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Case Studies on the Performance of Recycled Aggregate in Service

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ABSTRACT

The use of recycled aggregate in construction is relatively new in Qatar and the Gulf region and can make a significant contribution to sustainable development considering the vast infrastructure development witnessed over the last decade. Lack of experience with recycled aggregates in aggressive exposure conditions, such as the Gulf region, particularly lack of long-term performance data, have raised concerns on the durability and long-term performance of recycled aggregate in service. This paper presents case studies on the performance assessment of recycled aggregate in real exposure conditions up to 5 years in service. Recycled and alternative aggregates were used to replace primary aggregate at different proportions in various construction applications of structural and non-structural concrete in building and road construction. The assessment was made 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.

Keywords: Concrete, Recycled Aggregate, Aggressive Exposure, Environmental Benefits

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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, the government set targets to balance between development needs and protection of the environment. A target was set for the construction industry to achieve 20% recycling by end of 2022.

Construction in hot desert areas poses many challenges (Walker, 2012). 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. Additional problems are caused by the lack of suitable aggregates, 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. These challenges have raised concerns on the durability of recycled aggregate and how they will perform in service under such aggressive exposure environments.

This paper presents case studies on the performance of recycled and alternative aggregates in various applications of structural and non-structural concretes, as given below:

- Case study 1: Use of excavation waste (EW) and crushed rock fines (CRF) in C40 structural concrete
- Case study 2: Use of construction & demolition waste (CDW) and municipal incinerator bottom ash (IBA) in concrete blocks (non-structural concrete).
- Case study 3: Use of Wadi gravel, a by-product of sand washing plants, in structural concrete

Full-scale building and road trials were constructed and used to demonstrate the durability of recycled and alternative aggregates and compare performance up to 5 years in service. Such comparison offers practical validation of the performance of recycled aggregate in real exposure conditions and provides confidence for wider implementation in practice.

2 Case study 1: Excavation waste (EW) and Crushed Rock Fines (CRF) in Structural C40 Concrete

Three building trials were constructed in a heavily built-up area in the capital, Doha, within 1 km of the coast. The trials were made with C40 structural concrete, Table 1, and achieved cube strength of at least 40 MPa at 28 days water curing. The building design consisted of three similar rooms each measuring 2.5 m by 2.5 m by 4.0 m that consisted of ground beams, slab on grade, columns, roof beams and roof slab. Erection of the concrete structural elements was finalised by the end of June 2013. The building trials were periodically inspected up to the age of 5 years. Figure 1 shows the building trials after 5 years in service. The C40 concrete used for the construction of the buildings composed of Portland cement of 370 kg/m^3 and a fixed w/c of 0.44. A superplasticiser of naphthalene sulphonated polymer-based admixture was used in the range of 3.7 to 4.3 l/m^3 to maintain a minimum slump of 150mm. The structural concrete of Building 1 was made with the 50% EW (left), Control (middle) and 60% CRF (right). 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.

Table 1. Use of recycled and alternative 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)

Figure 1. EW and CRF building trials after 5 years in service.

The structural concrete elements of slabs, columns, and beams exhibited excellent performance with no signs of deterioration or cracking observed in any of the buildings at any age up to 5 years. Overall, the 3 buildings were in good condition with no apparent structural or non-structural damage in the concrete elements. Continuous monitoring is planned to provide longer-term performance data.

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, while maintaining the buildings intact. The beams were exposed to the same exposure environment as the building trials and were cored at different ages for testing at 28 days, 1 year and 5 years. The cores were tested for compressive strength, water absorption and rapid chloride permeability (RCP), as per the durability requirements of the Qatar Construction Specification (2014). Three core samples were used for each test and the average values are reported in Table 2. The QCS 2014 recommended ranges for durable concrete including water absorption of 2 to 4 %, in accordance with BS 1881-122 (2011), and RCP of 500 to 4000 Coulombs, as per ASTM C1202 (2012).

Table 2. Performance results of recycled and alternative aggregates in building trials

Property	Building 1			Building 2			Building 3		
	28d	1Y	5Y	28d	1Y	5Y	28d	1Y	5Y
Compressive strength (MPa)	33.0	47.0	58.0	33.0	42.5	63.0	41.0	53.0	70.0
Water absorption (%)	2.5	2.1	2.3	2.0	1.8	2.0	1.9	1.8	1.4
RCP (Coulombs)	4576	4330	4503	4681	4118	4152	3989	3668	3472

The 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, and the results in Table 2 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. At the age of 1 year, all the core results 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 63 and 58 MPa, respectively. The strength results indicate that recycled materials can be successfully used to achieve and exceed the desired concrete strength in the field.

The lowest water absorption value of 1.4% was obtained for the 60% CRF concrete after 5 years in service. The low value could be attributed to the fine particles of the CRF that improve the packing and densification of concrete. The more porous nature of EW aggregate, compared to conventional gabbro (Hassan et al., 2022), resulted in the highest average absorption between 2.1% and 2.5% at all tested ages, but still within the range 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 building trials were within the lower range of QCS 2014 recommended range for durable concrete. The RCP results show values within the range of 3472 to 4681 Coulombs, within the higher range for durable concrete. Cement replacement materials are generally used to enhance the pore structure and chloride resistance of concrete, but not considered in this study to limit the comparison to different aggregates. 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.

3 Case study 2: Construction & Demolition Waste (CDW) and Municipal Incineration Bottom Ash (IBA) in Concrete Blocks (Non-Structural Concrete)

Construction and demolition waste (CDW) and Municipal Incineration Bottom Ash (IBA) aggregates were used to partially replace gabbro as coarse aggregate for the production of concrete blocks in the building trials of Case Study 1, Figure 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 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. The chemical admixture used was a sulphonated naphthalene-based superplasticiser at the dosage of 2 l/m^3. Concrete blocks were made during construction and stored near to the building trials and used for compliance testing with the QCS 2014.

The QCS 2014 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. The average water absorption, as per the CML9-97 (1997), shall not exceed 7 %, with no individual block greater than 7.5 %. Three concrete blocks were tested at 28 days and 5 years, and the average results are presented in Table 3. The average compressive strength values ranged between 11.0 and 15.0 MPa, much higher the specified 7 MPa. The water absorption results showed average values between 3.4% and 6.9%, with the control blocks exhibiting the lowest water absorption value. All the results were lower than the maximum specified value of 7% water absorption.

The concrete blocks showed improved strength and absorption results with age, with values after 5 years better than those at 28 days. 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.

Table 3. Performance results of recycled and alternative aggregates in building trials

Property	Building 1		Building 2		Building 3	
	28d	5Y	28d	5Y	28d	5Y
Compressive strength (MPa)	11.0	15.0	13.0	15.0	12.0	13.5
Water absorption (%)	6.9	5.6	3.8	3.4	6.4	5.5

4 Case study 3: Wadi gravel in structural concrete

Deposits of Wadi gravel are available in Qatar and the Gulf region but have not been widely utilised as aggregate for concrete, mainly due to the possibility of internal sulphate attack, plus the perceived risk of alkali aggregate reactivity (AAR). The susceptibility of Wadi gravel to AAR was assessed through a multi-phase testing programme, comprising an initial aggregate assessment; an accelerated screening test; and longer-term expansion tests (Sims et al., 2020). Petrographic examination of the Wadi gravel indicated six main constituent rock/mineral types, accounting for at least 94% of the Wadi gravel. The main constituents include limestone, gypsum-bound deposits, quartz, rhyolite, granite and quartzite, all of which would be considered as having 'low' to 'normal' alkali-silica reactivity in relation to the UK guidance given in BS 7943 and BRE Digest 330. Processing of the Wadi gravel, through multistage mechanical crushing and washing, reduced the gypsum-bound deposits and consequently the sulphate content to acceptable levels for use in concrete (QCS, 2014). The Wadi gravel did not exhibit any reaction in the gel-pat test, with negligible values of alkali release despite the presence of potential alkali-releasable constituents within rhyolite and granite.

The accelerated mortar-bar test to ASTM 1260 (2014) showed non deleterious expansion of Wadi gravel, with values less than 0.2 % after 14 days immersion. For the constituent aggregate mortar-bars after 14 days immersion, the limestone and quartz exhibited innocuous behaviour. However, the rhyolite, granite and quartzite samples produced expansions of between 0.10 % and 0.20 %, indicating potentially either innocuous or deleterious in-field performance.

Five concrete mixtures were subjected to the long-term concrete prism tests using the RILEM AAR-4.1 at 60°C and BS 812:123 at 38°C test methods. The BS concrete prism testing is known to take a relatively long time (52 weeks), by comparison with the accelerated AAR-4.1 tests (20 weeks) but is considered to be probably more realistic at representing typical behaviour of aggregate materials used in the field. The concrete mixtures included a control gabbro aggregate and PC binder. Wadi gravel was used to replace 50% and 100% of gabbro for the same PC binder. The last 2 mixtures were made with 100% Wadi gravel with the use of cement replacement materials of 30% fly ash (FA) or 50% ground granulated blastfurnace slag (GGBS). The concrete prism expansion results are presented in Figure 2.

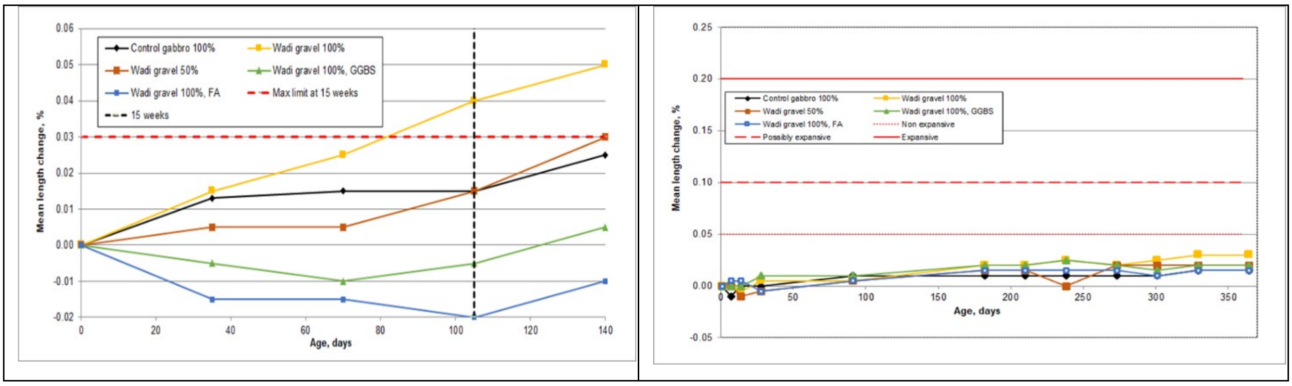

Figure 2. Long-term concrete prism expansion testing to RILEM AAR-4.1 (left) and BS 812 (right)

The guidance given in RILEM AAR-0 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. Blending the Wadi gravel with gabbro resulted in encouraging results with the expansion dropped to 0.015% at 15 weeks, which notably was exactly the same expansion as the control mixture made with 100% gabbro. The most substantial reduction in expansion of the 100% Wadi gravel concretes was noted when cement replacement materials (GGBS and FA) were used to replace proportions of the cement. Figure 2 (right) shows the expansion values of the same concrete mixtures using the BS 812-123 test method. By contrast, the measured prism expansions for all of the Wadi gravel mixtures, including 100 % Wadi gravel, fell into the non-expansive aggregate classification (based on UK experience), suggesting no significant expansive behaviour and a low reactivity type for the Wadi gravel.

Site trials were used to assess the in-situ performance of Wadi gravel concrete and potential AAR in the field. Three trial buildings were constructed in June 2016 and monitored up to 4 years in service, Figure 3. Wadi gravel aggregate was used to replace 50% and 100% of the conventional coarse aggregate of gabbro in the

C40 structural concrete. The concrete composed of Portland cement: fine aggregate: coarse aggregate (10 mm): coarse aggregate (20 mm) in the weight ratio of 340: 870: 383: 760 (kg/m^3), respectively. The water/cement ratio (w/c) was 0.44. A superplasticiser, based on naphthalene sulphonated polymer-based admixture was used to maintain a target slump of 200mm (±20). The highest SP dosage of 5.63 l/m^3 was used for the control 100% gabbro concrete. Replacing 100% and 50% of gabbro with Wadi gravel reduced the SP dosage by approximately 22% and 10%, respectively (Hassan et al., 2022).

Figure 3. Trial buildings, 4 years after construction: control (100% gabbro) on left; 50% Wadi gravel in centre; 100% Wadi gravel on right

The performance of Wadi gravel concrete was assessed by extracting cores, from additional beams cast behind the building trials, and testing for compressive strength and water absorption at the ages of 28 days, 1 year and 4 years. The results are given in Table 3. Additional cores were taken at the age of 4 years for petrographic analyses and identification of potential AAR.

Table 3. Performance results of Wadi gravel aggregate in building trials

Property	**100% gabbro**			**50% Wadi gravel**			**100% Wadi gravel**		
	28d	**1Y**	**4Y**	**28d**	**1Y**	**4Y**	**28d**	**1Y**	**4Y**
Compressive strength (MPa)	45.0	58.0	58.0	42.0	48.0	53.0	41.0	55.5	52.0
Water absorption (%)	1.6	1.1	1.2	1.8	1.1	1.7	1.9	1.7	1.2

The core compressive strength results show that all mixtures exceeded 40 MPa at the age of 28 days. The 100% gabbro concrete exhibited the highest strength of 45 MPa, with slightly lower average values of 42 and 41 MPa for the 50% and 100% Wadi gravel concretes, respectively. Strength development continued with age up to 4 years in service to reach 58, 53 and 52 MPa for the 100% gabbro, 50% Wadi gravel, and the 100% Wadi gravel, respectively. 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.

Wadi gravel was classified as potentially reactive in the RILEM AAR-4.1 accelerated concrete prism test, but of 'low reactivity' in the BS 812-123 test over the longer period of 12 months. As laboratory testing is not always adequate to assess the real performance of the materials in service, cores of the building trials were also examined for petrographic analysis after 4 years in service.

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. The concretes appeared generally sound with only minor evidence of leaching remobilising sulphate, giving rise to secondary ettringite deposits that were too limited to be indicative of damaging sulphate attack. The petrographic examination after 4 years supports the BS 812-123 finding of low alkali-silica reactivity of Wadi gravel.

5 Cost and environmental benefits

The case studies presented in this paper provide confidence on durability of recycled and alternative aggregates in real exposure conditions in Qatar and the Gulf region, with at least equivalent performance to that of conventional construction products made with primary aggregate. Recycling needs also to be justified financially and environmentally for effective implementation in practice. The Qatar government has enabled a consistent supply of recycled aggregate materials at regulated prices. Based on the selected application, the cost of recycled aggregate is lower by approximately 36 to 74 % compared to conventional aggregate.
Carbon and water footprint analysis were carried out on Qatar's aggregate sources. Recycled aggregates had an average carbon footprint of 3.0 kgCO_2e/t, which represents a saving of 71% on imported aggregates. 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, which could pose problems in a country like Qatar with an acute shortage of water. The overall water footprints associated with the production of recycled aggregate was found to be 2.8 l/t, making a relative saving of 86% over imported gabbro aggregate (Hassan et al., 2022).

6 CONCLUSIONS

Recycled and alternative aggregates were used for the production of structural and non-structural concretes, at different replacement levels of primary aggregates. Full-scale trials in real exposure conditions showed at least similar performance of the recycled and alternative aggregate concrete up to 5 years in service. The reported technical, economic and environmental benefits of recycled and alternative aggregates support the government strategy of sustainable development and greatly encourage their wider and efficient use in the construction industry.

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