 for the different sizes of < 300 mm, 300-800 mm, and > 800 mm respectively.

EW and RCA showed similar grading curves for the different pipe diameters, with the majority of sieve sizes falling towards the lower grading, indicating coarse grading. The EW aggregate failed the meet the grading requirement of specific sieve sizes between 5 and 14mm for different rigid pipes (highlighted in yellow in Table 7-4). Both materials had high content of coarse aggregate (> 5 mm). For pipes < 300 mm, the amount of coarse aggregate (> 5 mm) was 87 and 90% for the EW and RCA respectively. Although not specified in the QCS 2014, the fines content (passing 0.075 mm) was also determined and the results varied between 2.1-4.3 % for the EW and 0.9-1.9 % for the RCA. The fines content of EW and RCA are within the maximum specified value in the UK of 4 % for crushed rock, except the EW for pipes > 800 mm diameter. High fines content in the pipe bedding could adversely affect the cohesion and free-draining of the material.

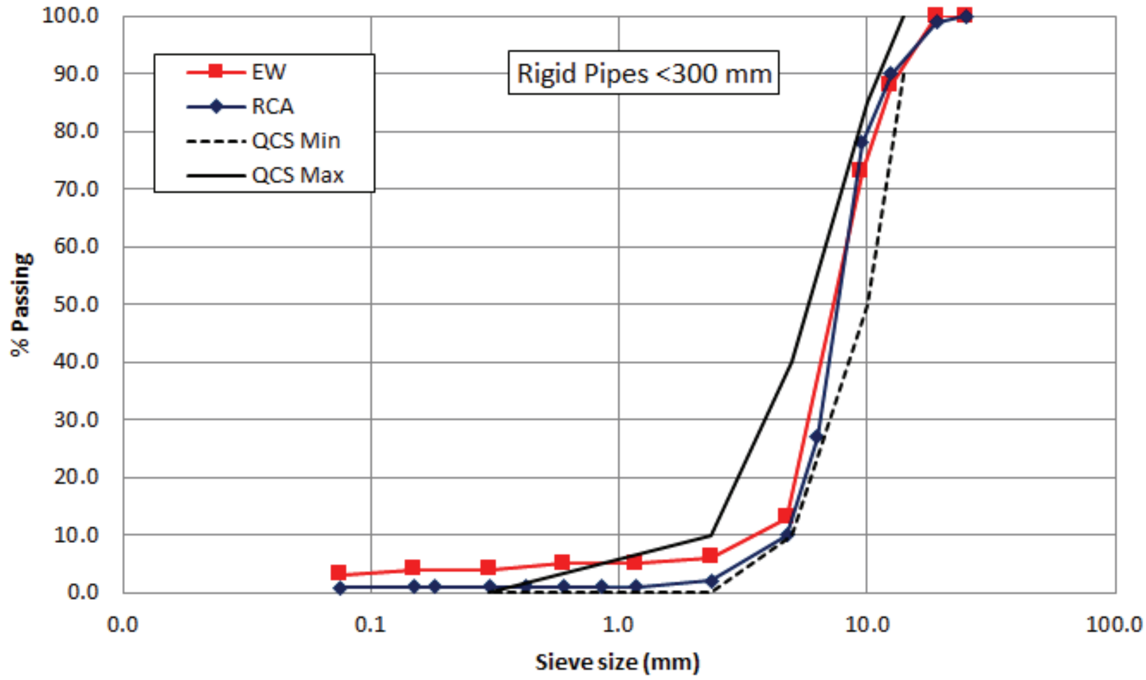

Figure 7-1 EW and RCA grading for rigid pipes (<300mm)

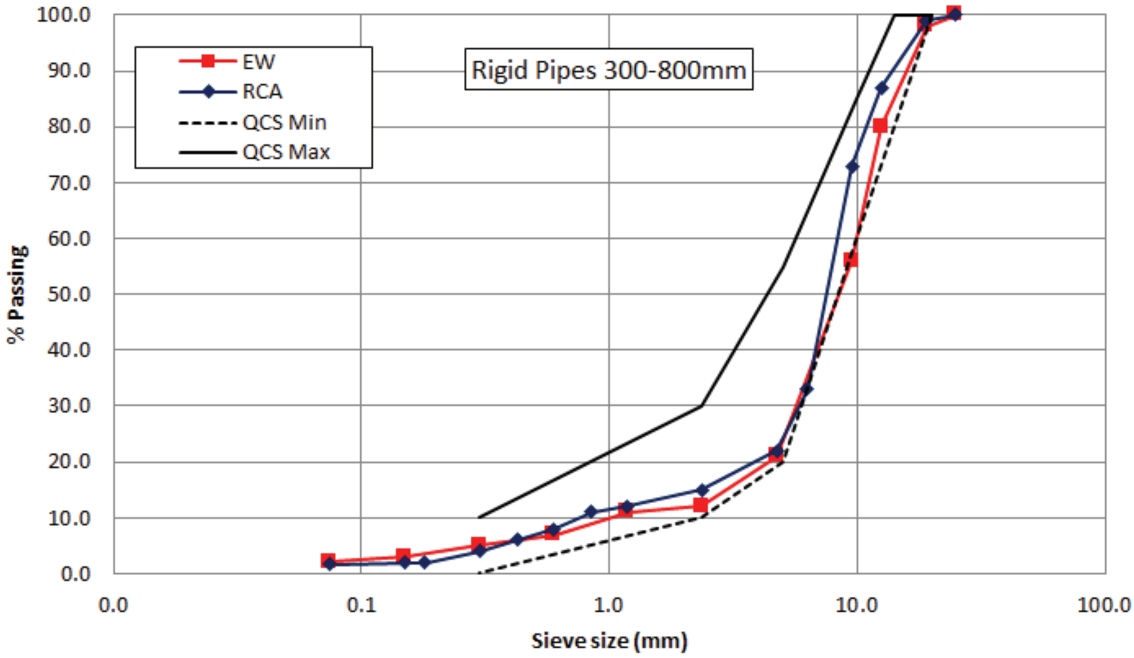

Figure 7-2 EW and RCA grading for rigid pipes (300-800mm)

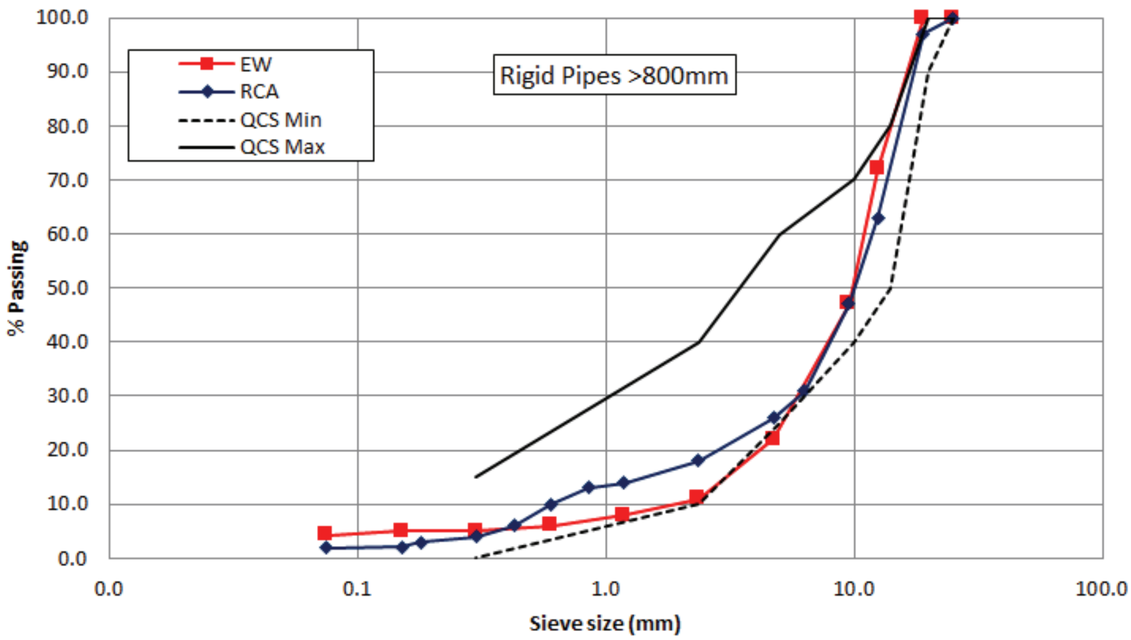

Figure 7-3 EW and RCA grading for rigid pipes (>800mm)

Table 7-5 presents the physical, mechanical and chemical properties of EW and RCA together with the QCS 2014 requirements for rigid pipes. The properties of clumps and friable pieces as per ASTM C142 (2017), lightweight pieces (ASTM C123, 2014), and shell content to BS EN 933-7 (1998) were determined. The EW showed higher content of clay lumps and friable materials for rigid pipes < 800 mm diameter, and exceeded the maximum specified limit of 1 %. The RCA aggregate showed relatively high values of clay lumps and friable materials for the different pipe sizes but within the maximum limit specified in the QCS 2014. Both EW and RCA satisfied the QCS 2014 requirements of lightweight pieces and shell content.

Table 7-5 EW and RCA properties for bedding rigid pipes

Property	EW			RCA			QCS limits
	<300	300-800	>800	<300	300-800	>800	
Clay lumps & friable particles	1.6	1.3	0.5	0.8	1.0	0.6	1% Max
Lightweight Pieces	0.0	0.0	0.0	0.4	0.2	0.3	0.5% Max
Shell Content	0.0	0.0	0.0	0.0	0.0	0.0	3% Max
Water Absorption (SDD)	2.8	3.0	1.1	1.6	6.4	5.1	2.0% Max
Loss by Los Angeles Abrasion	26	48	23	33	26	22	30% Max
Soundness (5 cycles $MgSO_4$)	29	32	34	3.5	22	20	15% Max
Acid soluble chloride	0.06	0.06	0.07	0.04	0.04	0.04	0.3% Max
Acid soluble sulfate	0.63	0.74	0.53	1.21	1.34	1.42	0.3% Max

As discussed earlier, the QCS 2014 requirement of clay lumps and friable materials for aggregate use in concrete (Section 5: Part 2: Table 2.1) is 2 %, which is double the value specified for pipe bedding.

The QCS 2014 specifies a maximum value of water absorption (ASTM C127, 2015) of 2 %. The results in Table 7-5 show values between 1.1 % to 3.0% for EW and a wider range of 1.6 % to 6.4 % for RCA. RCA generally comprises crushed stone aggregate partially coated with mortar or cement paste. The mortar is lighter and more porous than aggregates used in standard concrete, and could have a significant effect on the density and water absorption of RCA. The EW aggregate would be suitable as coarse aggregate for concrete as per the QCS 2014, Section 5 Part 2, with a water absorption requirement of 3 %. Further processing would be required for the RCA aggregate to minimise the volume of mortar surrounding the aggregate and meet the absorption requirement.

Particle strength and durability were assessed by the Los Angeles (LA) abrasion (ASTM C131, 2014) and soundness (ASTM C88, 2018) testing. The LA abrasion test is an indication of the aggregate strength by measuring how the particles are prone to fragmentation, with a lower value indicating greater resistance to fragmentation. The soundness determines an aggregate's resistance to disintegration by weathering; a low soundness value indicates durability to weathering and less likely to degrade in the field.

The QCS 2014 specifies maximum values of 30 % and 15 % for the LA abrasion and soundness, respectively. The LA abrasion results in Table 7-5 show that one sample of the EW (300-800 mm) and one samples of the RCA (< 300 mm) gave higher values than the maximum specified limit. The RCA was slightly higher, 33 %, whereas the EW gave a considerable higher value of 48 %. For the soundness test, all the tested samples gave higher values than the specified limit, with the exception of RCA (pipe diameter < 300 mm) with a very low value of 3.5 %. It is also the same materials that exhibited the low water absorption values of 1.6 %.

The acid soluble chloride and sulfate contents are also given in Table 7-5 and show low values for chloride compared to the maximum specified limit of 0.3%, with values between 0.04 and 0.07%. None of the tested samples met the sulfate requirement of 0.3%. The EW aggregate exhibited almost double, and the RCA aggregate at least 4 times the maximum specified value. The properties of RCA could vary depending on the quality of recovered concrete. Recycled concrete obtained from sources exposed to a high sulfate environment, such as groundwater, would be expected to have high levels of sulfate compared to concrete buildings and structures above the ground.

The results of pipe bedding for rigid pipes show that EW and RCA can comply with the QCS 2014 specifications for grading, cleanliness and acid soluble chloride. However, they do not meet the requirements for particle strength, soundness (durability) or sulfate. Care should be taken during the processing of recycled materials to ensure low sulfate content before selecting the desired application.

7.2.2 Flexible Pipes

Flexible pipes have the ability to deform to a significant extent before collapse, and therefore are more dependent on the support and structural strength of the surrounding aggregate. Table 7-6 presents the grading of EW and RCA materials, together with the QCS 2014 grading limits for flexible pipes. The grading curves are also graphically presented in Figure 7-4 and Figure 7-5 for flexible pipes of < 300 mm and ≥ 300mm, respectively.

Table 7-6 Grading of EW and RCA aggregate for flexible pipe bedding

Sieve size, mm	Pipes < 300mm			Pipes ≥ 300 mm		
	EW	RCA	QCS	EW	RCA	QCS
14	99	95	-	94	84	90-100
10	90	69	50-85	60	72	50-85
5	8	9	10-40	14	4	0-10
2.36	4	2	0-10	3	2	0-10
0.075	2.2	1.0	-	1.8	0.5	-

For flexible pipes < 300 mm, EW aggregate failed to meet the grading requirements at sieve sizes of 5 mm and 10 mm, whereas the RCA failed the 5 mm. For pipes ≥ 300 mm, the EW showed a finer grading at sieve size 5 mm, and the RCA showed coarser grading at sieve size 14 mm. The EW showed a higher content of fines, passing 0.075 mm, than the RCA aggregate.

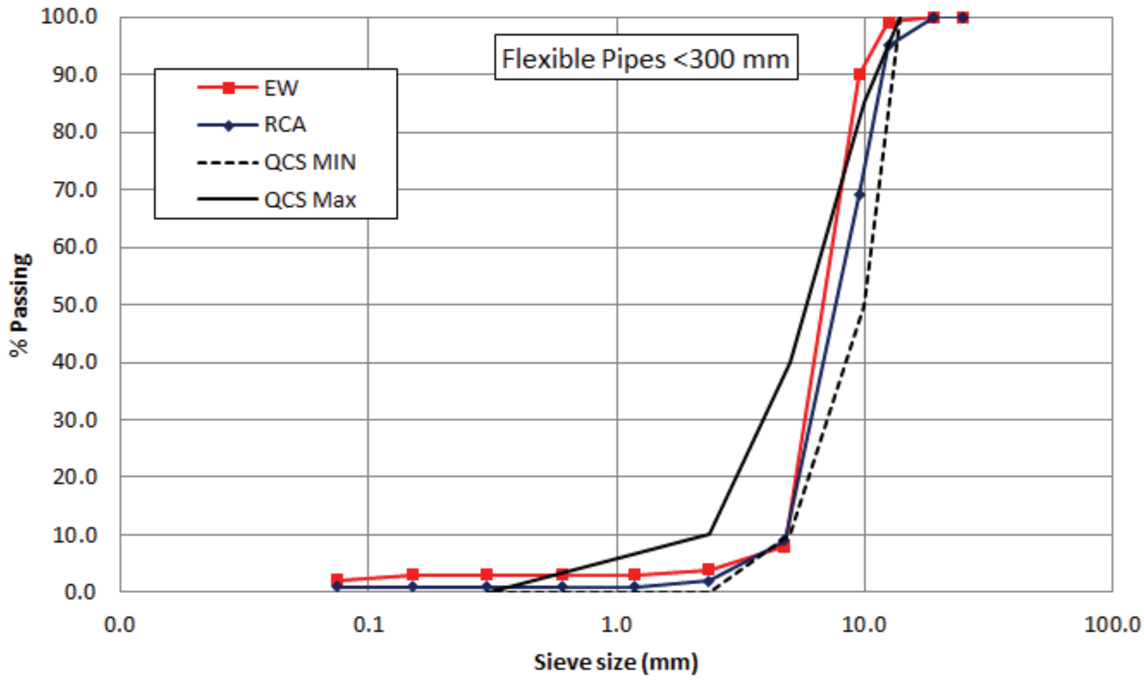

Figure 7-4 EW and RCA grading for flexible pipes (<300mm)

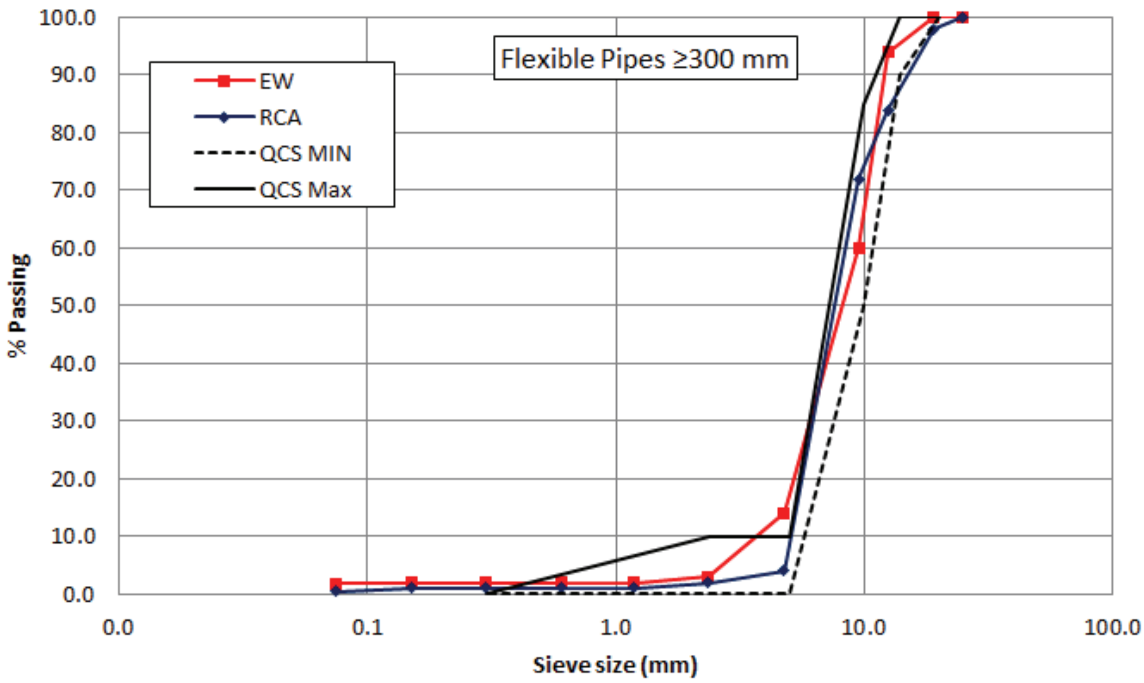

Figure 7-5 EW and RCA grading for flexible pipes (≥300mm)

The aggregate properties of clay lumps and friable pieces, lightweight pieces, and shell content are given in Table 7-7. The results indicate relatively clean EW and RCA aggregates, with the EW exceeding the maximum permissible value of clay lumps and friable pieces. Similar to the rigid pipes, the high content of clay lumps may be related to the relatively high fines content of the EW aggregate.

Table 7-7 EW and RCA properties for bedding flexible pipes

Property	EW		RCA		QCS limits
	<300	≥300	<300	≥300	
Clay lumps & friable particles	1.2	1.6	1.0	0.5	1% Max
Lightweight Pieces	0.0	0.0	0.2	0.3	0.5% Max
Shell Content	0.0	0.0	0.0	0.0	3% Max
Water Absorption (SDD)	3.2	2.8	4.9	5.3	2.0% Max
Loss by Los Angeles Abrasion	27	31	21	26	30% Max
Soundness (5 cycles $MgSO_4$)	16	17	2	2	15% Max
Acid soluble chloride	0.05	0.04	0.04	0.05	0.3% Max
Acid soluble sulfate	0.46	0.89	1.15	0.39	0.3% Max

The water absorption results exceeded the maximum specified value of 2 %, with higher values for RCA compared to EW aggregate. However, the RCA exhibited higher strength (LA abrasion) and resistance to weathering (soundness) to comply with the QCS 2014 requirements. Despite the relatively porous nature of the RCA, as reflected by the absorption results, the aggregate is relatively strong with good resistance to weathering and aggressive environment.

The EW aggregate satisfied the LA abrasion for pipes < 300 mm but gave a slightly higher value than the maximum specified value of 30 % for pipes ≥ 300 mm. The EW slightly exceeded the maximum soundness value of 15 % for both pipe sizes.

The chloride and sulfate results showed similar results to rigid pipes. Both EW and RCA gave very low contents of acid soluble chloride, but exceeded the maximum permissible limit of acid soluble sulfate.

7.2.3 Granular materials

Granular material in soakaway surrounds or trench soakaways are traditionally used to dispose of stormwater from buildings and paved areas. They must discharge their stored water sufficiently quickly to provide the necessary capacity to receive run-off from a subsequent storm. They have the coarsest grading and lowest fines content for all pipe bedding applications, as the material has to be clean and highly permeable.

Table 7-8 presents the grading of EW and RCA granular materials tested together with the QCS 2014 grading envelope. The maximum aggregate size is 37.5mm, compared to 25 and 14mm for rigid and flexible pipes, respectively. Also the amount of fine aggregate (less than 5 mm) is limited to a maximum of 2 %, compared to 40 and 10% for rigid and flexible pipes respectively.

Table 7-8 Grading of EW and RCA aggregate for granular materials

Sieve size, mm	EW	RCA	QCS 2014
37.5	100	100	100
20	60	55	60-90
14	9	7	5-30
10	4	2	2-10
5	1	1	0-2
0.075	1	1	-

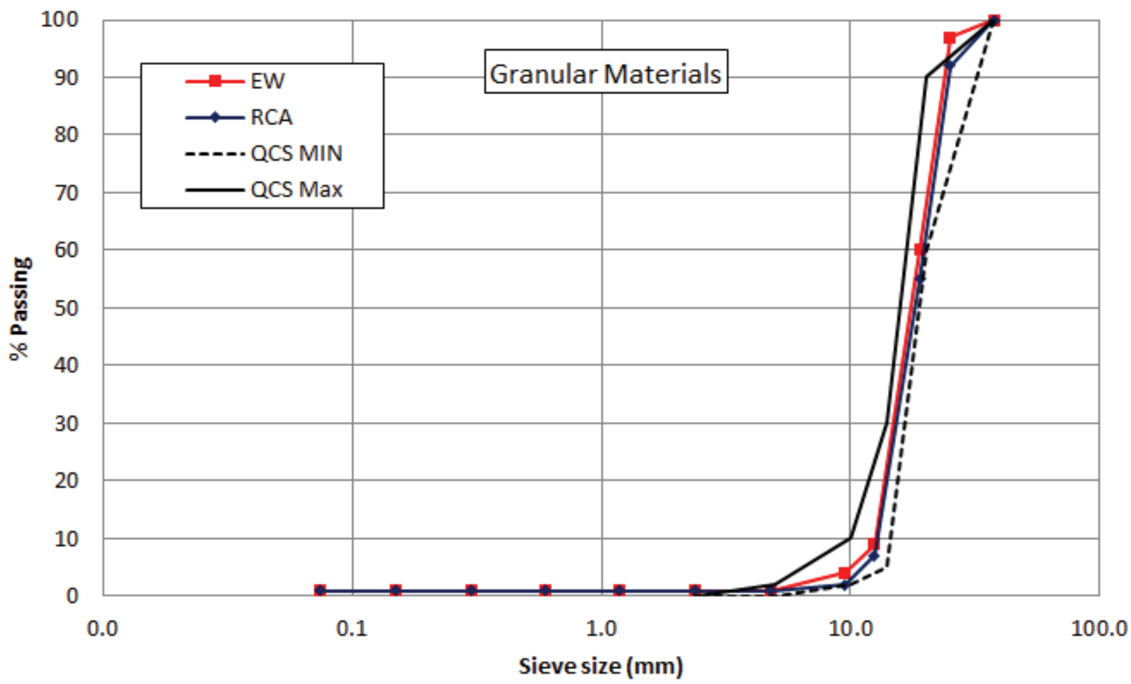

Figure 7-6 EW and RCA grading for granular materials

The grading results in Table 7-8 and Figure 7-6 show the general compliance of the EW and RCA granular materials with the QCS requirements, except the RCA at sieve size 20 mm. The amount of fines content, <0.075mm, was identical for EW and RCA aggregate, which is the same amount passing sieve size 5 mm.

EW and RCA aggregates satisfied the QCS 2014 requirements LA abrasion, soundness, and chloride content, but failed to meet with the sulfate limit. The carbonate content, to ASTM D4373 (2014), was carried out for the EW and RCA granular materials and the results are given in Table 7-9. As expected, the EW is mainly composed of limestone aggregate and contains 94 % of carbonate minerals, compared to 18 % for the RCA aggregate. RCA is mainly composed of hydrated cement, sand and coarse gabbro aggregate. Based on the age and exposure of recycled aggregate, the hydrated cement (calcium hydroxide) can react with the carbon dioxide from the surrounding environment to form calcium carbonate (Neville, 2011).

Table 7-9 EW and RCA properties for granular materials

Property	EW	RCA	QCS limits
Clay lumps & friable particles	1.0	0.4	1% Max
Lightweight Pieces	0	0	0.5% Max
Shell Content	0	0	3% Max
Water Absorption (SDD)	1.8	4.3	2.0% Max
Loss by Los Angeles Abrasion	24	30	30% Max
Soundness (5 cycles $MgSO_4$)	11	1	15% Max
Acid soluble chloride	0.05	0.04	0.3% Max
Acid soluble sulfate	0.55	1.0	0.3% Max
Carbonate content	94	18	50% Max

The results indicate the general compliance of recycled materials with the QCS 2014 requirements for use as granular materials. RCA is expected to meet the carbonate content requirement of less than 50 %, but would require appropriate processing to control the water absorption and sulfate content before use in pipe bedding and drainage applications.

7.2.4 Fine Aggregate Pipe Bedding

The gradings of EW and RCA fine aggregate are given in Table 7-10 and Figure 7-7. The EW showed well-graded aggregate with compliance with all sieve sizes specified in the Kahramaa specification (Kahramaa, 2005), the RCA aggregate showed non-compliance, with values exceeding the maximum permissible limits at sieve sizes of 0.6 and 0.15 mm.

The Kahramaa specification also limits the total quantity of fine dust through No. 22 mesh sieve in fine aggregate, equivalent to sieve size of 0.075mm, shall not exceed 8 % for crushed rock. Table 7-10 shows that the fines content of EW was 7.8 %, just within the specified limit, and 16 % for the RCA. The presence of high fines content in RCA is not recommended for pipe applications, as it may result in self-hardening due to the presence of high volume of unreacted cement particles.

Table 7-10 Grading of EW and RCA aggregate for utilities and Kahramaa specification

Sieve size, mm	EW	RCA	Kahramaa – Crushed rocks
4.76	98	92	90-100
2.4	67	81	60-90
1.2	42	71	40-80
0.6	28	57	20-50
0.3	18	24	5-30
0.15	13	17	0-15
0.075	7.8	16	8% max

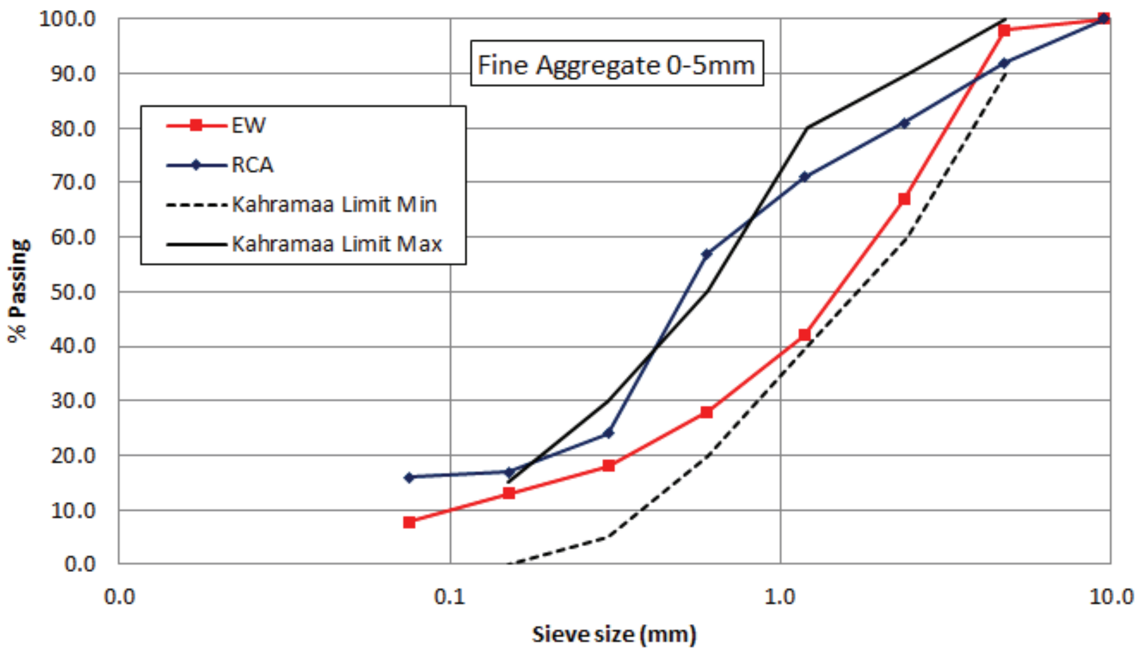

Figure 7-7 EW and RCA grading for utilities – Fine aggregate

No specific requirements for aggregate cleanliness are provided in the Kahramaa specification, but the materials were tested for the same properties as the QCS 2014 for coarse aggregate. Table 7-11 shows relatively low values of clay lumps and friable particles, with zero content of lightweight pieces for EW and RCA aggregate. Despite the high fines content of RCA, the material is relatively free from clay lumps and lightweight materials. EW was found to contain higher levels of clay lumps and friable materials than RCA.

The water absorption of the EW fine aggregate was relatively high, 5.3 %, compared to the extremely high value of 16.1 % for RCA fine aggregate. The high absorption of RCA fine aggregate clearly indicates the porous nature of the materials, but not necessarily weakness due to the presence of hydrated cement particles.

Table 7-11 EW and RCA properties for pipe bedding around utilities – Fine aggregate

Property	EW	RCA	Kahramaa limits
Clay lumps & friable particles	1.0	0.3	-
Lightweight Pieces	0	0	-
Water Absorption (SDD)	5.3	16.1	-
Soundness (5 cycles $MgSO_4$)	24	19	-
Acid soluble chloride	0.09	0.05	0.1% Max
Acid soluble sulfate	1.37	1.84	0.3% Max
Carbonate content	87	19	-

The Kahramaa specification specifies sulfate content (as SO_3) shall not exceed 0.3 % by weight and chlorides shall not exceed 0.10 % by weight. The results in Table 7-11 show compliance of the EW and RCA with the chloride requirement, however, both materials failed the sulfate test. The acid soluble sulfate of the EW fine aggregate was 1.37 % and a higher value of 1.84 % for RCA, much higher than the maximum specified limit of 0.3 %. The carbonate content results showed a value of 87 % for the EW aggregate compared to 19 % for the RCA aggregate.

7.3 Site Trial – Wadi Gravel for Trench Soakaway

A site trial was constructed in September 2018 to demonstrate the potential use of local Wadi gravel as granular material to replace imported gabbro for surround on a trench soakaway. The trial was on the Ashghal project entitled "Roads and Infrastructure for Umm Salal Integrated Worker Accommodation Community". The trench was under the footway and adjacent to the paved road, Figure 7-8. The distribution pipe was 300 mm in diameter and gabbro aggregate (20 mm) was specified as the granular material surrounding the pipe. A trial section of 80 m length was made with Wadi gravel in place of gabbro.

The Wadi gravel aggregate was supplied by Qatar Sand Treatment Plant (QSTP) of 14-20mm aggregate. The cost of Wadi gravel aggregate was 35 % cheaper than the cost of imported gabbro, with significant reduction in carbon footprint compared to imported gabbro, as discussed in section 8.

The performance of Wadi gravel in the trench soakaway was assessed in March 2020, 18 months after construction. The Wadi gravel granular material was exposed, by excavation of the overlaying layers as shown in Figure 7-8. Wadi gravel samples were collected for testing, Figure 7-9, to assess performance in service and compare to construction data and project specifications.

Figure 7-8 Exposure of granular materials under footway, adjacent to a carriageway

Figure 7-9 Sample collection of Wadi gravel after 18 months

The properties of Wadi gravel at construction and after 18 months in service were investigated. Testing was conducted by the Ashghal Centre for Research & Development, and the results are summarised in Table 7-12, together with the project specifications. The grading is also presented graphically in Figure 7-10. A single size aggregate of 20mm was specified in the project, with a slightly different grading to the QCS 2014 for granular materials pipe bedding. At construction, the grading of Wadi gravel was within the specified project envelope but near to the maximum specified limit for all sieve sizes, indicating a fine grade. After 18 months in service, the grading exceeded the maximum limits at sieve sizes of 14 and 10mm.

Table 7-12 Grading and properties of Wadi gravel for granular pipe bedding

Property	Wadi gravel		Project Specification
	At construction	After 18 months	
Grading, 37.5mm	100	100	100
Grading, 20mm	90	82	10-90
Grading, 14mm	9	13	0-10
Grading, 10mm	1.0	3.1	0-2
Clay lumps & friable particles	0.2	0.7	1% Max
Lightweight Pieces	0	0	0.5% Max
Shell Content	0	0	3% Max
Water Absorption (SDD)	0.8	1.0	2.0% Max
Loss by Los Angeles Abrasion	25	27	30% Max
Soundness (5 cycles $MgSO_4$)	6	2.4	15% Max
Acid soluble chloride	0.01	0.01	0.1% Max
Acid soluble sulfate	0.18	0.67	0.3% Max
Carbonate content	20	52	50% Max

It was not expected the Wadi gravel material would disintegrate with time, as no traffic loading was applied on the surface of the trench. It was noticed during the exposure of the granular materials that fine particles from the sides of the excavated trench fell on top of the geotextile filter membrane, Figure 7-9. The geotextile surface was cleaned before exposing the Wadi gravel, but the sampling process could not avoid some contamination with excavated materials that may have affected the grading. The increase in finer particles after 18 months shown in Table 7-12 and Figure 7-10 is very minor and may be due to the natural variability of the material, plus a little contamination during sampling.

The results in Table 7-12 show that the Wadi gravel is relatively clean aggregate with a value of 0.2 % of clay lumps and friable materials at construction. A higher value of 0.7 % was determined for the Wadi gravel after 18 months, but still within the maximum specified limit of 1.0 %. No traces of lightweight pieces or shell content were detected of the tested Wadi gravel at construction or after 18 months.

The water absorption of Wadi gravel was relatively low of 0.8 % and 1 % at construction and after 18-months, respectively, and lower than the project specified value of 2 % maximum. The LA abrasion value was 25 % and the soundness was 6 %, lower than the project specified values, and indicating a strong and durable aggregate.

The project specification of acid soluble chloride was 0.1 %. The Wadi gravel aggregate showed an identical value of 0.01% at construction and after 18 months in service.

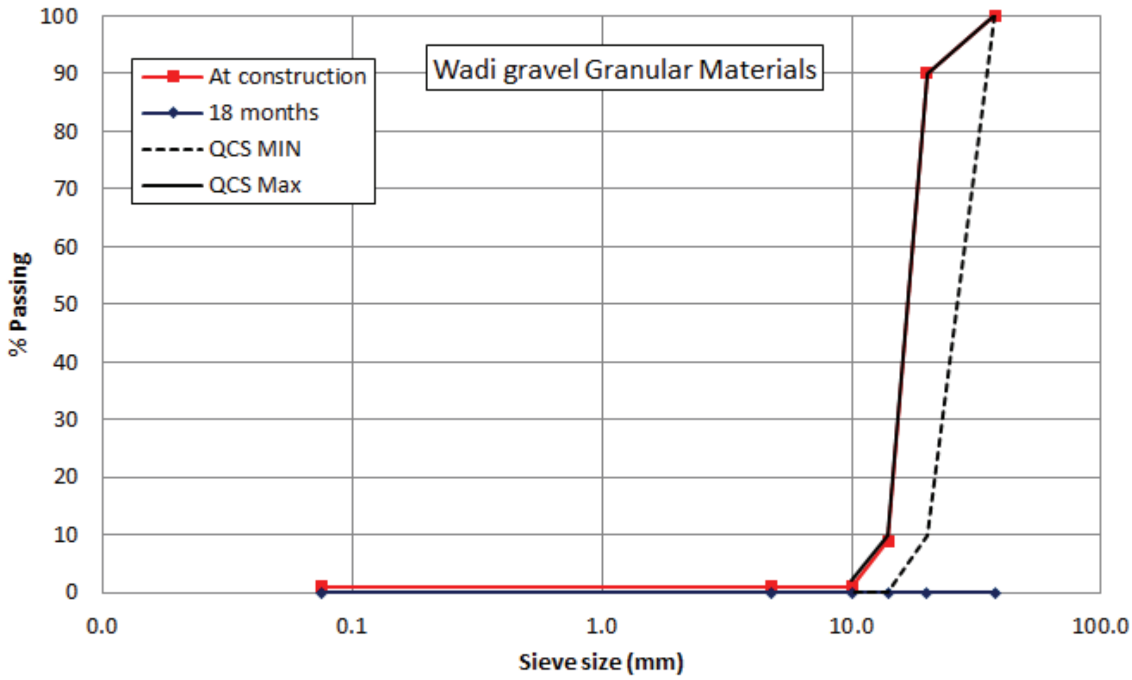

Figure 7-10 Grading of Wadi gravel as granular material for pipe bedding

The specified acid soluble sulfate was 0.3 %. The Wadi gravel aggregate met the sulfate requirement at construction, a value of 0.18%, but exhibited a higher value of 0.67% after 18 months. The difference in sulfate content could be attributed to the contamination of Wadi gravel, during sampling, with excavated materials from the sides of the trench. It was noticed during exposing the trench and collecting the sample after 18 months that there was no evidence of white precipitated gypsum compounds in the Wadi gravel. It may also represent variability in the quality of the Wadi gravel, in particular insufficient processing to remove gypsum encrusted onto individual particles of Wadi gravel (Section 3.4, Figure 3-11 to Figure 3-13). It is recommended that the production of Wadi gravel is checked, by visual inspection of samples and testing for acid-soluble sulfate, to ensure that the material is meeting the requirements of the QCS 2014 and the Ashghal Recycling Manual (2021).

It is a requirement of the project specification to limit the carbonate content, as per BS 1377: Part 3 (2018), to 50 %. The results in Table 7-12 show a value of 20.1 % for the Wadi gravel at construction, which seems to be a low value when compared to the petrographic analysis results presented in Section 3.4. A value of 52 % was determined for the Wadi gravel sample obtained after 18 months, which is slightly higher the maximum specified limit of 50%. The varying results of carbonate content at construction and after 18 months in service could be attributed to the varying composition of Wadi gravel aggregate, and the limited number of samples tested, knowing the varying composition of Wadi gravel aggregate. Further routine testing of the processed Wadi gravel would help to clarify the situation, as for the sulfate content.

The results show full compliance with the project specification and the QCS 2014 requirements for granular pipe bedding materials for trench soakaway at the time of construction. Regular checks during processing of the Wadi gravel are essential to maintain the overall sulfate level below the specified limit. As a local material, the Wadi gravel aggregate could be produced in different aggregate sizes for use in all pipe bedding applications. The wider use of Wadi gravel in replacing imported gabbro in the Ashghal specification and projects will reduce materials cost and support the government strategy of self-reliance and sustainable development, provided it gives satisfactory performance.

7.4 Summary

Two main topics were considered in the discussion: implications of the review of national and international specifications for pipe bedding, and; suitability of local recycled (EW and RCA) and alternative (Wadi gravel) aggregates for use in pipe bedding and drainage applications.

7.4.1 Specifications

The requirements for pipe bedding and land drainage are covered in various sections of the QCS 2014 and refer to other national specifications, such as Kahramaa. In order to improve the overall consistency of the requirements and avoid repetition of text, it is recommended to combine the requirements in a single document, similar to the UK-SHW 500 for drainage and service ducts.

The QCS 2014 grading requirements given for flexible pipes, Section 8.02 Table 2.4, need to be checked for consistency with revision of the limits provided. The QCS 2014 does not set any limiting values for fines content (< 0.075 mm of silt and clay-sizes particles) for all gradings. Increased fines content could clog the bedding materials or drainage system and affect its functionality. The grading results indicated that limiting the fines content resulted in improved aggregate properties, such as the case of granular materials of EW and RCA in Table 7-9. The QCS 2014 specifies the value of 2 % for concrete aggregate in Section 5.2. The UK SHW 500 for pipe bedding specifies 1.5% for natural and 4% for manufactured aggregate. It is recommended to use a value of 2% for all aggregate types, consistent with Section 5.2.

The aggregate cleanliness in the QCS 2014 is covered by various requirements of clay clumps and friable pieces, lightweight pieces, and shell content. The requirement for clay clumps and friable pieces is 1 %, half the value specified for concrete aggregate (Section 5.2), in order to reduce any risk of clogging of the material with fines.

Particle durability and strength are assessed in the QCS 2014 by the water absorption, soundness and LA abrasion testing; however, there is potential to revise the maximum specified limits and testing methods. The limiting value for water absorption is 2 % for pipe bedding, similar to the value specified for natural aggregate for concrete in Section 5.02. The QCS 2014 provides higher values for recycled aggregate of 3 % for structural concrete and 4 % for non-structural concrete. These higher values recognise that recycled materials have higher values of water absorption but can still provide suitable aggregate for concrete. It would be appropriate to apply these higher values to pipe bedding using recycled aggregates for the same reasons.

The QCS 2014 specified values for LA abrasion of 30 % and soundness of 15 % for pipe bedding are identical to those specified in Section 5.02 for concrete aggregate. The limiting values in the QCS 2014 for unbound subbase materials are 40 % for LA abrasion and 20 % for soundness. In the UK SHW 500, a maximum LA abrasion of 50% is specified for particle strength for pipe bedding, which is the same as the value for unbound subbase. Given the weak nature of local limestone and the possible increase in clay lumps and friable materials as a consequence of relaxing the LA value, it is recommended to maintain the current specified limits to ensure the best local material will be suitable for pipe bedding and drainage applications.

Whilst no values are specified in the QCS 2014 for limiting the chloride and sulfate content in pipe bedding, project specifications tend to specify values of 0.1 % and 0.3 % for acid-soluble chloride and sulfate, respectively. The requirement for acid soluble chloride is much higher the maximum specified value of 0.03% for aggregate for concrete (Section 5.02). However, the evidence from trials is that most recycled and alternative materials comfortably meet the chloride requirement. However, EW and RCA were found to exceed the sulfate limit on a regular basis, while Wadi gravel occasionally exceeded it. Careful control of processing should solve this problem for Wadi gravel. It may be more difficult to achieve compliance with the sulfate limit of 0.3% for EW and RCA, but good quality control should ensure that values much closer to the limit are achieved.

The main concern about the aggregate specification for pipe bedding is the prohibition of local and recycled materials, limiting the use to imported gabbro aggregate. It is believed that the restriction is due to the potential dissolving of weak limestone aggregate in wet conditions and the precipitation of the fine particles, affecting the permeability and flow of the drainage system with time.

Assessment of the carbonate content of local limestone revealed values between 80 % and 94 % for natural and EW materials. Limestone is predominantly composed of carbonate rock (calcite and dolomite) with small quantities of clay, gypsum and quartz. Reducing the carbonate content of limestone aggregate is practically impossible, and therefore it is recommended to revise this decision and specify the appropriate test method to improve the utilisation of local materials in government projects. The resistance of aggregate fragmentation in wet conditions, in particular the rubbing together of interlocking particles within an unbound material, is addressed by the micro-Deval coefficient determined in accordance with BS EN 1097-1 (2011). It is recommended to include a performance-based property based on a micro-Deval coefficient value of 20, similar to that specified by the UK water industry as additional requirement to pipe bedding materials.

Local materials of limestone aggregate and dune sand are permitted for use in pipe bedding, in the Kahramaa specifications (2005) for fine aggregate. The limiting values for fines content are reasonable and comparable to those of the UK specifications. The Kahramaa specification also provides general text for the cleanliness of aggregate and it is suggested to support this with specific requirements for liquid limit and plasticity index and organic content as specified in the QCS 2014 for fine aggregate for use in unbound pavement materials. It is also recommended to specify a value for the water absorption of fine aggregate, with consideration of the potential use of recycled aggregate.

7.4.2 Recycled and Local Aggregate

EW and RCA showed compliance with some aspects of the QCS 2014 and Kahramaa specifications for pipe bedding applications. The production of pipe bedding materials usually involves 3 cycles of crushing and screening and therefore the final product is expected to be the best quality of the feedstock material. The grading of tested recycled materials showed minor non-compliance with specific sieve sizes, but this is not a major issue and could be corrected with regular monitoring during processing and improved production.

EW and RCA are relatively clean recycled materials. EW was found to contain higher levels of clay and friable materials than RCA, probably due to the presence of clay particles, but the values were lower than 2%, maximum specified value for aggregate for concrete in the QCS 2014 Section 5.02. EW and RCA recycled materials easily met with the lightweight and shell content requirements.

The water absorption results for the EW ranged between 1.1 % and 3.2 % for coarse aggregate and 5.3 % for fine aggregate, compared to the RCA of 1.6 % to 6.4 % for coarse aggregate and 16.1 % for fine aggregate. The absorption of EW aggregate is relatively low and could be used as coarse aggregate for concrete as permitted by the QCS 2014 (limiting values of 3 % for structural concrete and 4% for non-structural concrete). The RCA exhibited relatively higher absorption values due to the presence of mortar surrounding the aggregate, but with adequate strength and durability. RCA was found to be stronger with higher resistance to weathering compared to EW as indicated by the LA abrasion and soundness results. EW also gave disappointing results for soundness (durability), and it may be hard to find local limestone of adequate quality to be suitable for use as pipe bedding. The fact that EW is dominantly composed of carbonate minerals would also disqualify it as coarse aggregate under the QCS 2014. RCA, however, is dominantly non-carbonate, so more suited for use as coarse aggregate in pipe bedding and drainage applications under the QCS 2014.

For the chemical properties, there is a concern about the high sulfate content results, particularly for the RCA. It is essential to monitor the sulfate content of recycled materials at source, and if not possible, before processing to identify the suitable application of the material. Blending with other aggregate materials is recommended to reduce the sulfate content to acceptable levels.

Wadi gravel aggregate was successfully used to replace imported gabbro as a granular material in trench soakaway. Performance assessment of Wadi gravel was conducted at construction and after 18 months in service and showed general compliance with the national and project specifications for use in pipe bedding. The sulfate content after 18 months in service had increased compared to that at construction and exceeded the project specification. However, this may have been due to variability in the original material, and particularly in the intensity of the processing, or to contamination from trench fill during sampling, rather than to any changes during service. Further sampling and testing of the Wadi gravel is recommended to ensure the processing set out in the Ashghal recycling manual is being followed. Wider utilisation of Wadi gravel in pipe bedding and drainage projects would potentially reduce the cost of aggregate and reduce the environmental impacts associated with the transport of imported gabbro. However, cost reductions must not be achieved by skimping on the processing requirements for the material.

8 Environmental and Economic Benefits

It is expected that use of local and recycled aggregates will have major economic and environmental advantages, in terms of greatly reduced carbon footprint, compared to the import of primary aggregates. Preliminary carbon footprint analyses indicated that at least 50% of the carbon footprint associated with the production of primary aggregates could be avoided if a viable recycled alternative can be produced locally (Hassan et al., 2016). The savings arise principally due to the transport that can be avoided in shipping the primary product to Qatar. The production of aggregate and other construction materials, also requires large quantities of water. High water demand poses problems in a country like Qatar with an acute shortage of water. Given the high priority placed on sustainable development, this Chapter covers the carbon and water footprint analyses for construction aggregates and derived products, covering primary and recycled materials. The cost reduction associated with the use of recycled aggregate is also discussed.

8.1 Scope and Methodology

The analysis of carbon and water footprints considered alternative aggregate sources and aggregate derived products, including asphalt and concrete, on the basis of a 'cradle to gate' scope. This approach considers products from raw material acquisition through to the factory 'gate' i.e. in this case, the point in the life cycle where the respective aggregate products have been produced and are ready to be transported and applied in construction projects in Qatar.

Limiting the analyses to 'cradle to gate' meant that no application, waste management or durability aspects of the products were considered within the scope. In this respect the study constitutes what is termed a 'partial life cycle assessment', which is suitable for third party disclosures and should be supported by information which defines which parts of the life cycle have been analysed. A further specification of the study was to consider 'absolute' carbon footprints, rather than just relative savings. This is consistent with the ISO methodology (ISO 14067, 2018) and meant that, for the life cycle steps that were considered, no activities could be 'cancelled out' if they were common to the alternative products analysed.

The functional unit was defined as 1 tonne of finished product. Aggregate is defined as the coarse aggregate, graded materials of different sizes, for use in bound and unbound construction applications. The aggregate materials covered imported gabbro and recycled aggregate, local sources of limestone and Wadi gravel. For sand this is defined as a tonne of fine aggregate material, washed sand for concrete and crushed rock for asphalt or unbound applications, awaiting dispatch to a construction site. For asphalt and concrete mixtures, this can be converted back to the more typical functional unit of a cubic metre using the densities of the products. Table 8-1 lists the aggregate and construction products that were assessed.

Primary aggregates for use in asphalt and concrete construction projects, typically gabbro, are currently imported, while local limestone and Wadi gravel are generally used in unbound applications. Primary imported aggregates originate from quarries in other Gulf States, such as Oman. These aggregates are blasted from the quarry face; the 'cradle' for primary aggregates, and then pass through a number of screens and crushers to arrive at the final graded products. From the quarry the products are shipped to the port at Mesaieed in Qatar using bulk carrier ships, unloaded and stockpiled for use. Local limestone also requires blasting whereas Wadi gravel and sand are simply excavated from their deposits, processed and stockpiled. For recycled aggregates the comparable 'cradle' is a construction waste stockpile where all aggregate sources have reached the end of their previous life cycle, irrespective of their origin. The recycled material is passed though screens and crushers and then stockpiled for further use.

Table 8-1 Products assessed for environmental and cost benefits

Product	Source	Final product evaluated
Imported primary aggregate	Three Gulf State quarries to Mesaieed Port	Graded aggregate for use in all applications
Local limestone	Umm Bab	Graded aggregate for use in unbound applications
Wadi gravel	A sand washing plant, Qatar Sand Treatment Plants	Graded aggregate for use in unbound applications
Washed sand	A sand washing plant, Qatar Sand Treatment Plants	Sand for use in all applications including concrete
Recycled aggregates	A mobile plant and a fixed plant	Graded aggregate for use in unbound applications
Ready mix concrete	Salwa Industrial Area (fixed plant)	Structural PC and GGBS C40 concrete
Asphalt	Mesaieed (fixed plant)	Base and wearing course asphalt

Bound applications, such as asphalt and ready-mix concrete, add other components to the imported aggregates at fixed plant, using inputs of energy and water to arrive at the final products. In bound applications, assessing the life cycle requires not only to look at the activities at the batching plant but also to assess the 'embodied' impacts of all the component materials including bitumen and Portland cement i.e. their own individual cradle-to-gate assessments and onward transport. The impacts of using RAP from demolition road pavements were included as these were thought to be potentially significant, particularly regarding water use in road milling operations.

Transport onwards from stockpiles in Qatar was not included in the analysis, since this distance is likely to vary depending on the actual location of the point of use: the construction site which could be anywhere in Qatar.

Targeted questionnaires were used to obtain data from quarry or plant managers regarding the production activities on their respective sites, unit cost of each product, and the onward transport of materials to Qatar. These additional datasets were used to supplement previous data collected in 2013 (Hassan et al., 2015), on two primary aggregate quarries (source 1 and source 2) and one recycled source (source 1), for which emissions data has been refreshed.

This 'bottom-up' approach to data collection has advantages in terms of the need to use less approximation and proxy figures, whilst at the same time relies on accurate data input from single sources such as quarry managers. Annual figures in tonnes for the calendar year 2018 at each of the newly evaluated production sites are presented in Table 8-2, alongside those from 2013 (imported primary aggregates sources 1 and 2 and recycled source 1).

Table 8-2 Annual production figures evaluated

Product	Total production (t)
Imported primary aggregates – source 1	12,203,000
Imported primary aggregates – source 2	3,420,000
Imported primary aggregates – source 3	1,500,000
Local limestone	1,560,000
Wadi gravel	780,000
Washed sand	6,800,000
Recycled aggregates – source 1	1,500,000
Recycled aggregates – source 2	200,000
Ready mix concrete	413,978
Asphalt	1,800,000

8.2 Carbon Footprint

Carbon footprinting is an environmental assessment approach which is used to identify the contribution of products (and services) to climate change, using a life cycle-based methodology. A life cycle approach is sometimes termed a ‘cradle to grave’ analysis, which considers a product from raw material acquisition: the ‘cradle’, through to disposal of the product at the end of its life: the ‘grave’. In carbon footprinting, all of the contributions the product makes to climate change across this life cycle are assessed and therefore form part of the final ‘carbon footprint’. These processes include energy use, chemical reactions, waste disposal and land use change. The methodology of the International Standards Organisation’s standard Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification (ISO 14067, 2018) has been followed in producing this analysis.

8.2.1 Quantifying the Carbon Footprint of Aggregate Sources

In order to determine the carbon footprint of the alternative aggregate sources, it is necessary to look in detail at the sources and sinks of emissions of the partial aggregate life cycles within the system boundaries. ISO 14067 (2018) defines a number of specific greenhouse gases (GHG) emission sources and sinks to consider. These are presented in Table 8-3, alongside the particular considerations for the aggregate life cycles.

Table 8-3 GHG emissions and removals in the aggregate life cycle

GHG emission/removal	Relevant?	Relevance to Qatari aggregate life cycle
Fossil carbon	✓	Direct combustion of diesel and other fossil fuels, consum in obtaining, processing and transporting aggregates. Dire combustion impacts incurred cradle-to-gate that a associated with the use of ancillary materials such explosiv and water are also included.
Biogenic carbon	×	Biomass cultivation and production is not relevant to the life cycles.
Electricity	✓	Consumption of grid electricity in Qatar or other Gulf Stat whilst obtaining, processing and transporting aggregate Double-counting should be avoided if generators powered fossil fuels are utilised.
Land use change	×	Significant land use changes occur in quarrying or recycling the desert landscape switches to exposed rock, or stockpil rock. However, this has no effect on the ability of the land act as a sink for GHGs, as the level of vegetation is negligib for the before and after scenarios.
Soil carbon change	×	A net increase or decrease in soil biomass does not occur the quarrying process that take place in the desert landscap
Carbon storage in products	✓/×	Crushed concrete is carbonated during its secondary life. this process carbon dioxide is absorbed to the surface crushed concrete. This process will occur beyond the gate recycled aggregate production process. Any carbonation the concrete during its service life will be out of scope for th analysis.
Non-CO_2 GHG emissions and removals from livestock, manure and soils	×	Livestock, manure and soils do not feature in the evaluat aggregate life cycles.
Aircraft GHG emissions	×	Air transport is not used in the evaluated aggregate life cycle

8.2.2 Emissions factors

Emissions factors associated with fuel consumption, transport and water treatment were obtained from the UK Department for Business, Energy & Industrial Strategy (BEIS) website entitled Government Conversion Factors for Company Reporting (BEIS, 2019). Whilst this is a UK publication, many of the factors are the best available approximation for Qatar, in the absence of Qatari-specific factors, as is presently the case. The emissions factor for Middle East electricity consumption was sourced from the grid emissions factors compiled by the Institute for Global Environmental Strategies (IEGS, 2019) and estimated for desalination from

Meier et al. (2013). Further emissions factors for ancillary and component materials have been used and are presented in Table 8-4.

Table 8-4 Emissions factors for component and ancillary materials

Material	Emissions factor ($kgCO2_e/t$)	Source
Portland cement (CEM I)	860	MPA (2019)
GGBS	80	MPA (2019)
Water - desalinated	4.08	Meier et al. (2013)
Water - groundwater	0.344	BEIS (2019)
Water – TSE consumed	0	-
Waste water - disposed	0.708	BEIS (2019)
Admixtures (superplasticiser)	1880	EFCA (2015)
Bitumen	150	Eurobitume (2020)
Explosives	4070	Wayman et al. (2014)
Mineral oils	1420	BEIS (2019)

8.2.3 Fossil fuel consumption

Diesel is a significant crude-derived energy source at all aggregate production sites, powering an array of machinery and vehicles on site. Primary aggregates imported from other Gulf States are excavated from the blasted quarry face and pass through a number of screens and crushers (up to four) on route to loading onto ships in port. Conveyance though the machinery on site is either by excavators or conveyor belts. For indigenous sources of primary and recycled aggregate the process is similar but may be with fewer passes through crushers and screens.

The asphalt plant uses primarily Liquefied petroleum gas (LPG) and to a lesser extent diesel in the heating and mixing process. Electricity is used at the cement plant in mixing (this is analysed in the next section).

Annual diesel and LPG consumption figures in litres are presented in Table 8-5 alongside the appropriate CO_2e production figures. The appropriate CO_2e emissions factor for diesel is 3.131 $kgCO_2e$ per litre and for LPG 1.714 $kgCO_2e$ per litre. These figures include the upstream impacts of the fuel, associated with extraction and refining, as well the emissions from combustion.

Table 8-5 Annual fossil fuel consumption figures

Product	Diesel consumption (L)	LPG consumption (L)	Total CO_2e (kg)	Total production (t)	CO_2e per t product
Imported – source 1	4,151,730	0	13,755,264	12,203,000	**1.127**
Imported – source 2	5,455,308	0	18,074,199	3,420,000	**5.285**
Imported – source 3	1,800,000	0	5,963,652	1,500,000	**3.976**
Local limestone	3,000,000	0	9,939,420	1,560,000	**6.371**
Wadi gravel	133,311	0	441,678	780,000	**0.566**
Washed sand	1,335,959	0	4,426,219	6,800,000	**0.651**
Recycled aggregates	400,000	0	1,325,256	200,000	**6.626**
Ready mix concrete	0	0	0	413,978	**0.000**
Asphalt	1,000,000	9,000,000	18,739,770	1,800,000	**10.411**

8.2.4 Electricity consumption

Electricity is directly consumed at two of the imported aggregate production sites and is the primary energy source used to produce washed sand, gravel and ready-mix concrete. The emissions factor for Middle East consumption of electricity is 0.816 $kgCO_2e/kWh$; this reflects production of the electricity, upstream impacts and transmission losses. In the absence of country-specific emissions factors for electricity, a single figure has been used to cover all Gulf States (IGES, 2019). Table 8-6 presents the contribution to the overall carbon footprints due to electricity consumption.

For the aggregate sources, if the contributions of diesel and electricity consumption of the production sites are considered together, an estimation of overall energy efficiency can be made. These range from 12.9 mega Joules per tonne (MJ/t) for indigenous washed sand to 76.6 MJ/t for recycled aggregates (source 2). Of the imported aggregate sources, the scale of source 1's operation is reflected in a high energy efficiency of 15.3 MJ/t.

Table 8-6 Annual electricity consumption figures

Product	Electricity consumption (kWh)	Total CO_2e (kg)	Total production (t)	CO_2e per t product
Imported – source 1	7,800,000	6,362,320	12,203,000	**0.521**
Imported – source 2	0	0	3,420,000	**0.000**
Imported – source 3	9,600	7,831	1,500,000	**0.005**
Local limestone	0	0	1,560,000	**0.000**
Wadi gravel	6,458,400	5,268,001	780,000	**6.754**
Washed sand	8,812,500	7,188,198	6,800,000	**1.057**
Recycled – source 1	0	0	1,500,000	**0.000**
Recycled – source 2	0	0	200,000	**0.000**
Ready mix concrete	953,953	778,122	413,978	**1.880**
Asphalt	0	0	1,800,000	**0.000**

8.2.5 Ancillary material consumption

In aggregate production, water and explosives, used for washing and blasting respectively, are consumed in the course of obtaining the aggregate products themselves. The life cycle footprints associated with both of these materials is included as a component of the overall footprints in Table 8-7, whereas Table 8-8 gives the component embodied carbon for asphalt and ready-mix concrete mixtures. Where water is concerned, only 'sweet' (tap) water is assumed to have an impact, since it has been through abstraction, refining and conveyance processes, from either a groundwater (0.344 kgCO_2e/t) or desalinated source (4.08 kgCO_2e/t). Where TSE is used, this is assumed to have zero impact at source, however, where waste water is produced and disposed of to a water treatment plant, as is the case for ready mix, this is accounted for (0.708 kgCO_2e/t). Water use is evaluated more thoroughly in the water footprinting section below.

Explosives have a life cycle impact that consists of production impacts and blasting impacts, together totalling 4070 kgCO_2e/t. Other ancillary materials such as lubricants, tyres, drill heads etc., are only accounted for where they make a significant contribution since most fall under the 1% total footprint cut-off criteria and are of minor significance.

8.2.6 Transportation

The three sources of primary aggregates originating in other Gulf States undergo two stages of transportation. The first stage is from quarry to port and the second from port to Mesaieed Port in Qatar. At one overseas quarry, conveyors are used to transport aggregates to the port from the quarry, with the associated energy consumption is already included in the annual production figures in Table 8-2 and the fossil foul consumption in Table 8-5. At the two other quarries, aggregates are moved to the port using articulated vehicles with a short one-way trip distance of 18-30 km. Vehicles of this size emit at a rate of 0.0745 $kgCO_2e$ per tonne.km (BEIS, 2019). Once at the port, all primary sources undertake a journey by sea to Qatar in bulk carriers of up to 100 kt deadweight, travelling 690 km on average. These vehicles emit at a rate of 0.0050 $kgCO_2e$ per tonne.km (BEIS, 2019). Using tonne.km emissions factors takes account of the return journeys that take place with an empty vessel. Upstream emissions are included for both road transport and shipping. There is also an element of fuel consumption associated with loading and unloading, depending on port configuration. Primary fuel consumption data was not available for this activity; however, a good secondary source of data is available that indicates that energy consumption for a grab bulk loader of the capacity required would be in the region of 0.27 kWh per tonne (Tilke et al., 2010). All local sources of sand, gravel, aggregates and derived products do not require this transport step. Movements of these products to the factory gate or stockpile by plant are included in the energy consumptions already evaluated in Table 8-2 (annual production) and Table 8-5 (fossil foul consumption). Table 8-9 summarises the transport contributions to the overall footprint of the different types of aggregate and derived products.

For asphalt and concrete, each component material requires transportation by road to the mixing plant. The impact of these journeys is presented in Table 8-10. For asphalt, imported aggregates – both coarse and fine fractions - are sourced less than 10 km from Mesaieed. Bitumen is imported to Mesaieed from different sources, and Singapore is considered in this document. Located in the Salwa industrial area, the concrete plant also sources imported aggregates from Mesaieed along with ground granulated blastfurnace slag (GGBS) and chemical admixtures. Cement and washed sand originate from QNCC, Umm Bab. The mixtures considered in the analysis are:

- PC C40 concrete: made with 100% Portland cement (PC), imported gabbro, local washed sand, water and chemical admixtures.
- GGBS C40 concrete: made with 65% GGBS and 35% Portland cement. Other ingredients are the same as PC C40 concrete.
- PC C40 concrete with 100% Wadi gravel: same as PC C40 concrete, with replacing 100% of imported gabbro with local Wadi gravel.
- PC C40 concrete with 20% recycled aggregate: same as PC C40 concrete, with replacing 20% of imported gabbro with recycled aggregate (RA or RCA).
- Asphalt wearing course (WC): made with 60/70 pen bitumen and imported gabbro aggregate.
- Asphalt WC with polymer modified binder (PMB): made with 4% modified binder and imported gabbro aggregate.
- Asphalt base course (BC): made with 60/70 pen bitumen and imported gabbro aggregate.
- Asphalt BC with 15% RAP: same as Asphalt BC, with replacing 15% of imported gabbro with RAP.

8.2.7 Carbonation

Carbonation is a process that occurs when CO_2 from the atmosphere chemically reacts with exposed surfaces of concrete. The process occurs when CO_2 from the atmosphere diffuses into concrete pore system in the presence of water to react with the cement hydration products to form calcium carbonate ($CaCO_3$). $CaCO_3$ has a detrimental effect on the concrete alkalinity and hence the loss of protection to reinforcement corrosion, however the process has an environmental benefit as CO_2 is effectively removed from the atmosphere (Kjellsen et al., 2005).

The rate of carbonation is dependent on environmental factors such as temperature and humidity, and whether the concrete is exposed or buried. In particular, the exposed surface area of concrete is a particularly important factor and, for this reason, crushed, recycled concrete has a higher absorption potential than cast concrete. Collins (2010) suggests that up to 41% of the CO_2 emitted in the production of concrete and its constituents may be re-absorbed during a 30 year secondary lifetime, which is a significant amount.

Concrete is likely to form a significant proportion of CDW waste, and, once processed and utilised in its secondary life, is likely to absorb some CO_2 from the atmosphere. This further reduces the overall footprint of the recycled aggregate products. However, for the purpose of this 'cradle-to-gate' analysis, carbonation is not quantified and included, since it is likely to occur most significantly beyond the boundaries of the study, and it is highly difficult to quantify its true effect due to the relatively dry exposure environment in Qatar and wide range of factors that are unknown at this time.

8.2.8 Total cradle-to-gate carbon footprints

Table 8-11 compiles the overall carbon footprints for the different types of aggregate and derived products, using the figures calculated in Table 8-5 to Table 8-10. A weighted average is calculated for the three imported sources, reflecting that, in 2019, sources 1 and 2 contributed two-thirds of total imports, whilst source 3 contributed one-third. A further weighted average is calculated for the recycled sources, given that source 2 is a relatively small, mobile operation and that source 1 will be the more representative of a scaled-up operation at Rawdat Rashid. The weighted averages are used in calculating the aggregate contributions to the derived products, concrete and asphalt, in Table 8-8 and in the water footprint calculations. The results are discussed below for the local vs. imported aggregate and also for the derived products.

8.2.8.1 Imported vs. indigenous sources of aggregate

The carbon footprint of imported aggregates (on average 10.43 $kgCO_2e$ per tonne) was higher than any local source of aggregate, which ranged from 1.7 $kgCO_2e/t$ for washed sand to 8.2 $kgCO_2e/t$ for local limestone. Much of the additional impact associated with the imported aggregates originates from the shipping that is required from the Musandam Peninsula to Qatar. The primary aggregate source with a quarry on the largest scale (imported source 1) demonstrated the benefit of scale in operation. This quarry had a high energy efficiency at 15.3 MJ/t, achieved primarily through using electricity in its energy mix.

One source of recycled aggregates had the lowest energy efficiency at 76.6 MJ/t, utilising diesel as its sole energy source in a relatively low scale operation, producing just 200,000 tonnes per annum. However, the larger-scale recycled source was more energy efficient at 29.1 MJ/t. The efficiency of recycling improves if scaled-up to produce greater quantities in a more continuous operation, as the case at Rawdat Rashid. Carbonation of concrete is a process that may further decrease the carbon footprint of aggregates derived from recycled concrete during its secondary lifetime. This would further enhance the relative savings of recycled aggregates over primary aggregates in a full life cycle study, cradle-to-grave.

Recycled aggregates had a carbon footprint of 3.0 $kgCO_2e/t$ on average, which represents a saving of 71% on imported aggregates. However, local sources of aggregate do not yet directly replace imported sources in terms of function, with local limestone primarily used in unbound applications and imported sources applied in bound applications including concrete and asphalt. This is with the exception of local washed sand, which is suitable for all applications, is low impact in carbon terms and high in energy efficiency at 12.1 MJ/t.

8.2.8.2 Derived products – carbon

The asphalt and ready-mix products combine imported aggregates with other components to form bound products for use in civil engineering applications. The applications are largely divergent, with asphalt primarily used in highways and concrete destined for a range of other construction applications. Concrete can be used in highways as a GGBS C40 concrete product though the clear advantage in carbon terms lies with asphalt cradle-to-gate.

Asphalt products had fairly similar carbon footprints with wearing course slightly higher due to a small additional fraction of imported bitumen. The footprint of wearing course including polymer-modified bitumen (PMB) is 25% higher, demonstrating the additional impact that a relatively small fraction of polymer adds to the mixture. The base course asphalt including RAP had the lowest impact and a 7% saving on a like-for-like product; this benefit could increase if RAP logistics are fully optimised i.e. RAP comes directly from currently milled, local roads without stockpiling that requires double-handling.

The ready-mix concrete products showed a much greater difference, with PC C40 concrete over two times more impacting than GGBS C40 concrete (144 kgCO2e/t compared to 69.6 kgCO2e/t). This reflects the lower content of Portland cement in the GGBS C40 concrete, where 65% of PC is replaced by GGBS; an industrial by-product of the steel industry. This analysis indicates the importance of utilising industrial by-products as substitutes for primary products wherever possible. The concrete mixtures utilising 100% Wadi gravel and 20% recycled aggregates respectively did not translate into appreciable savings, with the carbon footprints on a par with the PC C40 concrete product.

Table 8-7 Ancillary material consumption figures

Product	Water consumption (ML)	Total CO_2e (kg) - water	Explosive consumption (t)	Total CO_2e (kg) - explosives	Total CO_2e (kg) - other materials	Total production (t)	CO_2e per t product
Imported – source 1	3.41	1,173	1,285	5,229,950	0	12,203,000	**0.429**
Imported – source 2	59.10	20,330	421	1,714,870	0	3,420,000	**0.507**
Imported – source 3	0.03	11	2,880	11,721,600	0	1,500,000	**7.814**
Local limestone	45.60 TSE	0	600	2,442,000	416,948 (washed sand)	1,560,000	**1.833**
Wadi gravel	96.00 TSE	0	0	0	7,099 (mineral oils & flocculant)	780,000	**0.009**
Washed sand	804.00 TSE	0	0	0	214,113 (mineral oils & flocculant)	6,800,000	**0.031**
Recycled - source 1	27.28	9,383	0	0	0	1,500,000	**0.006**
Recycled - source 2	0	0	0	0	0	200,000	**0.000**
Ready mix concrete	11.36	46,496	0	0	**See** Table 8-8	413,978	**0.112**
Asphalt	10.80 TSE	0	0	0	**See** Table 8-8	1,800,000	**0.000**

Table 8-8 Component embodied carbon – asphalt and ready mix concrete

Component	Ready mix concrete – PC C40	Ready mix concrete – GGBS C40	Ready mix concrete – PC C40 100% Wadi gravel	Ready mix concrete – PC C40 20% recycled	Wearing course asphalt	Wearing course asphalt – polymer modified bitumen	Base course asphalt	Base course asphalt – 15% reclaimed asphalt
Imported coarse aggregate	4.766	4.797	0	4.048	5.731	5.690	6.290	5.358
Imported fine aggregate	0	0	0	0	3.804	3.828	3.311	2.835
Wadi gravel	0	0	3.342	0	0	0	0	0
Filler	0	0	0	0	0.406	0.393	0.372	0.376
Washed sand	0.561	0.553	0.554	0.534	0	0	0	0
Recycled aggregates	0	0	0	0.252	0	0	0	0
RAP	0	0	0	0	0	0	0	0.141
Portland cement (CEM I)	127.271	45.014	133.608	128.759	0	0	0	0
GGBS	0	7.731	0	0	0	0	0	0
Water	0.264	0.266	0.277	0.267	0	0	0	0
Admixtures (superplasticiser)	6.149	6.554	4.413	5.538	0	0	0	0
Bitumen	0	0	0	0	5.867	0	5.386	4.837
Polymer modified bitumen	0	0	0	0	0	12.684	0	0
CO_2e (kg) per t product	**139.017**	**64.921**	**142.194**	**139.399**	**15.807**	**22.596**	**15.359**	**13.547**

Table 8-9 Transportation emissions

Product	Quarry to port – total CO_2e (kg)	Shipping - total CO_2e (kg)	Loading and unloading - total CO_2e (kg)	Component material transport	Total production (t)	CO_2e per t product
Imported – source 1	0	37,351,759	1,026,240	0	12,203,000	**3.145**
Imported – source 2	4,584,989	10,468,165	575,226	0	3,420,000	**4.570**
Imported – source 3	3,351,600	6,218,248	252,292	0	1,500,000	**6.548**
Local limestone	0	0	0	0	1,560,000	**0.000**
Wadi gravel	0	0	0	0	780,000	**0.000**
Washed sand	0	0	0	0	6,800,000	**0.000**
Recycled – source 1	0	0	0	0	1,500,000	**0.000**
Recycled – source 2	0	0	0	0	200,000	**0.000**
Ready mix concrete	0	0	0	See Table 8-10	413,978	**0.000**
Asphalt	0	0	0	See Table 8-10	1,800,000	**0.000**

Table 8-10 Component transport – asphalt and ready mix concrete

Component	Ready mix concrete – PC C40	Ready mix concrete – GGBS C40	Ready mix concrete – PC C40 100% Wadi gravel	Ready mix concrete – PC C40 20% recycled	Wearing course asphalt	Wearing course asphalt – polymer modified bitumen	Base course asphalt	Base course asphalt – 15% reclaimed asphalt
Imported coarse aggregate	1.271	1.279	0	1.078	0.124	0.123	0.136	0.116
Imported fine aggregate	0	0	0	0	0.082	0.083	0.072	0.061
Wadi gravel	0	0	1.240	0	0	0	0	0
Filler	0	0	0	0	0.009	0.008	0.008	0.008
Washed sand	0.877	0.865	0.865	0.834	0	0	0	0
Recycled aggregates	0	0	0	0.062	0	0	0	0
RAP	0	0	0	0	0	0	0	0.031
Portland cement (CEM I)	0.740	0.262	0.776	0.748	0	0	0	0
GGBS	0.000	0.266	0	0	0	0	0	0
Water	0	0	0	0	0	0	0	0
Admixtures (superplasticiser)	0.009	0.010	0.006	0.008	0	0	0	0
Bitumen	0	0	0	0	2.186	0	2.007	1.786
Polymer modified bitumen	0	0	0	0	0	2.319	0	0
CO_2e (kg) per t product	**2.897**	**2.682**	**2.888**	**2.731**	**2.401**	**2.534**	**2.222**	**2.002**

Table 8-11 Total carbon footprints

Product	Fossil fuel	Electricity	Ancillary materials	Transport	Component embodied carbon	Component transport	Total per t product
	(kgCO₂e/t)						
Imported – source 1	1.127	0.521	0.429	3.145	0	0	**5.2**
Imported – source 2	5.285	0.000	0.507	4.570	0	0	**10.4**
Imported – source 3	3.976	0.005	7.814	6.548	0	0	**18.3**
Imported – weighted average							**10.3**
Local limestone	6.371	0.000	1.833	0	0	0	**8.2**
Wadi gravel	0.566	6.754	0.009	0	0	0	**7.3**
Washed sand	0.651	1.057	0.031	0	0	0	**1.7**
Recycled – source 1	2.518	0.000	0.006	0			**2.5**
Recycled – source 2	6.626	0.000	0.000	0	0	0	**6.6**
Recycled – weighted average							**3.0**
Concrete – PC C40	0	1.880	0.112	0	139.017	2.897	**143.9**
Concrete – GGBS C40	0	1.880	0.112	0	64.921	2.682	**69.6**
PC C40 100% Wadi gravel	0	1.880	0.112	0	142.194	2.888	**147.1**
PC C40 20% recycled	0	1.880	0.112	0	139.399	2.731	**144.1**
Wearing course (WC) asphalt	10.411	0	0	0	15.807	2.401	**28.6**
WC asphalt – PMB	10.411	0	0	0	22.596	2.534	**35.5**
Base course asphalt	10.411	0	0	0	15.359	2.222	**28.0**
Base course asphalt – 15% reclaimed asphalt	10.411	0	0	0	13.547	2.002	**26.0**

8.3 Water Footprint

Water footprinting is also a life-cycle based methodology, similar in some respects to that used to measure carbon footprints, but instead measuring the total volume of fresh water used by defined populations, organisations, products or services. However, whereas carbon footprinting measures a single impact category, contribution to climate change, a global indicator measured in carbon dioxide equivalents, measurement of a water footprint also requires assessment of the geography of water use; the availability of fresh water in locations where abstractions take place, where used (or polluted) water ends up and the potential impact that this may have. The methodology of the International Standards Organisation's standard Environmental management — Water footprint — Principles, requirements and guidelines (ISO 14046:2016) is applied to produce water footprints. This is supplemented with guidance from the Water Footprint Assessment Manual (Hoekstra et al., 2011).

8.3.1 Quantifying the Water Footprint of Aggregate Sources

So far, the impact of water use in the supply chain of aggregates has been evaluated in terms of the contribution that it makes to climate change, in the overall carbon footprints of aggregates and mineral-derived products. Expressed in this way, water makes a relatively low contribution to the overall product footprints, even if the water consumed originates from a desalinated source. Sustainable water management is a particular priority for Qatar, given the scarcity of water, low natural rates of replenishment and the infrastructure required to ensure fresh sources are maintained. A comprehensive overview of Qatar's water resources and consumption is provided by Alhaj et al. (2017).

In this section, water consumption is evaluated in a different way; through water footprinting of products. Here the high-level water consumption figures inventoried in the questionnaires for fuel, electricity and ancillary consumption (Table 8-7 and Table 8-8) are classified by type and explored geographically. Using a similar method by which the 'embodied' carbon has been calculated, the 'virtual' water stored in aggregate products can be also calculated, with contributions from energy use, transport and component products all evaluated. The virtual components of the water footprint are otherwise known as the 'indirect water footprint' and effectively measure the water consumption of the supply chain used to produce the aggregate products.

8.3.2 Water Use in Aggregate Products

The components of water use in relation to aggregate products are presented in Table 8-12. Geographically, each component of water consumption can be either domestic or overseas.

Table 8-12 Components of the overall water footprint evaluated

Component	Description	Data source
WF_D	Direct water use, sourced from groundwater aquifers or desalination plants.	Recorded at site, sourced via questionnaires.
WF_F	Indirect water use associated with fuel or electricity consumption or production (well-to-tank).	Mekonnen et al. (2015) Gerbens-Leenes et al. (2018)
WF_E	Indirect water use embodied in component or ancillary materials.	Gerbens-Leenes et al. (2018) (cement and GGBS) Eurobitume (2011, 2020) (bitumen) The Norwegian EPD Foundation (2018) (explosives) EFCA (2015) (superplasticiser)
WF_T	Indirect water use associated with transportation.	Mekonnen et al. (2015) Gerbens-Leenes et al. (2018)
WF_{TOTAL}	The overall water footprint	$WF_{TOTAL} = WF_D + WF_F + WF_E + WF_T$

8.3.3 Direct Water Use Classification

ISO 14046 requires water use to be classified by source, form of use, geographical location of source and discharge, and any impact on water quality through use. This analysis is presented for each product in Table 8-13. The table reports 'direct' water use during production (WF_D), used to wash away fines, in dust suppression and, in the case of concrete, product integration. A few examples of water use in aggregate production are provided in Figure 8-1 to Figure 8-3. Where an otherwise potable or 'sweet' source of water is used, this is coloured blue. This 'blue water' consumption reflects depletion of a ground or surface water source (Hoekstra et al., 2011). Where desalinated water is used this has also been classified as blue water consumption, given that this source of water is not freely available and requires an input of energy to replenish; it is a form of 'consumptive' water use.

TSE water use is not classified as blue water consumption since this practice makes effective use of a waste product that might otherwise be disposed of to a lagoon or deep-injected into a non-freshwater aquifer. The 'form' of water use is the destination for used water. The predominant destination is evaporation which would be expected given the nature of quarrying operations and climatic conditions; the impacts of this are explored later in the section on grey water below. In the operations that use significant quantities of TSE (Wadi gravel and washed sand), effective processes have been implemented to capture and recycle 80% of the TSE used, using filter presses and flocculants to remove clay particles. The residue from the filter press itself forms a useful product for agricultural use. Only the ready-mix operation produces waste water at a rate of 0.55 litres per tonne of product that enters foul sewers and needs treatment.

Table 8-13 Classification of direct water use for products

Product	Water consumption (ML/year)	WF_D (litres/tonne)	Direct water source(s)	Form of water use
Gabbro – source 1	3.41	0.28	Groundwater	Evaporation
Gabbro – source 2	59.10	17.28	Groundwater	Evaporation
Gabbro – source 3	0.03	0.02	Groundwater	Evaporation
Local limestone	45.60 TSE	0	Desalination/ TSE	Evaporation
Wadi gravel	96.00 TSE	0	TSE	Evaporation/Recycled with a filter press
Washed sand	804.00 TSE	0	TSE	Evaporation/Recycled with a filter press
Recycled – source 1	27.28 TSE	0	TSE	Evaporation
Recycled - source 2	0	0	None	-
Ready mix concrete	11.36	27.44	Desalination	Product integration/ Waste water treatment
Asphalt	10.80 TSE	0	TSE	Evaporation

Figure 8-1 Water use in a gabbro quarry to suppress dust

Figure 8-2 Production of washed concrete sand in Qatar

Figure 8-3 Water used for washing of recycled aggregate

8.3.4 Indirect Water Use

Each product also has a demand on water use that is 'indirect', that is embodied within the product. This form of water use derives from the use of energy, either directly consumed or consumed in forms of transport, and from consumption of component or ancillary materials, which themselves have required water to produce. Indirect blue water use can be calculated using factors akin to emissions factors for carbon, using the data sources presented in Table 8-12. The water footprints of various energy sources are important here.

Electricity has a blue water footprint of 4.241 m^3/GJ, whereas crude-derived fuels are 0.080, 0.028 and 0.002 m^3/GJ for diesel, fuel oil and LPG respectively. This is an immediate differential for products that utilise electricity as opposed to fossil fuels in production. An analysis has been conducted for each product using the raw data collected from aggregate producers. The results are presented in Table 8-14.

Table 8-14 Indirect water use for products

Product	WF_F (fuel & electricity	WF_E (embodied components)	WF_T (transport)	$WF_{INDIRECT}$
	(litres/tonne)			
Gabbro – source 1	10.80	0.41	1.25	**12.46**
Gabbro – source 2	4.89	0.48	2.87	**8.23**
Gabbro – source 3	3.77	7.45	4.30	**15.52**
Gabbro – weighted average	7.59	2.76	2.50	**12.86**
Local limestone	5.89	1.49	0	**7.38**
Wadi gravel	126.94	0	0	**126.94**
Washed sand	20.39	0.02	0	**20.41**
Recycled – source 1	2.33	0	0	**2.33**
Recycled - source 2	6.13	0	0	**6.13**
Recycled – weighted average	2.77	0	0	**2.77**
Concrete – PC C40	35.18	419.44	3.30	**457.92**
Concrete – GGBS C40	35.18	316.04	3.06	**354.28**
PC C40 100% Wadi gravel	35.18	483.71	3.29	**522.18**
PC C40 20% recycled	35.18	420.81	3.11	**459.10**
Wearing course asphalt	1.98	28.34	1.05	**31.37**
Wearing course asphalt – PMB	1.98	312.16	1.05	**315.19**
Base course asphalt	1.98	27.29	1.05	**30.32**
Base course asphalt – 15% RAP	1.98	27.41	1.05	**30.44**

8.3.5 *Total Water Footprints*

Combining direct and indirect water footprints gives the total water footprints for each product in Table 8-15. These are provided in litres per tonne and also in the more common unit of cubic metres per tonne. Whilst not strictly part of a water footprint calculation according to ISO 14046, total TSE use per product is also provided in litres per tonne so that issues around sustainable water management can be discussed later.

Table 8-15 Total water footprints

Product	$WF_{INDIRECT}$	WF_D	WF_{TOTAL}	WF_{TOTAL}	WF_{TSE}
	(litres/tonne)			(m^3/tonne)	(l/tonne)
Gabbro – source 1	12.46	0.28	**12.7**	0.01	0
Gabbro – source 2	8.23	17.28	**25.5**	0.03	0
Gabbro – source 3	15.52	0.02	**15.5**	0.02	0
Gabbro – weighted average	12.86	2.67	**15.5**	0.02	0
Local limestone	7.38	0	**7.4**	0.01	29.23
Wadi gravel	126.94	0	**127.0**	0.13	123.08
Washed sand	20.41	0	**20.4**	0.02	118.24
Recycled – source 1	2.33	0	**2.3**	0.00	18.18
Recycled – source 2	6.13	0	**6.1**	0.01	0
Recycled – weighted average	2.77	0	**2.8**	0.00	16.05
Concrete PC C40	457.92	27.44	**485.4**	0.49	38.16
Concrete GGBS C40	354.28	27.44	**381.7**	0.38	37.61
PC C40 100% Wadi gravel	522.18	27.44	**549.6**	0.55	93.75
PC C40 20% recycled	459.10	27.44	**486.6**	0.49	37.61
Wearing course asphalt	31.37	0	**31.4**	0.03	6.00
Wearing course – PMB	315.19	0	**315.2**	0.32	6.00
Base course asphalt	30.32	0	**30.3**	0.03	6.00
Base course – 15% RAP	30.44	0	**30.4**	0.03	6.00

8.3.6 *Grey Water*

Whilst not sub-divided in ISO 14046, the Water Footprint Assessment Manual (Hoekstra et al., 2011) sub-divides the overall water footprint into three components, made up of blue, green and grey water. The blue water component derives from surface and groundwater and has been calculated in Table 8-13 to Table 8-15. As previously stated, TSE use has been evaluated but does not form a part of the blue water footprint. The green component of water use would reflect water from precipitation on land that does not run off or recharge the groundwater but is stored in the soil and can be consumed to produce crops. This component of water consumption is not relevant to the life cycles of aggregate products. The final component, grey water, is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011) (ibid.) i.e. the volume of water that is required to dilute pollutants back to harmless levels. Grey water could be relevant to industrial processes including aggregate, asphalt and concrete production.

The scope of this study did not extend to evaluating the water quality of waste water that might be deposited on land after use in quarry processes, or disposed of to foul sewers in the case of concrete production. However, a useful insight into grey water evaluation and its relevance to aggregate product cycles can be gained from other published sources, such as Gerbens-Leenes et al. (2018) who evaluated the total water footprints of both ordinary and composite Portland cement (CEM II/B).

The overall grey water footprints of cement and composite cement are very similar and both are dominated by the contribution of gypsum. In the published source (Gerbens-Leenes et al., 2018), gypsum is obtained from flue gas desulphurisation (FGD) and is allocated some of the impacts from this polluting process that is primarily associated with power generation. It can be argued that this allocation of impacts to a secondary product should not take place, but the gypsum does have an economic value and therefore takes on some of the impact. If gypsum were obtained from a mine, then its grey water impact would be lower and the grey water footprint of cement would be greatly reduced.

Part of this grey water contribution could be embodied into the overall water footprint of ready-mix concretes, which include around 150 kg of cement or composite cement per tonne in their mixture recipes. The volumes of water needed to dilute chemical pollutants arising from the cement production process in litres per tonne of cement are also provided by Gerbens-Leenes et al. (2018). If these contributions are totalled up, then the uplift of approximately 112 m^3/tonne of ready mix would hugely outweigh the blue water contribution. For this reason, the grey water contribution is not included in the overall footprints presented here.

A further point to note here is that the grey water contributions from mining limestone/dolomite, mining sand and crushing & washing limestone, all are zero at the accuracy reported. This suggests that the grey water component of other aggregate products evaluated is likely to be negligible.

8.3.7 The Geography of Blue Water Consumption and Virtual Water Flows

The overall blue water footprints (WF_{TOTAL}) presented in Table 8-15 also have a geographical component that can be used to provide an insight into the pressures the aggregate life cycles exert on particular groundwater sources. In order to conduct this analysis it is necessary to assume that any fuel consumed within Qatar, for industrial processes or transportation, also originates in Qatar, whether electricity, gas or crude-derived products. This seems a reasonable assumption given Qatar's wealth of these resources. Water statistics (PSA, 2018a) seem to confirm that water from either ground or desalinated sources are the principal sources of water used in the oil & gas industry and electricity generating industries. The geographical demand on blue water resources, split between domestic and overseas sources is presented in Table 8-16.

Table 8-16 Geographical split of blue water consumption for aggregate products

Product	WF (domestic)		WF (overseas)		WF_{TOTAL}
	(l/tonne)	%	(l/tonne)	%	(l/tonne)
Gabbro – source 1	0.10	1%	14.63	99%	**14.7**
Gabbro – source 2	0.10	0%	47.54	100%	**47.6**
Gabbro – source 3	0.10	1%	15.44	99%	**15.5**
Gabbro – weighted average	0.10	1%	19.71	100%	**19.8**
Local limestone	7.38	100%	0	0%	**7.4**
Wadi gravel	126.94	100%	0	0%	**127.0**
Washed sand	20.41	100%	0	0%	**20.4**
Recycled – source 1	2.33	100%	0	0%	**2.3**
Recycled - source 2	6.13	100%	0	0%	**6.1**
Recycled – weighted average	2.77	100%	0	0%	**2.8**
Concrete – PC C40	28.84	6%	439.76	94%	**468.6**
Concrete – GGBS C40	30.20	7%	335.00	93%	**365.0**
PC C40 100% Wadi gravel	14.18	3%	516.72	97%	**531.7**
PC C40 20% recycled	25.50	5%	444.00	95%	**469.6**
Wearing course asphalt	33.15	93%	2.32	7%	**35.5**
Wearing course asphalt – PMB	316.95	99%	2.32	1%	**319.3**
Base course asphalt	32.11	92%	2.32	8%	**34.4**
Base course asphalt – 15% RAP	28.18	81%	5.79	19%	**34.0**

The analysis indicates that, for imported gabbro aggregates, the majority of water demand resides overseas, whereas for local sources of aggregates the demand on water resides domestically. For the derived products, ready mix demands are principally domestic, with the exception of the imported aggregates used. For asphalt, the demand is largely overseas, given the imported sources of aggregates, bitumen and polymers that it utilises. Some sources of blue water demand are hard to pinpoint in terms of location (e.g. for imported bitumen), however, much of demand can be more or less identified to two principal aquifer systems, alongside desalination plants. Qatar's water statistics (PSA, 2018) indicate that, in 2016, 71% of blue (or freshwater) came from desalinated sources, with the remainder from groundwater. The main groundwater source is the Umm er Radhuma-Dammam (Central) aquifer system (see Figure 8-4; UN-ESCWA and BGR, 2013) that is also exploited by Bahrain and parts of Saudi Arabia. The Umm er Radhuma-Dammam aquifer has hydraulic continuity with the Rus formations in north and south Qatar.

Imported aggregates originating in the Musandam Peninsula utilise water from Umm er Radhuma-Dammam Aquifer System (South), a source of groundwater situated under Oman, Saudi Arabia, UAE and Yemen (see Figure 8-5, ibid.). Abstraction takes place in the Dhofar-Najd region common to both Oman and the UAE. Oman, for example, relies more heavily (92%) on this groundwater source for blue water than desalination (Oman Water Society, 2014).

UN-ESCWA and BGR (2013) report the Umm er Radhuma-Dammam (South) aquifer system to be more sustainable than the Umm er Radhuma-Dammam (Central) system. Over-abstraction locally is still apparent in the Southern aquifer with overall levels dropping year-on-year. However, the Central system already shows signs of significant depletion and a drop in the water table that make it unusable in some locations.

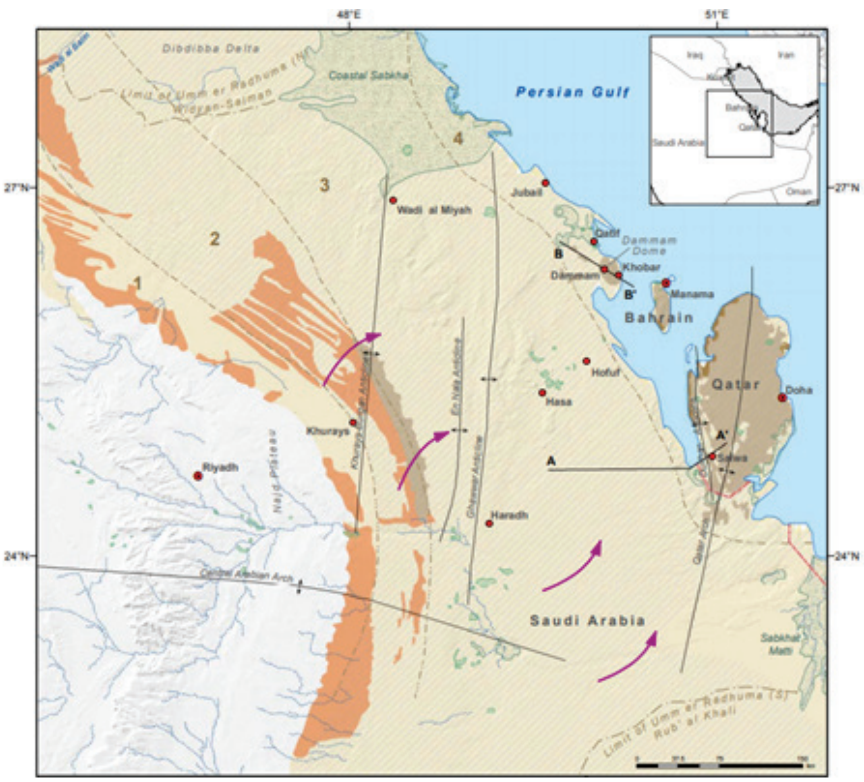

Figure 8-4 The Umm er Radhuma-Dammam (Central) aquifer

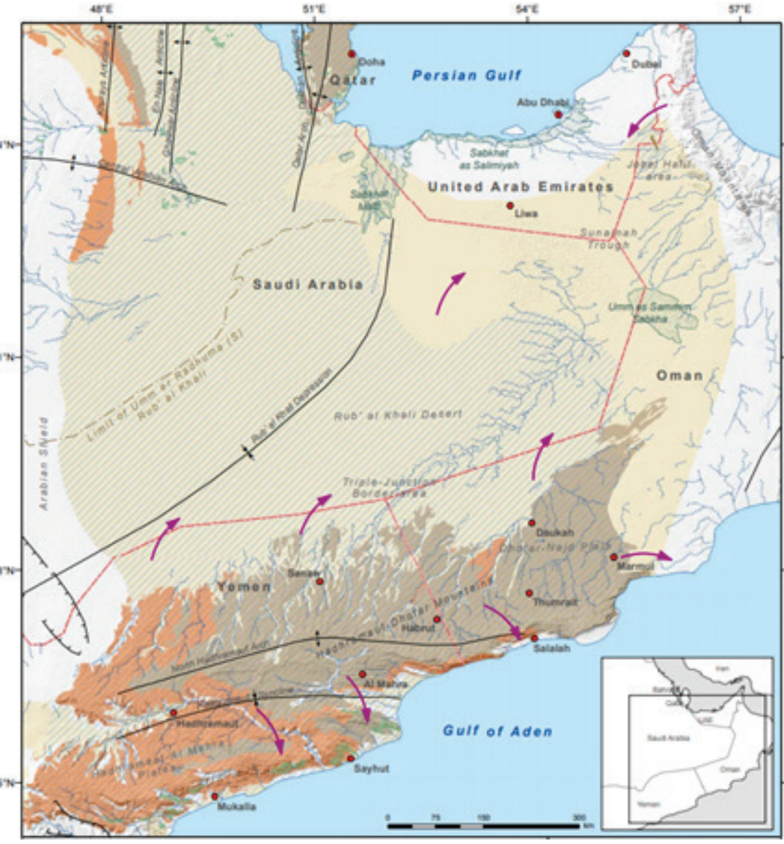

Figure 8-5 Umm er Radhuma-Dammam (South) aquifer

This analysis highlights the potential issues with importing products. The geographical burden of water abstraction shifts from one nation to another and, in this case, from Qatar that is classified at ‘extremely-high’ in terms of baseline water stress, to Oman and UAE that are classified at ‘high’ water stress in the region where aggregates are quarried (World Resources Institute, 2019). Importing aggregates, whilst a contributor, is not likely to push Oman and UAE into higher levels of water stress as a solitary factor. More water-intensive industries such as agriculture that also export from the Musandam Peninsula are likely to have a more critical effect.

8.3.8 Discussion

Water is used directly in dust suppression and washing operations in the aggregates supply chain and to mill asphalt at end-of-life. Water is also added to cement to facilitate the chemical process of hydration in concrete. These processes are examples of direct water use from either a blue (groundwater or desalinated) source, or utilising TSE. Imported aggregates and cement produced locally used blue water that might otherwise be used for drinking water whereas the domestic aggregate processors mostly used TSE, which might be upheld as sustainable practice, given that Qatar has clear strategies to make better use of TSE rather than disposing of it. Domestic gravel and sand operations also seek to mitigate their relatively high use of TSE by further recycling 80% of it on site and this should be upheld as ‘best practice’.

Use of water to process aggregates in overseas quarries varied quite considerably between 0.02 and 17.28 litres per tonne. This may highlight a problem in data collection at one source or quite possibly that water use is in fact not measured with any degree of accuracy, potentially treating water as an unlimited commodity in these operations.

Fresh water is used in concrete with the mixture in terms of setting time and strength, corrosion of reinforcement, staining and reduced durability. Fresh water for concrete production must meet the requirements of the Qatar Construction Specifications (2014) and/or BS EN 1008 (2002). An interesting analysis to conduct in further work would be to see if TSE or other sources of industrial waste water can meet these standard requirements to be used in concrete mixing and further limit the use of freshwater in this sector. A similar analysis would be useful for the use of TSE in road milling machines that are currently modelled using blue water.

No direct water use was reported in relation to the smaller-scale aggregates recycling operation. This is feasible given that it is a mobile operation, working potentially on one homogenous source of RCA or EW waste at a time. With a water footprint of 6.1 l/t, the relative saving of this operation over imported aggregates (15.5 l/t) is 61%. However, it is common practice in recycling operations to remove contaminants using water, as used in the larger-scale recycling operation. This larger plant directly used 18.2 litres of water per tonne of product and had an overall water footprint of 20.5 l/t. This is indicative of how much water a scaled-up operation at Rawdat Rashid may consume and is on a par with other domestic sources of aggregates. Should recycling be scaled up at Rawdat Rashid to deal with heterogeneous sources, washing operations may need to be integrated to promote the quality of the recycled aggregates. If this is the case, then the water source should be TSE, as has been modelled in this assessment.

Conducting a full water footprint analysis on the aggregate supply chains allowed indirect water use to be highlighted, demonstrating that each aggregate product contains ‘hidden’ or embodied flows of water associated with it. These indirect flows are demands on water used to produce the product arising from energy consumption, transportation, component materials and ancillary material use. Most of these additional blue water flows also have a geographical component that can be pinpointed to particular water sources.

The overall water footprints associated with the aggregate products ranged from 6.1 l/t for one source of recycled aggregates to 485.4 l/t for one PC C40 concrete. Most aggregate sources did not exceed 20 l/t, with the main exception being Wadi gravel at 127 l/t.; something that can be attributed to high use of electricity in production as opposed to other crude-derived fuels. Water in electricity use is high due to the use of steam to drive turbines and act as a coolant.

The water footprints of the concrete products were an order of magnitude higher than any of the other products, with the exception of polymer-modified asphalt and this was mainly due to the water use associated with Portland cement production. To reduce water use associated with bound products, asphalt should be the selected material where it can act as a direct substitute (e.g. in road construction). In this respect polymer modification should be carefully matched to the application, since this increases the impact of asphalt tenfold. For the ready-mix concrete products, there a small saving is observed for the 20% recycled product over the conventional PC C40 concrete product. The Wadi gravel footprint remains high due to the electricity use at this production site. Despite the high calculated water footprint for concrete products, these are still considerably lower than the blue water footprint for unalloyed steel which amounts to 11,830 L/t (Gerbens-Leenes et al., 2018). Grey water footprints were also investigated and were found to be potentially significant for the mineral-derived products, depending on the source of gypsum used.

8.4 Cost Savings

For effective implementation, recycling needs to be justified financially as well as environmentally. The initial cost of a material is a major factor on the decision of its use. In a country like Qatar, with high aggregate demand and shortage of local supply, the price of local materials, including recycled aggregate, would be expected to be cheaper than that of imported gabbro. The main cost savings will be in the transport and handling of imported materials. Other factors that could affect the price of recycled aggregate are availability, processing costs, and incentives.

The availability of materials has a significant impact on price, with larger quantities resulting in cheaper prices. The quantity of construction waste estimated at Rawdat Rashid Recycling site is within the range of 60-80 Mt (NDS-2, 2018; Hassan et al., 2016), which could provide a sustainable supply of materials for large investment. The long-term agreement set between the MME and QPMC, chapter 2, and the participation of the private sector (PPP investment) can make a major impact in the aggregate supply in Qatar. Provided that a consistent quality of recycled aggregate is available locally in compliance with the specification requirements, there will be less reliance on imported aggregates.

One of the main challenges facing the consistent supply of recycled aggregate is the variability of construction waste materials, which are obtained from a number of different sources. This variability requires greater efforts in processing with impact on both the quality and price of the final recycled products. For example, processing of mixed CDW materials will require greater efforts in separation, crushing, screening and washing when compared to a relatively clean EW aggregate that will only require crushing and screening. The recovery rate from the processing of clean waste materials will be also higher than the rate from mixed and non-segregated wastes. The MME initiative of pre-demolition audits (Section 3.3.3) will minimise waste contamination and maximise recovery rate. The QPMC plan to introduce washing facilities for mixed CDW at Rawdat Rashid will also improve the quality and recovery rate of recycled aggregate but will increase the processing cost.

Introducing a revenue from waste generation and disposal can assist the government to send less material to landfill and recycle more. Many countries are currently applying tipping fees for the disposal of waste materials. This fee could be applied to Qatar with the aim of improving the quality of recycled aggregate. In Kuwait, a tipping fee is applied for each truck dumping demolition waste at the rate of 4-6 KWD/truck, which is equivalent to 50-75 QR/truck. The fees are paid to the contractor processing the recycled materials. In Europe, many governments have set targets for the reduction of waste going to landfill and imposed taxes on material sent to landfill. These taxes are in addition to the tipping fees charged by the landfill site operators. These policies are driven by a shortage of landfill capacity as well as a desire to be more sustainable. This is a situation that Qatar is likely to find itself in fairly soon if it continues with the present policy of allowing contractors to send material to tip without any charges or taxes.

The government could make a large contribution to encouraging recycling by imposing taxes and/or tipping fees on material sent to landfill. The taxes/charges should be related to the potential harm to the environment and ease of recycling; thus, inert materials, like excavation waste or clean concrete, would be taxed at a low rate whereas mixed CD&EW would be charged at a higher rate. Hazardous materials, such as asbestos, should not be permitted at general sites such as Rawdat Rashid, but should be sent to special sites where they can be handled safely.

In the UK there are two rates of landfill tax:

- The lower rate of £2.65/tonne (approx. 13 QAR/tonne) for inert materials (e.g. clean concrete or excavation waste);
- The standard rate of £84.40/tonne (approx. 420 QAR/tonne) for other waste, including mixed CD&EW with wood, paper, plastic, metal and other contaminants.

The landfill tax was first introduced in 1997 in the UK and the standard rate has risen very considerably over the last 20 years. Introducing an initial landfill tax at fairly low rates, with a commitment to increase rates over time to discourage sending waste to landfill and encourage recycling, combined with the other initiatives for the uptake of recycled aggregates, would send a strong signal to the construction industry that the government wish to see a change in the current practice of sending everything to landfill. This is in line with government policy of economic development without damage to the environment as set out in the Qatar National Vision 2030.

8.4.1 Recycled Aggregate vs. Primary Aggregate

As part of the sustainable supply of recycled aggregate, QPMC regulated the prices of both primary and recycled aggregate and made the prices publically available on their website. Table 8-17 lists the prices of imported gabbro and recycled aggregate sold by QPMC (QPMC, 2021). It also includes the prices of local limestone aggregate, traditionally used in subbase and fill applications, and processed Wad gravel.

Table 8-17 shows the prices of 77.00 QR/t for imported gabbro and 40.00 QR/t for local limestone aggregate. Gabbro is currently used as aggregate for asphalt, concrete and pipe bedding applications, whereas local limestone aggregate is mainly used in road base and subbase unbound applications and low strength concrete products. A cost saving of 48% could be achieved when replacing imported gabbro by local limestone aggregate, provided the latter satisfies the specification requirements. However, the local and recycled materials cannot replace imported gabbro entirely; in concrete and asphalt, for example, they are not permitted for use in asphalt wearing course applications. Other materials, such as Wadi gravel, are only available in limited quantities.

The price of local sand is relatively cheap at QR 22.00 per tonne, compared to other aggregate materials. The material is collected from sand deposits and processed through washing for the removal of clayey and other fine particles. The oversize material of Wadi gravel is almost double the price of washed sand, mainly due to the additional processing of crushing and washing for the removal of adhering gypsum and reducing the sulfate content to acceptable levels for use in construction. With the increased processing cost of Wadi gravel, the material offers a 35% cost reduction in comparison to the price of imported gabbro when used in concrete applications.

Table 8-17 Prices of primary and recycled aggregate materials (QPMC, 2021)

Material	Unit cost (QR/t)	Cost saving relative to imported gabbro (%)
Imported gabbro	77.00	-
Local limestone (Primary)	40.00	48%
Washed sand	22.00	-
Wadi gravel	50.00	35%
Local limestone (Recycled, EW)	11.00	73%
Recycled aggregate for asphalt (RAP)	49.50	36%
Recycled aggregate for concrete	20.00	74%
Aggregate for pipe bedding	20.00	74%

The greatest reductions in aggregate prices are for the recycled aggregates, as shown in Table 8-17. A cost saving in the range of 36 % to 74 % can be achieved by replacing conventional primary materials. For example, the use of recycled EW aggregate to replace local limestone aggregate will reduce the aggregate price by 73%. Similarly, the use of recycled aggregate to replace imported gabbro in concrete and pipe bedding applications will result in 74% cost saving of the aggregate prices. A cost saving of 36% is achieved when RAP aggregate is used to replace gabbro in asphalt pavement.

8.4.2 Prices of Aggregate-Derived Products

Asphalt, concrete and unbound subbase were selected as the aggregate-driven products for the comparison of cost savings associated with the use of recycled aggregates. These construction materials are widely used in Qatar and can uptake large quantities of recycled aggregate. Aggregate is probably the cheapest ingredient of these products but occupies greater than 85% by weight of each product. Therefore, a reduction in the aggregate price will be expected to reduce the price of the derived product. The unit price per tonne of each product is given in Table 8-18 for the selected construction applications.

The Ashghal Recycling Manual (2021) permits the use of maximum 15% RAP in asphalt base course (BC) layers, without modifying the mix design (JMF). RAP is not permitted for use in wearing course (WC) applications. The results in Table 8-18 show that the cost of asphalt mixture made with 15% RAP is 192 QR/t, compared to 197 QR/t for the conventional asphalt mixture made with 100% gabbro aggregate. A cost reduction of 3%, which is relatively small compared to the cost saving values for the aggregate prices, Table 8-17. However, RAP is available in large quantities and this could lead to significant cost savings if it is widely used in base course.

An identical cost saving of 3% is found with the use of 20% recycled aggregate in C40 concrete. Table 8-18 shows the prices of C40 concrete with and without 20% recycled aggregate are 315 QR/t and 306 QR/t, respectively. Increasing the aggregate replacement level to 100% of Wadi gravel resulted in a cost reduction of 10% in C40 concrete. The greatest cost saving in Table 8-18 is 47% and is related to the use of recycled subbase materials as opposed to subbase made with natural limestone materials. Recycled aggregate, consisting of EW and RCA, will be available in large quantities from Rawdat Rashid, so the bulk use of these materials will lead to significant cost savings overall.

Table 8-18 Prices of aggregate-derived construction products (reworks)

Material		Unit cost (QR/t)	Cost savings (%)
Asphalt products	Asphalt wearing course (bitumen 60/70)	198	-
	Base course asphalt BC-A	197	-
	Base course asphalt – BC-B 15% RAP	192	3%
Concrete	Concrete – C40 OPC Normal	315	-
	Concrete – C40 100% Wadi gravel	284	10%
	Concrete – C40 20% recycled aggregate	306	3%
Subbase	Subbase (Primary aggregate, unbound)	44.00	-
	Subbase (Recycled aggregate, unbound)	26.00	47%

Whilst the cost savings of recycled aggregate prices ranged from 35% to 74% compared to the prices of primary materials, the equivalent cost savings were between 3% and 10% for asphalt and concrete mixtures, and 47% for subbase applications. The different in cost savings is attributed to the proportion of recycled materials used in each application, the cost of other ingredients, and other costs related to the transporting of materials to the plant, handling, and mixing of the materials. The greatest cost saving of subbase material was obtained from the regulated QPMC prices for recycled aggregate and products, whereas the cost of asphalt and concrete mixtures were obtained from individual mixing plants. More reduction of the prices of asphalt and concrete mixtures, made with recycled aggregate, will be expected with the wider uptake and use of recycled materials in practice.

8.5 Summary

Carbon and water footprint analysis were carried out on Qatar's aggregate sources and eight mineral-derived products, cradle-to-gate. A feasibility study was also conducted to assess the prices of recycled aggregate and derived products compared to conventional construction materials. Whilst there is no specific requirement in the NDS-2 on carbon emissions and water consumption of construction products, such analyses have been proved feasible to conduct and provide relevant information to support the delivery of government strategy of sustainable development. Some of the practices observed can contribute to meeting the objectives of NDS-2, particularly use of TSE in domestic aggregate production and recycling of construction waste to produce recycled aggregates. In the aggregates sector, an effective climate change response in the absence of using fewer aggregates overall, would be to substitute use of imported aggregates with as many local or recycled aggregates as possible, since clear carbon savings and cost savings are associated with the local sources.

To reduce overall water use, there is also a benefit associated with using recycled aggregates in place of primary aggregates in unbound applications, whether imported or local. If the operation at Rawdat Rashid is scaled-up and requires more heterogeneous sources of CDW and EW to be washed in processing to remove contaminants, this advantage will be maintained only if the water consumed is TSE.

Where there is a direct choice between asphalt and concrete, asphalt should be selected since it has both significantly lower carbon and water footprints per tonne, notwithstanding durability aspects. Introducing reclaimed asphalt in new asphalt mixtures has a benefit in terms of carbon footprint and causes no additional water consumption overall, even if groundwater is used to mill the expired asphalt. It is however logical to explore whether TSE can feasibly be used in road milling machines to avoid unnecessary freshwater use. The same effect is observed in concrete mixtures that include recycled aggregates but to a lesser extent. The use of 15% RAP in asphalt or 20% recycled aggregate in concrete results in only 3% cost saving. When 100% of Wadi gravel is used to replace imported gabbro, the cost saving of concrete is 10%. More reduction in the cost of recycled aggregate-derived products is expected with the wider implementation of recycling and regulating the prices of recycled products, similar to the QPMC approach. Even the relatively small cost reductions of 3% to 10% reported above amount to significant overall cost savings when used in large quantities in widely used construction materials such as asphalt and concrete.

Enhanced use of composite cements should be promoted in appropriate applications to reduce the use of Portland cement which is the highest consumer of water in any of the product supply chains, contributing 60-70% to the overall footprint. The water footprint of concrete products, which is a magnitude higher than any other aggregate product, may further be lowered if TSE or other industrial wastewater of consistent quality could substitute some of its freshwater demand, particularly in cement production. It is recommended that an analysis is conducted to determine the feasibility of this substitution. Greater use of cement replacement materials such as GGBS or FA would also reduce the carbon footprint of concrete, while improving durability.

The geographical analysis of the blue water demand of the product supply chains highlighted the particular challenges encountered in the Gulf region with regards to the sustainability of groundwater resources in aquifers. This problem is bigger than the aggregates supply-chain alone and will apply to many imported products, whether sourced regionally or globally. An holistic and internationally-coordinated approach will be required to find a sustainable solution to this problem.

9 Towards Wider and more Efficient Implementation

The previous chapters covered the government's vision, strategy and initiatives to achieve sustainable development in the construction industry through the efficient use of natural resources and the use of recycled aggregate. A national target has been set to recycle 20% in government projects by 2020. Enabling specifications, guidelines and manuals have been published to facilitate the use of recycled and alternative aggregates in construction. A sustainable supply of recycled aggregate is guaranteed by QPMC through their long-term agreements with MME and Ashghal to manage and process construction wastes at different locations.

Case studies on the successful uptake and implementation of recycled and alternative aggregates in various construction applications are presented. The main durability concern on the performance of recycled aggregates in service, within the aggressive exposure conditions in Qatar, is addressed from site investigations with up to 5 years real exposure conditions. This chapter focuses on the wider and more efficient use of recycled and alternative aggregates in construction. It reviews potential technical and non-technical barriers that can inhibit the wider utilisation of recycled aggregate and proposes practical solutions on how to overcome them to achieve the government's recycling target.

9.1 Quality of Recycled Aggregates

As discussed in chapter 2, construction waste accounts for approximately 80 % of solid waste generation in Qatar, which is literally 8 Mt per year. In additional, over 80 Mt of construction waste are accumulated in landfill sites. Mixed CDW occupies by far the greatest volume of construction waste in landfill sites. Compared to other recycled aggregates of RAP, EW, and RCA, mixed CDW materials are composed of different quantities of concrete, bricks, gypsum products (e.g. plasterboard and building plaster), asphalt, ceramic products, glass and metal. They can also contain lightweight materials of wood, paper, cardboard, plastic, and cloths that can impact on the quality of recycled products. The composition of CDW aggregates highly depends on their source and the processing method. The diversity of the construction materials and methods mean that mixed CDW will change in quality and composition, which will produce recycled aggregate of varying quality. Much greater effort – and hence cost – is therefore required to produce quality recycled aggregates from mixed CDW compared to single material types such as RAP, EW, RCA and steel slag.

Standards and specifications tend to restrict the composition of recycled aggregate, and to limit the amount of foreign and lightweight materials in construction. For example, the QCS 2014 permits the use of EW and RCA up to 20 % and 50 % by aggregate weight in structural and non-structural concrete, respectively. Where the recycled aggregate is derived from mixed CDW, the material is not permitted in structural concrete and the maximum fraction is 25% in non-structural C25 concrete. Similarly, the Ashghal Recycling Manual (Ashghal, 2021) allows up to 100% EW in unbound road base and subbase applications. However, the maximum level of recycled aggregate derived from mixed CDW is limited to 30 % in road base and 50 % in subbase applications.

Considering the large quantities in Qatar, there is an urgent need for a quality protocol system to control the consistent supply of CDW materials. Separation of CDW materials at source produces higher quality aggregate, fewer contaminants, lower processing cost, and a higher recovery rate than mixed CDW materials.

To provide more confidence in the quality production of recycled aggregate, there is a need to certify the QMS and the recycled products by an independent body. The certification system will enable an independent review and inspection of the production process and final products, and their compliance with the QMS and relevant specifications. Currently the Ashghal Quality and Safety Department (QSD) performs quality audits on asphalt plants and testing laboratories in Qatar, with updated lists of approved asphalt suppliers and testing houses for use in Ashghal projects. The QSD has the relevant expertise and facilities to carry out the audits on recycled aggregates and perform the required conformity testing in their Ashghal Centre for Research & Development testing facilities. There is no doubt that the QSD audit and certification of recycled aggregates, generated by QPMC and their partner contractors, will greatly support the wider acceptance and uptake of recycled aggregate in Ashghal projects.

Recommendations on improving the quality of mixed CDW at source and during processing are discussed in the following sections.

9.1.1 Code of Practice for Mixed CDW

The current MME plan to introduce demolition permits and pre-demolition audits to maximise waste recovery can be included into a Code of Practice with the aim of reducing the overall amount of waste, increasing the recovery of materials, and improving recycling efficiency. The Code of Practice will help in maximising the amount of inert demolition waste that can be recycled as aggregate and to achieve the national target of 20% recycling by 2022. The operation of the Code of Practice is illustrated in Figure 9-1 and will include the following actions:

9.1.1.1 A Demolition Permit:

Prior to being granted a demolition permit, the contractor must carry out a pre-demolition audit of the building/structure to be demolished. The pre-demolition audit will identify materials that can be removed for reuse or recycling, such as furnishings and fittings, false ceilings and floors, partitions, air conditioning units and other mechanical plant. The audit should also identify the possible presence of any hazardous materials such as asbestos. If necessary, specialist surveys should be carried out to establish whether hazardous materials are present and to identify the correct procedures for removing them prior to demolition.

9.1.1.2 Pre-demolition Audit

The pre-demolition audit should identify the main structural features of the building and enable an estimate of the total amount and nature of demolition waste to be made. The contractor should plan the demolition to maximise the quantity of high quality, segregated material – clean concrete, blocks, bricks, etc. – that can be generated, as this will yield better quality recycled aggregates than mixed materials or materials contaminated with wood, plastic, paper, metal or other substances.

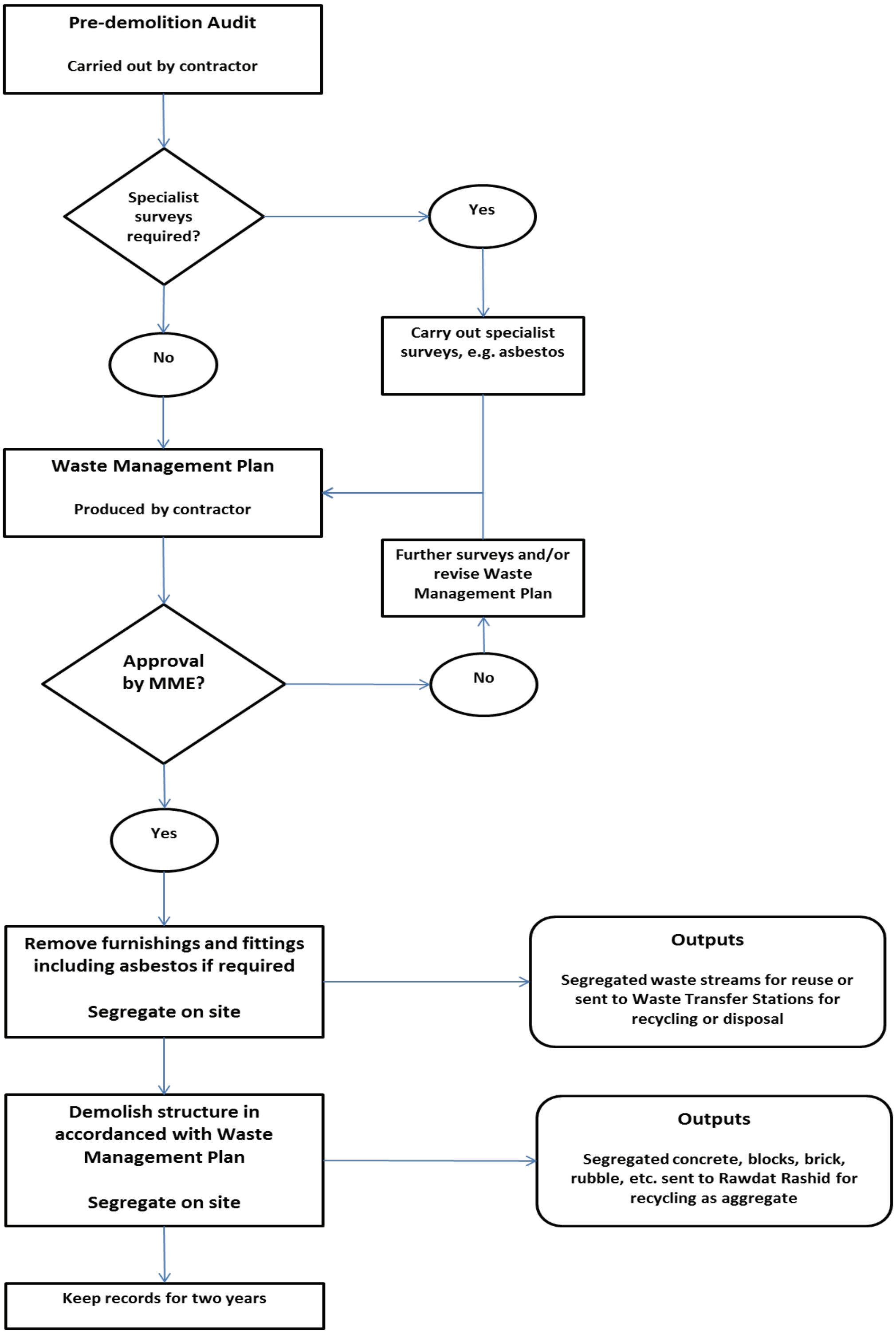

Figure 9-1 Code of practice for demolition waste

9.1.1.3 Waste Management Plan

Based on the results of the pre-demolition audit, the contractor must prepare a waste management plan showing how he intends to handle materials before and during demolition so as to minimise contamination of the materials and achieve maximum value from reuse and recycling. The plan should indicate arrangements for storage and segregation of waste on site, a programme for demolition showing the various activities and an estimate of the likely quantities of different types of waste and where they will be sent for reuse, recycling or disposal.

9.1.1.4 Demolition Process

The contractor must submit the pre-demolition audit, waste management plan and any specialist surveys that have been carried out to MME when applying for a demolition permit. MME will only issue a permit once the waste management plan has been approved. Demolition must proceed in accordance with the programme shown in the waste management plan, subject to any changes required for health and safety reasons or due to discovery of unexpected materials or structural conditions. The contractor should keep records of the quantities of different waste streams and where they were sent for processing, recycling or disposal. The records should be available for inspection at the site office during the demolition works and should be kept at the contractor’s main office for a minimum of two years after completion of the work.

9.1.1.5 MME Checks

The destinations of the various waste streams must not change from those set out in the waste management plan without approval from MME. MME should carry out spot checks on vehicles arriving at Rawdat Rashid and other waste treatment facilities to confirm that materials are being delivered to the correct destinations.

9.1.2 Washing of Recycled Aggregate

Mixed CDW materials have been accumulated in Rawdat Rashid landfill site for many years. The materials are contaminated with dust and foreign materials that limit their utilisation in construction. Current practice of processing mixed CDW materials includes the use of air blowers for the removal of lightweight materials. As addressed by the QPMC team, the air blowing system does not removal all lightweight materials and therefore may impact on the uptake and use of material. With the long-term agreement set with the MME, QPMC are planning to invest in washing facilities to further reduce the dust and lightweight impurities in the final product.

Washing of mixed CDW, if done properly, will effectively remove the dust and lightweight materials and increase the recovery rate from waste. While the washing will add to the cost of processing, it will also increase the uptake of recycled materials in construction and prevent the unnecessary disposal of a useful material in landfill facilities. Washing of aggregate is not new to Qatar and is currently used for the processing of concrete sand for the removal of harmful clayey particles and the reduction of gypsum or sulfate content. The washing could be conducted in a cheap and effective way, as reported in section 8.3, based on the utilisation of TSE water as an alternative to potable water. This is in line with the government strategy for the efficient use of natural resources, and the NDS-2 encouragement to the wider use of TSE in various projects in order to minimise its disposal.

Considering the diminishing sand deposits in Qatar, washing of fine recycled aggregate could improve the supply of concrete sand. The remaining sand deposits in Qatar tend to contain high levels of sulfate content that may impact on the properties of concrete. Recycled materials of fine aggregates can be blended with natural sand with the aim of improving the grading of fine aggregate, reducing the overall sulfate content of fine aggregate, and enhancing the durability performance of resultant concrete.

9.1.3 Processed Wadi gravel

Wadi gravel is a local aggregate in Qatar that could contribute to enhanced sustainability by replacing expensive imported gabbro. Successful case studies are presented in this document on the potential replacement of 100% gabbro in structural concrete, section 5.2, and pipe bedding applications, section 7.3. However, the material needs to be processed before use to reduce sulfate content to acceptable levels to meet the required specifications.

It is important to stress that if Wadi gravel is used as aggregate in concrete or pipe bedding, it must be produced under a quality control system that ensures it is subject to rigorous processing to remove the gypsum-bound material and reduce the sulfate content to acceptable levels. If excessive quantities of gypsum-bound deposits are included in the concrete, the resulting expansive reactions will result in poor quality concrete, which will deteriorate rapidly and bring the material into disrepute. Similarly, Wadi gravel with low sulfate content is required for pipe bedding, especially within the aggressive ground conditions in Qatar, to minimise the risk of corrosion to adjacent pipes.

Wadi gravel is generated as a by-product of the sand washing plants and is currently available for sale as processed and unprocessed aggregate. The cost of processed Wadi gravel is higher than that of unprocessed material. It is strongly recommended that the use of unprocessed Wadi gravel in construction is banned by the government to avoid any damage to infrastructure. Similar to construction waste, Wadi gravel aggregate should be collected and managed by a single supplier who should process the material to the required specification before sale. The added cost of processed Wadi gravel is compensated by the improved quality, and the cost is still lower than imported gabbro, as shown in section 8.4.1.

MME is expected to lead the effective implementation of processed Wadi gravel in the construction industry, with its control over the sand and Wadi gravel deposits, and the sand washing plants in Qatar. An example of the effective processing of Wadi gravel is demonstrated by the Qatar Sand Treatment Plant (QSTP), who successfully implemented the procedure described in section 3.4 using existing facilities, and successfully produced quality aggregate for use in structural concrete and pipe bedding applications.

9.1.4 Quality Audits

One of the main factors controlling the uptake of recycled materials is quality, especially with the general perception that recycled aggregates are of inferior quality and higher variability than primary aggregates. Recycled aggregates possess varying properties to primary aggregate, which could influence their use and performance in the final product. For example, RCA are covered with a porous layer of mortar that increase its porosity and affect the required water content in concrete. Similarly, RAP aggregate is coated with a layer of bitumen that can increase the binder content in the asphalt mixture and hence requires further consideration at the mix design stage.

A practical evidence is presented in the case studies reported in this document that when recycled aggregates are properly processed and used in the appropriate construction application, they should give performance at least similar to primary aggregate in asphalt, concrete and unbound applications. Considering the potentially high variability of the composition of the construction waste, there is a need to control the changes of aggregate properties within certain limits, known as tolerance. Provided the recycled aggregate is produced within the specified tolerance, the material can be widely used without adjusting the mix design to accommodate the inconsistent supply of recycled aggregate. The QCS 2014 and the Ashghal Recycling Manual (2021) provide detailed information on the required properties and tolerance of recycled aggregates for use in various applications.

It is strongly recommended to develop and implement a quality management system (QMS) for the consistent supply of recycled aggregate in Qatar. The QCS 2014 and the Ashghal Recycling Manual (2021) provide detailed information on the quality requirements, with a dedicated section in the QCS 2014 (Section 2) on Quality Assurance and Quality Control. The QMS is graphically presented in Figure 9-2. It should cover the various processes of:

- Separation of raw waste materials, preferably at source, to provide a relatively clean feedstock materials and maximise the recovery rate.
- A defined production process with required equipment and facilities to achieve the desired products.
- Methods of storage and stockpiling of the processed materials in clearly marked areas and prevented from contamination from dust and other sources.
- The criteria for evaluation of the processed products, including type and frequency of testing with regular monitoring during production.
- Procedures to implement changes, based on screening testing and monitoring, to achieve the desired properties.
- Finally, the QMS should also cover non-conformity of products, with records on causes and implemented actions implemented to prevent reoccurrence.

Recycled aggregates should not be classed as ready for sale until they have been tested and shown to be compliant with the relevant construction applications. Test results for each product should be made available for contractors on request together with history of production data to assess the variability of production with time. Regular checks and tests should be carried out during production and of the end product to ensure quality and a consistent supply of aggregate. The Ashghal Recycling Manual (2021) provides clear guidance on the production, type of tests, and frequency of testing for the main type of recycled aggregate covered in this document.

Figure 9-2 QMS for recycled aggregate

9.2 Benefits of Recycling

The construction industry is always focused on new opportunities to give competing companies an advantage and make them more efficient. With the shortage of quality aggregate in Qatar and the government interest of reducing reliance on imports, the development of a local market for recycled aggregates provides an opportunity for reducing the cost of construction with added benefits of being green and sustainable. QPMC announced lower cost for recycled aggregate, compared to imported aggregate as given in Table 8-17. However, the cost benefits associated with the use of recycled aggregate are not yet fully recognised. Based on the outcomes of the performance of recycled aggregate in various construction applications, the following recommendations are made to maximise the cost and other benefits associated with recycling in the construction industry.

9.2.1 More Recycling Lower Cost

As discussed in section 8.4, with the wider use of recycled and alternative aggregates the cost of construction products is likely to become cheaper with time, as more recycling will result in lower costs. The long-term agreement set between MME and QPMC in January 2020 has enabled regulating the prices of recycled aggregate. The recycling agreement is relatively new, but based on the projected high production QPMC offered low prices of recycled aggregate of up to 74 % cheaper than imported gabbro. As the use of recycled aggregate in construction projects is still relatively low, it is expected with more use of recycling that both contractors and clients can realise the cost benefits of recycling. The sustainable supply of recycled aggregate promised by QPMC, and preferably certified by Ashghal, should provide assurance for the construction industry for more use of recycled aggregates. The main action will be on the contractors to revise and improve their rates based on the reduced prices of recycled aggregate.

The availability of regulated recycled aggregates highlights opportunities for contractors to work intelligently on achieving the government target of 20 % recycling and be more cost-effective in delivering their construction projects. Contractors are more likely to use locally available materials, compared to imports, differentiate themselves with lower costs and greater sustainability, and therefore potentially increase their scores in tender opportunities.

It is expected that the procurement of government construction contracts, such as Ashghal projects, will focus more on the principles of value engineering and sustainability. The aim is to develop and maintain the infrastructure at reduced environmental impact throughout its life cycle. Ashghal is currently encouraging their contractors to implement recycling in new construction and maintenance projects to meet the government target of 20 %, and contractors will be recognised for implementing recycling.

9.2.2 Other Benefits

The accumulation of waste materials in landfill sites poses a threat to our environment. The case studies presented in this document provide confidence in the conversion of waste materials into high-value aggregate products. In addition to cost savings, other benefits that could be achieved form recycling include:

- Efficient use of resources: The wider use of recycled aggregate will reduce the accumulation of waste in landfill sites and minimise the use of natural aggregate, in line with the government strategy. The use of TSE as an alternative to potable water in construction provides another example of efficient use of resources.
- Reduce reliance on imports: Qatar relies heavily on imported gabbro, and the development of a local market of recycled aggregate will improve the aggregate supply to fuel ongoing infrastructure projects, with a first-hand control on quality production.
- Protection of the environment: The use of recycled aggregate represents a potential saving of up to 71 % in carbon footprint, and up to 80 % in water footprint, when compared to imported aggregates. Energy and water are the main environmental factors considered by the government for protecting the environment and coping with the global warming and scarcity of water to achieve sustainable development.
- Social benefits: The PPP investment for developing a local market of recycled aggregate in Qatar creates new business opportunities and allows the private sector to participate in government projects. Such investment supports the government strategy of diversifying the production base in promising infrastructure projects.

The wider use of recycled aggregates will therefore provide many benefits to Qatar, including protection of the environment, productive use of materials that would otherwise be waste, reduction of imports of natural aggregates, cost savings, new business opportunities and reduction in generation of greenhouse gases.

9.3 Training and development

Training and development programmes are essential to ensure appropriate processing of recycled materials and utilisation in various construction applications to achieve the government recycling target of 20% by 2022. Training can be delivered in a number of ways, and the approach adopted during the delivery of this project was to tailor for specific audiences of senior managers, users of recycled aggregate and producers of recycled aggregates. This approach was found useful in making the required changes in the construction industry in terms of decision making and implementation in projects, and quality of recycled products. The same approach is recommended for the wider implementation of recycled aggregate in construction projects. Detailed of the 3 level training courses are given below.

9.3.1 Senior Managers – Decision Makers

The training course is a short session of a high level briefing aimed at decision makers who need to be informed of the government strategic decisions and recycling target, and the benefits that could be achieved from recycling. The actions required for the effective implementation of recycled aggregates in construction projects in terms of contractual issues and enforcement of recycled aggregate should be also addressed for their considerations. An example is the training course delivered to the MME Project Management & Development Department on 27th December 2020 for the effective implementation of recycling in MME projects.

9.3.2 Users of Recycled Aggregates

This training course is aimed at contractors, producers of construction products made with recycled aggregates, consulting engineers in design and supervision organisations, and clients. The training programme should include presentations of the type of recycled and alternative aggregates and their permitted applications in construction, successful case studies, site visits, and group discussions. The training should be interactive for delegates to understand how to assess whether the recycled aggregate is suitable for a specific application and how to apply in practice. Quality is essential if recycled aggregates are to perform satisfactorily, so delegates should be aware of the main criteria to look for when viewing the aggregate properties and how to interpret test results for particular applications. An example of the training course delivered to the users of recycled aggregate is the workshop held on 9th December 2020, Figure 9-3, as part of the project dissemination.

9.3.3 Producers of Recycled Aggregates

The only current producer of recycled aggregates in Qatar is QPMC, through their long-term agreement with the MME for managing the production of recycled aggregates at Rawdat

Rashid landfill site. QPMC is also managing the production of recycled aggregate at the Ashghal recycling sites. QPMC is working in partnership with private industry on processing the construction waste materials to develop recycled aggregate products, and already appointed an independent test house for assessing the quality of recycled aggregate products. Due to the large quantities of mixed CDW materials at Rawdat Rashid landfill site, the material will need a multi-stage process for processing into suitable materials for use in general fill and subbase applications. Similarly, the Wadi gravel aggregate generated as oversize material from the sand washing plants will require intensive multistage treatment to produce a complaint aggregate for use as coarse aggregate in concrete (refer to section 3.4, Figure 3-11).

MME organises recycling workshop

QNA
Doha

The Ministry of Municipality and Environment's scientific research team organised a workshop yesterday on the use of recycled stones in buildings, roads and the manufacture of construction materials.

The workshop aimed to enhance the integration of efforts around the application of scientific research results related to the utilisation of construction waste in Rawdat Rashid, which is estimated at more than 40mn tonnes, and to convert it into recycled stones and sands for use in building projects, roads and the manufacture of construction materials.

The workshop also focused on technical and scientific methods to use waste in construction, while presenting the approved national and international technical specifications, field and laboratory experiments, and discussing the related technical issues.

The workshop was attended by officials and specialists from the Ministry, the infrastructure research centre, Qatar Primary Materials Co (QPMC), Qatar National Research Fund (QNRF), Public Works Authority (Ashghal) and a group of related contractors and consultants.

Assistant Undersecretary and Director of the Environmental and Municipal Studies Institute at the Ministry of Municipality and Environment Eng Mohamed bin Saif al-Kuwari confirmed that the workshop focused on the use of recycled materials such as stones, sand, etc., which are located in Rawdat Rashid, in construction industries such as bricks, interlocks, tiles, concrete units, etc.

Al-Kuwari added that it was agreed during the workshop that there would be future bilateral or group meetings between companies specialised in recycling construction waste and converting them into stones and sand and the scientific research team, expressing the team's full readiness to provide scientific and technical advice to any company working in this field, and to organise training courses on how to use these stones, in buildings, roads and infrastructure.

He pointed out that the scientific research team presented to the companies during this workshop a summary of the experiences and technical expertise obtained since its inception, by showing a presentation related to the recycling of construction waste with an indication of the strength and quality of the test rooms and the test method that was carried out five years ago and these facilities are still It is characterised by high quality, strength and durability with time.

He also said that the ministry was seeking to exert efforts and co-operate with the private sector in order to exchange experiences in this field, as well as the ministry's keenness to promote scientific research in a way that serves Qatar National Vision 2030.

Eng Mohamed bin Saif al-Kuwari

The workshop also focused on technical and scientific methods to use waste in construction.

Figure 9-3 MME workshop to users of recycled aggregates (Gulf Times, 2020)

The training for the producers should be aimed at plant managers and other managers responsible for the quality aspects of the operations to ensure recycled aggregates are produced to the desired specification.

It is recommended that the above training programme, tailored to different audiences, is delivered on a regular basis to ensure continuous and wider implementation of recycled aggregates in construction projects. The training should be provided by the MME, Ashghal and leading experts in the recycling industry for effective delivery of the different courses. It is suggested that a certification system should be awarded at the end of the training course, and subject to the successful completion of an assessment exercise at the end of each training course. The certificate can be valid for up to 2 years and issued jointly by the MME and Ashghal on the successful completion of the various training courses on the strategy, uses, and production of recycled aggregate in construction. The certification system will motivate practicing engineers and help them to climb the professional ladder in recycling and encourage continuous education and development of the construction industry.

In addition to the training tailored for specific audiences, the MME issued a number of press releases during the course of the project to raise awareness of the public. Examples of the press releases are shown in Figure 9-4 and Figure 9-5. Further dissemination of the recycling work is strongly recommended for wider implementation.

ابتكرها فريق علمي بتمويل من الصندوق القطري للبحث العلمي

تقنيات هندسية جديدة لتقليل تكلفة المشاريع

استخدام أحجار الوادي بديلاً للجابرو في الإنشاءات

تغليف مواسير الصرف بأحجار الوادي في مشروع بأم صلاك

نتائج إيجابية لإعادة استخدام الأسفلت وتدويره في 5 مناطق

الدوحة -الراية: نجح فريق بحثي هندسي في استخدام أحجار الوادي الناتجة من عملية غسل الرمل في مشروعات البناء والطرق والصناعات الإنشائية كبديل مناسب لأحجار الجابرو، بالإضافة إلى استخدام الأسفلت المعاد تدويره في مشاريع الطرق، ما سيكون له مردود إيجابي على الاقتصاد والبيئة من خلال تعزيز أطر الاستدامة البيئية وتقليل تكلفة المشاريع، وذلك بتمويل من الصندوق القطري لرعاية البحث العلمي، وبالتعاون بين وزارة البلدية والبيئة وهيئة الأشغال العامة «أشغال» وخبراء واستشاريين عالميين.

كان الصندوق القطري لرعاية البحث العلمي منح الإجازة العلمية والتمويل لفريق البحث العلمي التطبيقي المكون من الدكتور مهندس محمد بن سيف الكواري ممثل وزارة البلدية والبيئة والدكتور خالد حسن المدير العام لمركز أبحاث البنية التحتية بواحة العلوم والتكنولوجيا - قطر والدكتور البروفيسور أيان سميز الخبير والاستشاري العالمي في مجال الجيولوجيا والهندسة - المملكة المتحدة والدكتور ميري ريد الخبير والاستشاري الهندسي - المملكة المتحدة، وبالتعاون مع هيئة الأشغال العامة «أشغال»، لإجراء بحث علمي هندسي حول تدوير المخلفات الإنشائية واستغلال بعض المواد الطبيعية الاستغلال الأمثل وتطبيقها في بعض المشاريع الهندسية.

ركز البحث العلمي على استخدام النظريات العلمية والفنية والتقنيات الحديثة والوسائل المتطورة في مجال إعادة تدوير المواد الإنشائية في المباني والطرق، واستغلال المواد الطبيعة الاستغلال الأمثل بعد معالجتها، وبالتالي استخدامها في المباني والطرق والصناعات الإنشائية.

وقام فريق البحث العلمي بالتفكير حول استخدام أحجار الوادي، الناتجة من عملية غسل الرمل، في بعض المشاريع الهندسية الخاصة بالمباني والإنشاءات والطرق، حيث إن هذه الأحجار موجودة في ترسبات الوديان بمناطق جنوب قطر، خاصة في مناطق الخرج والخرارة ومكينس والذي يوجد بها لوحدها ما يقارب من 4.5 مليون طن ، وهي المناطق التي يتم استخراج الرمل المغسول منها، حيث إن هذه الأحجار تمتاز بأنها على درجة عالية من الصلابة والقوة والمتانة، وأثبتت الدراسات إمكانية استخدامها بصورة كبيرة في مشروعات البناء والطرق.

د. محمد سيف الكواري

د. خالد حسن

كما قام فريق البحث العلمي بفحص وتحليل هذه الأحجار فيزيائياً وكيميائياً وميكانيكياً في مختبرات متخصصة في بريطانيا بالإضافة إلى إدارة الطرق ومختبر المواد بمركز أشغال للبحث والتطوير التابع لإدارة الجودة والسلامة، حيث أثبتت التحاليل والاختبارات أن هذه الأحجار تمتاز بقوة ومتانة عالية، وتصلح لاستخدامها في المباني والطرق والصناعات الإنشائية، وهي تشابه أحجار البازلت والجابرو والأحجار الدلوميتية في خصائصها وقوتها، ولكنها تحتاج لإزالة المواد الجبسية وأملاح الكبريتات العالقة بها من التربة وكذلك المواد الطينية، ومن ثم تكسيرها في الكسارات وفق التدرج والأحجام المطلوبة في المواصفات المعتمدة، وبالتالي يمكن استغلالها في أعمال الخرسانة بخلطها مع الجابرو بنسب متساوية، أي بنسبة 50 ٪.

كما لاحظ الفريق توفر كميات كبيرة واقتصادية من هذه الأحجار في مصانع غسل الرمال، وهي ستكون بديلاً مناسبًا لأحجار الجابرو، ما سيكون له مردود إيجابي على الاقتصاد والبيئة.

ونظرًا لأهمية البحث العلمي في خدمة المشاريع الإنشائية، تعاون الفريق العلمي مع إدارة الطرق بهيئة الأشغال العامة من خلال استخدام أحجار الوادي في بعض المشاريع الهندسية، وبالتالي تم استخدام كميات من أحجار الوادي بدلًا من أحجار الجابرو المستوردة والمكلفة اقتصاديًا وذات التأثيرات البيئية، بكميات تقدر بـ 27 طنًا لتغليف مواسير الصرف الصحي في أحد مشاريع البنية التحتية بمدينة أم صلال، وأوضحت النتائج المخبرية قوة هذه الأحجار ومطابقتها للمواصفات والاشتراطات والمعايير المعتمدة، وذلك بعد مرور 18 شهراً من الخدمة.

من ناحية أخرى شارك الفريق العلمي الخبراء والاستشاريين بهيئة الأشغال العامة أثناء الدراسات العلمية الحقلية حول تطبيق استخدام الإسفلت المعاد تدويره في مشاريع أشغال، وهي تقنية تعتمد على تكسير وخلط ورصف ودمك الطبقات الإسفلتية المتواجدة مع طبقات جديدة، مع تعويض نسبة البيوتومين المفقود منها نتيجة العوامل الجوية، بحيث سيكون للطبقات الجديدة خصائص أفضل من تلك القديمة في بعض الحالات، وذلك وفق المواصفات المتبعة وبما يحقق الجودة والقوة لها، وبالتالي فإن ذلك سوف يساهم في المحافظة على موارد الدولة الطبيعية من خلال توفير كميات كبيرة من البيوتومين والأحجار، من أجل تعزيز أطر الاستدامة البيئية وتقليل تكلفة المشاريع.

ومن المتوقع أن يكون لمشروع إعادة استخدام الأسفلت وتدويره نتائج إيجابية على الاقتصاد والبيئة، حيث تتمثل في إعادة استخدام المواد بنسبة 100٪ من مواد الطريق، كما سوف تساهم هذه الطريقة في تسريع مدة إنجاز المشروع التي تستغرقها عمليات إنشاء أو صيانة الطرق العادية، لذلك شارك الفريق في دراسة وتحليل النتائج وفحص عينات من التقنية الجديدة لتدوير الأسفلت التي تم تنفيذها في 5 مواقع في قطر وهي منطقة الوكرة والمطار القديم وأزغوي وأم صلال وغيرها، حيث ظهرت جميع النتائج إيجابية ومشجعة لاستخدام هذه التقنية الحديثة والمبتكرة.

وأعرب فريق البحث عن فخره بهذا الإنجاز العلمي الذي يخدم السياسة العامة للدولة المبنية على تحقيق الاستدامة البيئية واستغلال الموارد الطبيعية الاستغلال الأمثل، بما ينعكس إيجابا على كفاءة المشاريع الهندسية من خلال توفير الوقت والجهد والمال، وبما يحقق رؤية قطر 2030 واستراتيجية التنمية الوطنية 2018 – 2022.

Figure 9-4 MME Press Release of the benefits of recycled aggregates (Raya, 2020)

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تقارير

استغلال المواد الطبيعية في المشاريع الهندسية.. فريق علمي قطري:

أحجار الوديان تصلح لمشروعات البناء والإنشاءات والطرق

صلاح بديوي

نجح فريق علمي قطري برئاسة الدكتور المهندس محمد بن سيف الكواري مدير مركز الدراسات البيئية والبلدية وممثل وزارة البلدية والبيئة بالفريق في إجراء بحث علمي هندسي حول تدوير المخلفات الإنشائية واستغلال بعض المواد الطبيعية الاستغلال الأمثل وتطبيقها في بعض المشاريع الهندسية. ومنح الصندوق القطري لرعاية البحث العلمي QNRF بمؤسسة قطر في عام 2018، الإجازة العلمية والتمويل للفريق والذي يضم إلى جانب رئيسه كلا من الدكتور خالد حسن المدير العام لمركز أبحاث البنية التحتية بواحة العلوم والتكنولوجيا، والدكتور البروفيسور أيان سميز Dr Ian Sims الخبير والاستشاري العالمي في مجال الجيولوجيا والهندسة - المملكة المتحدة بريطانيا، والدكتور ميري ريد Dr Murray Reid الخبير والاستشاري الهندسي - المملكة المتحدة بريطانيا، وبالتعاون مع هيئة الأشغال العامة (أشغال).

تدوير المواد الإنشائية

ووفق ما أعلنته البلدية والبيئة، يركز البحث العلمي على استخدام النظريات العلمية والفنية والتقنيات الحديثة والوسائل المتطورة في مجال إعادة تدوير المواد الإنشائية في المباني والطرق، واستغلال المواد الطبيعية الاستغلال الأمثل بعد معالجتها، وبالتالي استخدامها في المباني والطرق والصناعات الإنشائية.

ووفق خطة العمل، من هذا المنطلق فقد قام فريق البحث العلمي بالتفكير حول استخدام أحجار الوادي، الناتجة من عملية غسيل الرمل، في بعض المشاريع الهندسية الخاصة بالمباني والإنشاءات والطرق، حيث إن هذه الأحجار موجودة في ترسبات الوديان بمناطق جنوب قطر خاصة في مناطق الخرج والخرارة ومكينس والذي يوجد بها لوحدها ما يقارب 4,5 مليون طن، وهي المناطق التي يتم استخراج الرمل المغسول منها، حيث إن هذه الأحجار تمتاز بأنها على درجة عالية من الصلابة والقوة والمتانة، وقد أثبتت الدراسات إمكانية استخدامها بصورة كبيرة في مشروعات البناء والطرق.

ويؤكد الخبراء أن فريق البحث العلمي قام بفحص وتحليل هذه الأحجار فيزيائياً وكيميائياً وميكانيكياً في مختبرات متخصصة في بريطانيا بالإضافة إلى إدارة الطرق ومختبر المواد بمركز أشغال للبحث والتطوير التابع لإدارة الجودة والسلامة، حيث أثبتت هذه التحاليل والاختبارات بأن هذه الأحجار تمتاز بقوة ومتانة عالية، وتصلح لاستخدامها في المباني والطرق والصناعات الإنشائية. وتصف الدراسة الأحجار بأنها تشبه أحجار البازلت والجابرو والأحجار الدلوميتية في خصائصها وقوتها، ولكنها تحتاج إلى إزالة المواد الجبسية وأملاح الكبريتات العالقة بها من التربة وكذلك المواد الطينية ومن ثم تكسيرها في الكسارات وفق التدرج والأحجام المطلوبة في المواصفات المعتمدة، وبالتالي من الممكن استغلالها في أعمال الخرسانة بخلطها مع الجابرو بنسب متساوية أي بنسبة 50%. كما لاحظ فريق البحث العلمي توفر كميات كبيرة واقتصادية من هذه الأحجار في مصانع غسيل الرمال، وهي ستكون بديلاً مناسبا لأحجار الجابرو مما سيكون له مردود إيجابي على الاقتصاد والبيئة.

تجربة عملية بأم صلال

ومن هذا المنطلق، ونظرا لأهمية البحث العلمي في خدمة المشاريع الإنشائية يشير الفريق العلمي بأنه تعاون مع إدارة الطرق بهيئة الأشغال العامة من خلال استخدام أحجار الوادي في بعض المشاريع الهندسية، وبالتالي فقد تم استخدام كميات من أحجار الوادي بدلا من أحجار الجابرو المستوردة والمكلفة اقتصاديا وذات التأثيرات البيئية، وذلك بكميات تقدر بـ 27 طنا لتغليف مواسير الصرف الصحي في أحد مشاريع البنية التحتية بمدينة أم صلال، وأوضحت النتائج المخبرية قوة هذه الأحجار ومطابقتها للمواصفات والاشتراطات والمعايير المعتمدة، وذلك بعد مرور 18 شهراً من الخدمة.

من ناحية أخرى يوضح الفريق العلمي أنه شارك الخبراء والاستشاريين بهيئة الأشغال العامة أثناء الدراسات العلمية الحقلية حول تطبيق استخدام الإسفلت المعاد تدويره Reclaimed asphalt pavement (RAP) في مشاريع أشغال، وهي تقنية تعتمد على تكسير وخلط ورصف ودمك الطبقات الإسفلتية المتواجدة مع طبقات جديدة، مع تعويض نسبة البيوتومين المفقود منها نتيجة العوامل الجوية، بحيث سيكون للطبقات الجديدة خصائص أفضل من تلك القديمة في بعض الحالات وذلك وفق المواصفات المتبعة وبما يحقق الجودة والقوة لها.

ووفق البحث فإن ذلك سوف يساهم في المحافظة على موارد الدولة الطبيعية من خلال توفير كميات كبيرة من البيوتومين والأحجار، وذلك من أجل تعزيز أطر الاستدامة البيئية وتقليل تكلفة المشاريع.

ومن المتوقع أن يكون لمشروع إعادة استخدام الأسفلت وتدويره نتائج إيجابية على الاقتصاد والبيئة، حيث تتمثل في إعادة استخدام المواد بنسبة 100% من مواد الطريق، كما سوف تساهم هذه الطريقة في تسريع مدة إنجاز المشروع التي تستغرقها عمليات إنشاء أو صيانة الطرق العادية.

ويؤكد فريق البحث العلمي أنه شارك أشغال في دراسة وتحليل النتائج وفحص عينات من التقنية الجديدة لتدوير الأسفلت التي تم تنفيذها في خمسة مواقع في قطر وهي منطقة الوكرة والمطار القديم وأزغوى وأم صلال وغيرها، حيث ظهرت جميع النتائج إيجابية ومشجعة لاستخدام هذه التقنية الحديثة والمبتكرة.

إنجاز علمي مهم

وأعرب فريق البحث العلمي عن فخره بهذا الإنجاز العلمي الذي يخدم السياسة العامة للدولة المبنية على تحقيق الاستدامة البيئية واستغلال الموارد الطبيعية للدولة الاستغلال الأمثل بما ينعكس إيجابيا على كفاءة المشاريع الهندسية من خلال توفير الوقت والجهد والمال، وبما يحقق رؤية قطر 2030 وإستراتيجية التنمية الوطنية 2018 – 2022، وتقدم الفريق البحثي بوافر الشكر والتقدير والعرفان إلى سعادة المهندس عبدالله بن عبدالعزيز بن تركي السبيعي وزير البلدية والبيئة لتشجيعه الدائم ودعمه اللامحدود لتعزيز البحث العلمي في الوزارة، والشكر موصول للشيخ الدكتور فالح بن ناصر آل ثاني وكيل الوزارة المساعد لشؤون الزراعة والثروة السمكية والدكتور سعد بن أحمد المهندي رئيس هيئة الأشغال العامة على دعم الباحثين، وكذلك يشكر فريق البحث العلمي الصندوق القطري لرعاية البحث العلمي QNRF لاهتمامه ورعايته ودعمه للبحث العلمي والباحثين بما يخدم الوطن ويحقق الرخاء والرفاهية للمجتمع.

■ المواد المكتشفة تشبه أحجار البازلت والجابرو والأحجار الدلوميتية في خصائصها وقوتها

■ م. محمد سيف الكواري

■ د. خالد حسن

ب الأرقام

50 %
من الأحجار تخلط بنسب متساوية مع الجابرو وتستغل بأعمال خرسانية

27
طنا من المواد المكتشفة استخدمت لتغليف مواسير الصرف الصحي في مشاريع البنية التحتية

100 %
نسبة المحافظة على موارد الدولة الطبيعية من خلال توفير كميات كبيرة من البيوتومين والأحجار

5
مناطق في قطر أخذت منها عينات من التقنية الجديدة لتدوير الأسفلت

Figure 9-5 MME Press Release of the benefits of recycled aggregates (Lusail, 2020)

9.4 Future work

In the case studies described in this book, recycled and alternative aggregates were used to replace primary aggregate in various construction application. Despite the harsh exposure environment in Qatar and the region, the case studies presented provide practical evidence on the similar performance of construction products made with recycled aggregates compared to primary aggregate. Based on the project outcomes, the following topics are suggested for future work to support the wider and more efficient use of recycled aggregates in construction.

Case studies are presented in this book on the successful performance of recycle aggregates in various construction applications. However, the number of cases was limited due to the project duration. Further case studies on the performance of recycled aggregates in a range of applications are required to provide more confidence. The new case studies can extend to cover the production of recycled aggregate and main parameters to be considered in the appropriate selection of recycled aggregate in various applications. Historic data on the properties of recycled aggregate will also provide confidence for the asphalt and concrete suppliers to understand the variability of material properties and how to produce consistent mixes with recycled aggregates.

Environmental assessment of construction materials: The ability to measure the embodied impacts of aggregates and aggregate-driven products provides new tools for the environmental assessment of construction materials. The carbon and water footprint studies conducted in this project provide valuable information on the most widely used construction materials in Qatar, which could be extended to all construction materials. Such assessment will determine the optimal environmental impact with more focus on sustainability and green construction.

Continuous development is an essential requirement for the efficient use of recycled aggregate in construction. With the development of more data and experience on the performance of recycled aggregates in service, lessons will be learnt on the appropriate selection of recycled aggregates in a range of applications with increased confidence in their use. Training and dissemination will be required to ensure that all parts of the construction industry are aware of the possibilities of using recycled aggregates. Continued monitoring of the case studies considered in this book up to 10 years in service would provide reassurance on the durability of materials within the harsh exposure conditions in Qatar and the region.

10 References

AASHTO T283 (2014). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. American Association of State Highway and Transportation Officials (AASHTO), USA.

AASHTO T324 (2019). Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. American Association of State Highway and Transportation Officials (AASHTO), USA.

AASHTO T315 (2019). Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR). American Association of State Highway and Transportation Officials (AASHTO), USA.

Ahmedzade P, and Sengoz B (2015). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. Journal of Hazardous Materials 165 (1-3) pp.300-305. https://doi.org/10.1016/j.jhazmat.2008.09.105.

Airey GD, Collop AC, Thom NH (2014). Mechanical performance of asphalt mixtures incorporating slag and glass secondary aggregates. 8th Int. Conf. on Asphalt Pavements for Southern Africa pp.243-255.

Alhaj, M., Mohammed, S., Darwish, M., Hassan, A. and Al-Ghamdi, S.G. (2017). A review of Qatar's water resources, consumption and virtual water trade. Desalination and Water Treatment 70 pp.70–85.

Al-Saad H, Nasir S, Sadooni F and Al-Sharhan A (2002). Stratigraphy and Sedimentology of the Hofuf Formation in the State of Qatar, in relation to the tectonic evolution of the Eastern Arabian Block. Neues Jahrbuch fuer Geologie und Palaeontologie Abhandlung 7,426-448 (Schweizerbart, Stuttgart).

Ashghal (2018). Ashghal Recycling Initiatives – Roadmap. Public Works Authority, Ashghal, Doha, Qatar.

Ashghal (2021). Ashghal Recycling Manual. Ashghal Centre for Research & Development, Public Works Authority – Ashghal, Doha, Qatar.

Ashghal Memorandum (2016). Test for carbonate rocks and revision of drawings. Issued by the Ashghal Drainage Networks and Design Department on 16/04/2016. Doha, Qatar.

Ashghal Memorandum (2018). QA000 – Drainage works – Backfill gabbro. Issued by the Ashghal Drainage Networks and Design Department on 14/06/2018. Doha, Qatar.

Asphalt Institute (2014). MS-2 Asphalt Mix Design Methods. 7th Edition. Asphalt Institute, USA. ISBN: 9781934154700.

ASTM C1202 (2012). Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. ASTM International, USA.

ASTM C123 (2014). Standard Test Method for Lightweight Particles in Aggregate. ASTM International, USA.

ASTM C1231 / C1231M (2015). Standard practice for use of unbonded caps in determination of compressive strength of hardened cylindrical concrete specimens. ASTM International, USA.

ASTM C127 (2015). Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. ASTM International, USA.

ASTM C131/C131M (2014). Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. ASTM International, USA.

ASTM C142 (2017). Standard Test Method for Clay Lumps and Friable Particles in Aggregates. ASTM International, USA.

ASTM C88 (2013). Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate. ASTM International, USA.

ASTM D113 (2017). Standard Test Method for Ductility of Asphalt Materials. ASTM International, USA.

ASTM D1883 (2016). Standard test method for California Bearing Ratio (CBR) of laboratory-compacted soils. ASTM International, USA.

ASTM D2041 (2019). Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures. ASTM International, USA.

ASTM D2172 (2017). Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures. ASTM International, USA.

ASTM D2419 (2014). Standard test method for sand equivalent value of soils and fine aggregate. ASTM International, USA.

ASTM D2726 (2017). Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Asphalt Mixtures. ASTM International, USA.

ASTM D2872 (2019). Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test). ASTM International, USA.

ASTM D36 (2014). Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus). ASTM International, USA.

ASTM D4318 (2017). Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, USA.

ASTM D4373 (2014). Standard Test Method for Rapid Determination of Carbonate Content of Soils. ASTM International, USA.

ASTM D4867 (2014). Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures. ASTM International, USA.

ASTM D5 (2013). Standard Test Method for Penetration of Bituminous Materials. ASTM International, USA.

ASTM D5404 (2017). Standard Practice for Recovery of Asphalt from solution using the Rotary Evaporator. ASTM International, USA.

ASTM D5444 (2015). Standard Test Method for Mechanical Size Analysis of Extracted Aggregate. ASTM International, USA.

ASTM D6927 (2015). Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures. ASTM International, USA.

ASTM E2583 – 07 (2015). Standard test method for measuring deflections with a light weight deflectometer (LWD). ASTM International, USA.

Autelitano F and Giuliani F (2015). Swelling behaviour of electric arc furnace aggregates for unbound granular mixtures in road construction. International Journal of Pavement Research and Technology, 8(2), 103-111. https://doi.org/10.6135/ijprt.org.tw/2015.8(2).103.

BEIS (2019). Greenhouse gas reporting: conversion factors 2019. Department for Business, Energy & Industrial Strategy. Website: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019.

BRE Digest 330 (2004). Alkali-silica reaction in concrete. Building Research Establishment, Watford, UK.

BS 1377-3 (1990). Methods of test for soils for civil engineering purposes. Chemical and electro-chemical testing. BSI, London, UK.

BS 1881-122 (2011). Testing concrete. Method for determination of water absorption. BSI, London, UK.

BS 6073-2 (2008). Precast concrete masonry units. Guide for specifying precast concrete masonry units. BSI, London, UK.

BS 812-104 (1994). Testing aggregates. Method for qualitative and quantitative petrographic examination of aggregates. BSI, London, UK.

BS 812-123 (1999). Method for determination of alkali-silica reactivity – Concrete prism method. BSI, London, UK.

BS EN 1008 (2002). Mixing water for concrete - Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete. BSI, London, UK.

BS EN 1097-1 (2011). Tests for mechanical and physical properties of aggregates. Determination of the resistance to wear (micro-Deval). BSI, London, UK.

BS EN 12350-2 2009. Testing Fresh Concrete: Slump-test. BS, London, UK.

BS EN 12390-3 (2009). Testing hardened concrete. Compressive strength of test specimens. BSI, London, UK.

BS EN 12504-1 (2009). Testing concrete in structures. Cored specimens. Taking, examining and testing in compression. BSI, London, UK.

BS EN 13286-51 (2004). Unbound and hydraulically bound mixtures. Method for the manufacture of test specimens of hydraulically bound mixtures using vibrating hammer compaction. British Standards Institution, London, UK.

BS EN 1744-1 (2012). Tests for chemical properties of aggregates. Chemical analysis. British Standards Institution, London, UK.

BS EN 197-1 (2011). Cement. Composition, specifications and conformity criteria for common cements. BSI, London, UK.

BS EN 1997-2 (2007). Eurocode 7. Geotechnical design. Ground investigation and testing. British Standards Institution, London, UK.

BS EN 933-11 (2009). Tests for geometrical properties of aggregates. Classification test for the constituents of coarse recycled aggregate as of recycled aggregate. BSI, London, UK.

BS EN 933-7 (1998). Tests for geometrical properties of aggregates. Determination of shell content. Percentage of shells in coarse aggregates. British Standards Institution, London, UK.

Cavelier C, Sallatt A and Heuze Y (1970). Geological description of the Qatar Peninsula (explanation of the 1/100,000 geological maps of Qatar). Bureau de recherches geologiques et minieres, Government of Qatar, Department of Petroleum Affairs. 46 pages et cartes.

CML (1997). 1-97: Standard method of test for the 10 minute rotational test for aggregate – Immersion Rotational Test. Central Materials Laboratory, Ministry of Municipal Affairs & Agriculture, currently called Ministry of Municipality & Environment, State of Qatar.

CML (1997). 9-97: Standard method of test for determination of water absorption of precast concrete paving blocks. CML Test Method. Central Materials Laboratory, Ministry of Municipal Affairs and Agriculture, Qatar.

Collins, F. G. (2010). Inclusion of carbonation during the life cycle of built and recycled concrete. Influence on their carbon footprint, International Journal of Life Cycle Assessment, 15(6), pp.549-556.

Coomarasamy A, Walzak TL (1995). Effects of moisture on surface chemistry of steel slags and steel slag-asphalt paving mixes. Transportation Research Record 1492 (995) 85-95. http://onlinepubs.trb.org/Onlinepubs/trr/1995/1492/1492-010.pdf.

Cripps J C, Reid J M, Czerewko M A and Longworth I (2019). Tackling problems in civil engineering caused by the presence of pyrite. Quarterly Journal of Engineering Geology and Hydrogeology, Vol 52, pp 481-500.

EFCA (2015) Environmental Product Declaration: Plasticisers and superplasticisers. European Federation of Concrete Admixtures Associations Ltd. Website: http://www.efca.info/efca-publications/environmental/.

EPA (2019). Energy Recovery from the Combustion of Municipal Solid Waste (MSW). United Stated Environmental Protection Agency. Available on (https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw).

Eurobitume (2011). The Eurobitume life-cycle inventory for bitumen. Version 2.

Eurobitume (2020). The Eurobitume life-cycle inventory for bitumen. Version 3. Available at: www.eurobitume.eu.

FEHRL (2009). ELLPAG Phase 2: A guide to the use of long-life semi-rigid pavements. Forum of European National Highway Research Laboratories, FEHRL Report 2009/001, Brussels (ISSN 1362-6019).

FHWA (2016). User Guidelines for Waste and Byproduct Materials in Pavement Construction: Reclaimed Asphalt Pavement. Federal Highway Administration published report. Available on (https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/97148/049.cfm).

FHWA (2016a). User Guidelines for Waste and Byproduct Materials in Pavement Construction: Steel Slag. Federal Highway Administration published report.

Fookes PG and Higginbottom IE (1980). Some problems of construction aggregates in desert areas, with particular reference to the Arabian Peninsula. 1. Occurrence and special characteristics. Proc. Ins. Civ. Eng. Part 1, 68, 39-67.

Fookes PG and Lee EM (2019). The engineering geology of concrete in hot drylands. Quarterly Journal of Engineering Geology and Hydrogeology, 52, 257–279, https://doi.org/10.1144/qjegh2018-185.

Gagg C (2014. Cement and concrete as an engineering material: An historic appraisal and case study analysis. Engineering Failure Analysis. Vol. 40, 114-140. https://doi.org/10.1016/j.engfailanal.2014.02.004.

Gerbens-Leenes, P.W., A.Y.Hoekstra, A.Y. and Bosman, R. (2018). The blue and grey water footprint of construction materials: Steel, cement and glass. Water resources and industry, 19, pp.1-12.

GSDP (2008). Qatar National Vision 2030. Published by the General Secretariat for Development Planning, currently the Planning and Statistics Authority, Doha, Qatar.

GSO 2489 (2015). Specifications of Recycled Aggregates from Construction Waste to be used in Construction Work. GSO Standardization Organisation, Riyadh, Kingdom of Saudi Arabia.

GSDP (2011). Qatar National Development Strategy. Published by the General Secretariat for Development Planning, currently the Planning and Statistics Authority, Doha, Qatar.

Hassan K E, Nicholls J C, Harding H M and Nunn, M E (2008). Durability of continuously reinforced concrete surfaced with asphalt. TRL Report 666; TRL Ltd, UK.

Hassan K E, Reid J M and Al-Kuwari M S (2016) Recycled Aggregate in Construction – Qatar Experience. Ministry of Municipality and Environment, Doha, Qatar.

Hassan KE, Al-Kuwari MS, and MS Reid (2014). Site trials of recycled and secondary aggregate in concrete and concrete blocks in Qatar. The International Journal of Pavement Engineering and Asphalt Technology (PEAT). ISSN 1464-8164. Vol. 15, Issue 2, pp.37-53.

Hassan KE, Al-Kuwari MS, Reid JM (2020a). Field performance of recycled and alternative aggregate in concrete. The International Journal of Pavement Engineering and Asphalt Technology (PEAT) ISSN 1464-8164, 21, 174-190.

Hassan KE, Al-Kuwari MS, Reid JM, Berhane A, Collis C (2013). Developing the use of recycled and secondary aggregate in Qatar. The International Journal of Pavement Engineering and Asphalt Technology (PEAT) ISSN 1464-8164. Vol. 14, Issue 1, pp. 24-46.

Hassan KE, Attia MIE, Reid JM, Al-Kuwari MS (2021). Performance of steel slag aggregate in asphalt mixtures in a hot desert climate. Case Studies in Construction Materials, Volume 14, June 2021, e00534. https://doi.org/10.1016/j.cscm.2021.e00534.

Hassan KE, Brooks JJ and Erdman M (2000). The use of reclaimed asphalt pavement (RAP) aggregates in concrete. Proceedings of the International Conference "Waste Materials in Construction", WASCON 2000, Harrogate-UK, ISBN: 0-08-043790-7, 121-128. https://doi.org/10.1016/S0713-2743(00)80024-0.

Hassan KE, Elghali L and Sowerby CR (2004) Development of new materials for secondary and recycled aggregates in highway infrastructure. TRL Report 598. TRL Ltd, Corwthorne, UK.

Hassan KE, El-Hussain O, Al-Kuwari MS, Al-Emadi K (2020c). Development and Performance of Cement Bound Materials in Road Pavements. Proceedings of the International Conference on Civil Infrastructure and Construction (CIC 2020). http://dx.doi.org/10.29117/cic.2020.0069.

Hassan KE, Reid JM and Al-Kuwari MS (2015). Use of recycled and secondary aggregates in Qatar – Guidance document. TRL Published Project Report PPR736. TRL Limited, Wokingham, UK.

Hassan KE, Reid JM and Al-Kuwari MS (2016). Recycled aggregates in construction – Qatar experience. Published by the Ministry of Municipality and Environment, Doha, Qatar.

Hassan KE, Reid JM, Sims I, Al-Kuwari MS, Attia M, Sediq A and Al-Naemi A (2020b). Wadi gravel – a new concrete aggregate in Qatar: Part 1 – investigation, processing and trials. Quarterly Journal of Engineering Geology and Hydrogeology. Vol. 53 (3), 386–399. DOI: 10.1144/qjegh2019-086.

Hassan KH, Chaddock B, Chandler JWE, Roberts C, Coley C, Badr A (2008a). Development of performance tests for HBM. Waste and Resources Action Programme (WRAP) AGG79-004. Final Report. https://www.yumpu.com/en/document/view/26934986/technical-report-templates-sustainable-aggregates

Highways England (2009). Interim Design guidance for road pavement foundations (Draft HD25). IAN 73/06, revision 1. Design Manual for Roads and Bridges Volume 7 Part 2. http://www.standardsforhighways.co.uk/ha/standards/ians/pdfs/ian73rev1.pdf.

Highways England (2016). UK Specification for Highway Works, Series 800 Road Pavements – Unbound, cement and other hydraulically bound mixtures. Manual of Contract Document for Highway Works Volume 1. Highway England, London, UK.

Highways England (2020). Series 500 Drainage and Service Ducts. Volume 1 of the UK Manual of Contract Documents for Highway Works (MCHW1). UK Specification for Highway Works. 3021655 MCHW Vol 1 Series 500.indd (standardsforhighways.co.uk).

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M. (2011) Water footprint assessment manual. Setting the global standard. Earthscan, London.

IGES (2019). List of Grid Emission Factors version 10.6. Institute for Global Environmental Strategies. Website: https://pub.iges.or.jp/pub/iges-list-grid-emission-factors.

ISO 14046 (2016). Environmental management — Water footprint — Principles, requirements and guidelines. ISO 14046:2016. International Standards Organisation. Geneva, Switzerland.

ISO 14067 (2018). Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. International Standards Organisation. Geneva, Switzerland.

Kahramaa Specification (2005). Kahramaa General Specification for Main Laying Contracts. Qatar General Electricity & water Corporation, Doha, Qatar.

Khodary F (2015). Comparative study of using steel slag aggregate and crushed limestone in asphalt concrete mixtures. Int. J. of Civil Engineering and Technology 6 (3) pp.73-82.

Kjellsen K.O., Guimaraes M. and Nilsson, Å. (2005). CO_2 uptake during the concrete life cycle: The CO_2 Balance of concrete in a life cycle perspective. Nordic Innovation Centre, Norway. ISBN: 87-7756-758-7.

Kou SC and Poon CS (2008). Mechanical properties of 5-year-old concrete prepared with RAs obtained from three different sources. Magazine of Concrete Research, vol. 60, pp. 57–64.

Leblanc J (2008). A Fossil Hunting Guide to the Tertiary Formations of Qatar, Middle East, 1st Edition. Available online at https://www.scribd.com/doc/3021629/A-Fossil-hunting-guide-to-the-tertiary-formations-of-Qatar-Middle-East.

McDaniel RS, Kowalski KJ, and Shah A (2012). Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures. Report No. FHWA/IN/JTRP-2012/06. Indiana Department of Transportation and Purdue University. DOI: 10.5703/1288284314665.

Meier, A., Darwish, M. and Sabeeh, S. (2013). Complexities of saving energy in Qatar in ECEEE Summer Study Proceedings: Panel 1 Foundations of Future Energy Policy.

Mekonnen, M.M., Gerbens-Leenes, P.W. and Hoekstra, A.Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. Environ. Sci. Water Res. Technol., 1, pp. 285-297.

MOF (2021). Public Budget Statement 2021. Published by the Ministry of Finance, Doha, Qatar.

MPA (2019). Fact sheet 18. Embodied CO_2e of UK cement, additions and cementitious material. Mineral Products Association, London.

Neville AM (2011). Properties of concrete. 5th Edition, Longman, England.

NOL (2013). No objection letter for the use of steel slag as aggregate replacement in construction. Ministry of Municipality and Environment. Doha, Qatar.

Oman Water Society (2014). Water resources. Available at: http://www.omanws.org.om/en/page/about_oman.

PSA (2018). Qatar Second National Development Strategy 2018-2022. Published by the Planning and Statistics Authority, Doha, Qatar.

PSA (2018a). Water statistics in the state of Qatar 2017. Planning and Statistics Authority. Available at: www.mdps.gov.qa.

QCS (2014). Qatar Construction Specifications. 5^{th} edition, published by the Qatar General Organisation for Standardisation and Metrology – Qatar Standards, Doha, Qatar.

Read J and Whiteoak D (2003). The Shell bitumen handbook. Shell Bitumen, 5^{th} Edition, Shell UK Oil Products Limited, UK.

Reid JM, Chandler JWE, Schiavi I, Hewitt A, Griffith R and Bendall E (2008). Sustainable choice of materials for highway works: A guide for local authority highway engineers. TRL Published Project Report PPR 233, TRL, Wokingham, UK.

Reid JM, Hassan KE, Sirin O, and Taha RA (2016). Demonstrating the worth of recycled aggregates—A case study from Qatar. Published in the Geo-Chicago 2016: Geotechnics for Sustainable Energy. Edited by Farid A, Anirban De, Reddy KR, Yesiller N, and Zekkos D. Chicago-USA, ISBN 9780784480137.

RILEM AAR-0 (2016). In Nixon, P.J. and Sims, I (eds.), RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reaction in New concrete Structures. RILEM State-of-the Art Reports 17.

RILEM AAR-4.1 (2015). Recommended Test Method for the detection of potential alkali-reactivity—60 °C test method for aggregate combinations using concrete prisms. RILEM TC 219-ACS (Unpublished committee draft).

Sims I, Hassan KE, Reid JM, Al-Kuwari MS, Attia M, Sediq A and Al-Naemi A (2020). Wadi gravel – a new concrete aggregate in Qatar: Part 2 – Alkali aggregate reactivity. Quarterly Journal of Engineering Geology and Hydrogeology. 2020, 53 (3), 400-412. DOI: 10.1144/qjegh2019-089.

Sims I, Hassan KE, Reid JM, Smith A, Al-Kuwari MBS (2021). Assessing AAR potential of processed Wadi Aggregates in Qatar, Arabian Gulf. Accepted for publication in the 16th International Conference on the Alkali Aggregate Reaction in Concrete. Lisbon, Portugal.

Sirin O, Paul DK, Kassem E and Ohiduzzaman M. (2017). Effect of ageing on asphalt binders in the State of Qatar: A case study. Road Materials and Pavement Design, Vol. 18, pp.165-184.

Stuyt L.C.P.M., Dierickx W., and Martínez Beltrán J. (2005). Materials for subsurface land drainage systems. Published by the Food and Agriculture Organisation of the United Nation, FAO Irrigation and Drainage Paper 60, Rev., Roma, Italy.

The Norwegian EPD Foundation (2018). Environmental Product Declaration: Bulk emulsion explosives. Available at: www.epd-norge.no.

Tilke, Ch., Rakitsch, S. & Günthner, W.A. (2010). Specific Energy Consumption of Ship Unloaders. Bulk Solids Handling, 30(5), 250-254. ISSN: 0173-9980.

TRL (1993). A guide to the structural design of bitumen-surfaced roads in tropical and sub-tropical countries. TRL Overseas Road Note 31. TRL Limited, Crowthorne, UK.

UN-ESCWA and BGR (2013). Inventory of Shared Water Resources in Western Asia. United Nations Economic and Social Commission for Western Asia; Bundesanstalt für Geowissenschaften und Rohstoffe, Beirut.

Walker MJ (ed.) 2012. Hot Deserts: Engineering, Geology and Geomorphology. Geological Society Engineering Geology Special Publication No. 25, ed. M J Walker, the Geological Society, London.

Wayman, M., Schiavi-Mellor, I. & Cordell, B. (2014). Protocol for the calculation of whole life cycle greenhouse gas emissions generated by asphalt – TRL PPR575.

World Resources Institute (2019). Aqueduct Country Rankings. Available at: https://www.wri.org/applications/aqueduct/country-rankings/.

Wu S, Xue Y, Ye Q, Chen Y (2007). Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures. Building and Environment 42 pp.2480-2585.

Yaqub M and Anjum Javed M (2006) Comparison of core and cube compressive strength of hardened concrete. Thirty-First Conference on 'Our World in Concrete and Structures'. CI–Premier PTE LTD, Singapore.

11 Acronyms

AAR	Alkali Aggregate Reaction
Ashghal	Public Works Authority
ASR	Alkali Silica Reaction
BC	Base Course
CBM	Cement Bound Mixture
CDW	Construction & Demolition Waste
CRF	Crushed Rock Fines
CF_{TOTAL}	Total Carbon Footprint
CR	Crumb Rubber
CRMB	Crumb Rubber Modified Binder
DSR	Dynamic Shear Rheometer
EW	Excavation Waste
G_{mm}	Maximum Specific Gravity
HBM	Hydraulically Bound Mixture
HMA	Hot Mix Asphalt
IBA	Incinerator Bottom Ash
IBAA	Incinerator Bottom Ash Aggregate
IDT	Indirect Tensile Test
IRD	Infrastructure Research & Development
JMF	Job Mix Formula
MDD	Maximum Dry Density
MME	Ministry of Municipality and Environment
MPa	Mega Pascal
Mt	Million Tonnes
NDS-1	Qatar First National Development Strategy
NDS-2	Qatar Second National Development Strategy
NMAS	Nominal Maximum Aggregate Size
NPRP	National Priorities Research Programme
OMC	Optimum Moisture Content
PAV	Pressure Aging Vessel
PC	Portland Cement

PMB	Polymer Modified Binder
QCS	Qatar Construction Specification
QMS	Quality Management System
QNRF	Qatar National Research Fund
QNV	Qatar National Vision
QPMC	Qatar Primary Materials Company
QSTP	Qatar Science & Technology Park
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Concrete Aggregate
RCP	Rapid Chloride Permeability
RTFO	Rolling Thin Film Oven
TSE	Treated Sewage Effluent
TSR	Tensile Strength Ratio
VFA	Voids Filled with Asphalt
VIM	Void In Mix
VMA	Voids in Mineral Aggregate
WC	Wearing Course
WF_{TOTAL}	Total Water Footprint

Authors

Dr Khaled Hassan is a specialist in construction materials with over 25 years of experience in academia and industry, combining both innovative research and practical applications in the Infrastructure sector. Khaled led the TRL Infrastructure work in the Middle East from 2008 to 2017, and currently leading the IRD at the Qatar Science & Technology Park. His main technical background is in the use of use of recycled and secondary materials in construction, concrete performance and durability, pavement design and construction, standards and specifications, and sustainable construction.

In the UK, Khaled led the TRL pavement group to develop the UK new designs and materials, which were implemented into the UK Design Manual for Roads and Bridges (DMRB), and acted as the Secretary of European Long Life Pavement Group. In Qatar, he is a member of the QCS National Committee, and the Chairman of the Solid Waste Group in the Qatar Green Building Council.

Dr Murray Reid is a chartered geologist with over 35 years' experience in geotechnical and geoenvironmental engineering in consultancy and research. He has particular expertise in the areas of sustainable construction, use of recycled and secondary aggregates, earthworks, geochemical aspects of civil engineering and training and dissemination. He has contributed substantially as a technical expert and project manager to a wide range of projects in the UK and Qatar, which has given him an excellent understanding of the issues these client bodies face in implementing a sustainability agenda.

Murray was a member of the British Standards committee on aggregate test methods from 2006 to 2016 and member of the Working Group for the updating of BS 1377-3, published in 2018. He has overseas experience in Nigeria, Jamaica and Qatar. He is an experienced author and presenter, and acted as an expert witness in cases involving aggregate in construction.

Dr Mohammmed B S Al-Kuwari is the Assistant Undersecretary, Director & Senior Engineering Consultant of the Environmental and Municipal Studies Institute at the Ministry of Municipality and Environment. He has over 35 years of experience in concrete, asphalt and construction materials. Throughout his career, he worked with many engineers and consultants to improve the manufacturing and production of construction products.

Dr. Al-Kuwari represented the State of Qatar in more than 90 regional and international venues, most of which were related to Housings, Standardization, International Trade and Human Rights. He authored 16 books in various scientific and environmental issues and contributed to 39 scientific and technical research papers in the fields of materials engineering, buildings and construction specifications and other related areas. He was also invited to speak in more than 40 venues ranging from technical lectures to general public awareness seminars.

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