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Durability of untreated fine recycled aggregate concrete: a literature review

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Abstract. Unlike natural aggregate particles, recycled concrete aggregates contain hardened cement paste phases and multiple interfacial transition zones. These differences in properties may be linked to a decrease in durability performance in recycled aggregate concrete. This paper presents a review of the literature published on the durability performance of concrete produced using untreated fine recycled concrete aggregate (fRCA). From the available literature, the durability performance of concrete made using fRCA is strongly linked to the w/b used and the porosity of the resulting concrete matrix. Water absorption, gas permeability, and chloride penetration were found to increase with fRCA replacement. A possible maximum replacement level of 30% was observed in this regard. Carbonation resistance was found to increase with fRCA replacement due to the presence of calcium hydroxide in fRCA samples.

1 Introduction

Material flows in the construction of concrete infrastructure typically follow a linear lifecycle model. This entails the extraction and use of virgin material resources and, once the infrastructure has fulfilled its intended service, the demolition of this infrastructure. The resulting demolition waste is then often downcycled to be used as fill and subbase material or treated as a waste and deposited in a landfill. A potential alternative use for the concrete demolition waste is as a full or partial replacement of aggregate material in the production of new concrete. This would improve the flow of material resources and, therefore, improve the sustainability of the construction industry.

As reported in EN 206:2016 [1], coarse recycled concrete aggregate (cRCA) can replace up to 50% of natural coarse aggregates in the production of new concrete, depending on the properties of the cRCA as well as the strength class environmental exposure conditions of the concrete produced. However, fine recycled concrete aggregate (fRCA), the finer material produced during the crushing and processing of concrete waste, cannot currently be used as a natural fine aggregate replacement [1]. Moreover, there are limited studies detailing the long-term behaviour of concrete produced using fRCA [2]. Therefore, before fRCA can be used in the production of concrete in practice, a better understanding of how the use of this material affects the long-term behaviour of concrete is required.

fRCA is a multiphase material composed of anhydrous cement clinker, homogenous natural fine aggregate particles, hardened cement paste, and natural fine aggregate particles with adhered hardened cement paste, as illustrated in Figure 1. Aggregate particles with adhered hardened cement paste may have one or more interfacial transition zones between these different phases.

The presence of hardened cement paste phases and multiple interfacial transition zones has been linked to a reduction in the durability performance of concrete produced using recycled concrete aggregate [2]. Furthermore, the proportion of hardened cement paste phases present increases as the fineness of recycled concrete aggregate is increased [3]. This suggests that concrete produced using fRCA may have poorer durability performance compared to concrete produced with cRCA, which has a lower overall proportion of hardened cement paste phases, and, by extension, concrete produced using conventional natural aggregates, which contains no hardened cement paste phases.
Therefore, this paper aims to review available literature discussing the durability performance of concrete produced using untreated fRCA to determine if literature supports the use of fRCA in concrete production.

2 Durability performance of concrete with fine recycled aggregate

Concrete durability is the ability of concrete infrastructure to withstand prevailing environmental conditions over its service life, without a reduction in serviceability or the need for major repair. A reduction in durability performance may be caused by physical attack, namely abrasion; erosion; cavitation; and freeze-thaw, chemical attack, namely acid attack; sulphate attack; and alkali aggregate reaction (AAR), or a combination of physical and chemical attack in the form of reinforcement corrosion caused by the ingress of carbon dioxide or chloride ions [4]. These deterioration processes can be simulated in a laboratory setting and tested directly, or concrete transport mechanisms are measured through test methods for permeability, capillary suction, and conductivity and results are then linked to deterioration processes to provide a quantitative measure of concrete durability [4]. Investigations of the durability performance of fRCA concrete thus far have been limited to studies of water absorption, gas permeability, accelerated carbonation, and chloride penetration. Therefore, this review will focus on the beforementioned performance parameters and how these relate to concrete durability performance.

2.1 Water absorption

The mechanisms of water absorption into unsaturated concrete are by immersion, representing the effective porosity, and by capillarity, representing the rate of absorption by capillary ascension and giving an indication of the concrete pore structure [5]. Water absorption by capillarity is used to inform decisions of the choice of concrete used in the construction of members exposed to wetting and drying cycles of fluids containing aggressive agents such as chloride or sulphate ions [6].

Berredjem et al. [7] investigated the influence that replacement of cRCA and fRCA had on capillary absorption and water accessible porosity of concrete. The w/b ratio was varied between 0.47 and 0.66 to achieve an acceptable slump with the changes in water demand associated with recycled concrete aggregate. This increase was the highest for concrete made with 100% fRCA (0.59) and concrete made with 100% cRCA and cRCA (0.66). Concrete made with the full replacement of coarse and fine natural aggregates by cRCA and fRCA respectively showed higher results for capillary water absorption. Furthermore, water accessible porosity increased for mixes containing recycled concrete aggregates. This increase was more significant where fRCA was used. Results for fRCA concrete made with natural coarse aggregate was 42% higher than that of the control mix and the results for fRCA concrete made with cRCA was 62% higher than that of the control mix. This may be due to the porous network of hardened cement paste phases present on the recycled concrete aggregate.

This reduction in water absorption performance was also observed by Evangelista and de Brito [8][9]. In 2010, Evangelista and de Brito [8] observed a decrease of 34.4% in the sorptivity coefficient at 30% fRCA replacement and a 70.3% decrease at 100% fRCA replacement. This is because fRCA concrete produced had longer and more numerous capillaries, thereby increasing capillary stress. Results observed by Evangelista and de Brito in 2016 [9] are comparable, with a 70.2% increase in capillary absorption at 100% fRCA replacement in spite of the fact that a w/b of 0.48 was used in 2010 [8] and a w/b of 0.56 was used in 2016 [9]. Additionally, the w/b was altered from 0.41 to 0.48 and from 0.53 to 0.56 respectively to account for changes to water demand due to the irregular shape, high fineness modulus, and high absorption of fRCA. This, in turn, would have increased the free water available in the fresh concrete and, therefore, potentially increased porosity.

Changes to the water absorption by immersion were less than that of water absorption by capillarity [8]. However, both sets of results decreased linearly with replacement level [8]. Evangelista and de Brito [8] observed a 16.8% increase in water absorption by immersion at 30% fRCA replacement and a 46% increase at 100% fRCA replacement in 2010, but a 20% increase at 100% replacement in 2016 [9]. This difference in results may be due to a difference in effective porosity, associated with a difference in w/b, or a difference in fRCA quality.

Poon et al. [10] observed the new and old interfacial transition zones of concrete produced using three different fRCA sources, namely normal strength parent concrete and high-performance concrete. It was found that normal concrete fRCA produced a microstructure with granular CSH and an interface with a similar porosity to that of natural aggregates. However, high strength concrete fRCA produced an interface mainly composed of CSH gel with a lower porosity. Additionally, Sosa et al. [11] investigated the effect of varying parent concrete sources on sorptivity as a function of compressive strength. Where a standard crushing and processing method was used, parent concrete sorptivity of the different concrete sources corresponded to the water absorption of fRCA produced. It was also found that sorptivity of concrete produced using fRCA containing granite aggregates increased between 18% and 86% in comparison to parent concrete sorptivity, while sorptivity of concrete produced using quartz aggregates were the same or lower than that of parent concrete. Therefore, the types and quantities of different phases present in fRCA particles, the physical and chemical properties of these phases, and the interfacial transition zone quality have a significant influence on the transport properties observed.

Cartuxo et al. [12] investigated the influence of regular and high-performance superplasticizer on water absorption by capillary action and water absorption by
immersion. The dosage of superplasticizer was maintained at a constant volume, but w/b was varied from 0.51 to 0.60 where no superplasticizer was used, from 0.43 to 0.55 where regular superplasticizer was used, and from 0.38 to 0.46 where high-performance superplasticizer was used. This decision was made to attain a consistent slump for a given dosage of superplasticizer. It was found that without superplasticizer there is a linear increase in water absorption by immersion up to 52% at 100% fRCA replacement, and a linear increase in water absorption by capillary action up to 45% at 100% fRCA replacement. The addition of normal superplasticizer was found to reduce effective w/b by up to 16%. The variation in effective w/b decreased as fRCA replacement increased. This, in turn, resulted in a decrease in water absorption by immersion up to 28% and a decrease in water absorption by capillary action up to 48%. The addition of high-performance superplasticizer was found to reduce the w/b further by up to 25% from the control, but this is not significantly impacted by the addition of fRCA. This, in turn, resulted in a decrease in water absorption by immersion up to 43% and a decrease in water absorption by capillary action up to 66%.

Furthermore, Dhir et al. [13] investigated the effect of fRCA replacement levels on initial surface absorption at a constant w/b and for different parent concretes. Findings showed that up to 20% replacement of fRCA has no influence on initial surface absorption. This value increased beyond this replacement level due to an increase in the proportion of hardened cement paste phases and, therefore, higher water absorption of the aggregate particles. Water absorption levels have been observed to increase from 0.8-2.19% for natural fine aggregates to 8.5-13.1% for fRCA [7]–[9], [14]. The findings of Dhir et al. are confirmed by Tam and Tam [15] and Tam et al. [2] where it is stated that fRCA replacement levels varying between 20% and 100% are associated with an increase in water penetration due to the higher water absorption of fRCA, but there is little difference in water absorption at or below 20% replacement levels. Moreover, Zega and di Maio [14] observed an increase of 13.7% in water absorption at 20% fRCA replacement and a 15% increase at 30% fRCA replacement in comparison to control mixes. While a constant w/b of 0.45 was used, effective w/b was reduced to 0.43 and 0.41 at 20% and 30% replacement levels respectively due to the absorption of a portion of free water by fRCA particles.

2.1.1. Summary and relevance

In general, water absorption was shown to increase with an increase in fRCA replacement level. However, findings suggest that a substitution level up to 20% has a limited effect on fRCA concrete water absorption performance. The findings suggest that where concrete is exposed to wetting and drying cycles of aggressive agents, fRCA replacement level should be limited to 20%. Where fRCA is used in such scenarios, concrete performance can be optimised. The performance of fRCA concrete in water absorption was found to be dependent on the overall porosity and pore structure of the concrete which, in turn, is linked to the w/b used. As in conventional concrete, w/b can be optimised through the use of normal and high-performance superplasticizers. Performance was also found to be linked to the composition and properties of fRCA used. This, in turn, is linked to the composition and properties of the parent concrete. Performance can be improved through limiting the hardened cement paste phases present in the fRCA sample used.

2.2 Gas permeability

Gas permeability is the ease with which gases are able to penetrate concrete under an externally applied pressure [4]. As gas permeability is theoretically linked to gas diffusivity, it is used to assess concrete performance in the penetration of carbon dioxide [6]. Test results can be related to analytical models to estimate diffusion coefficients or can be related to the rate of carbonation through empirical models [4]. Gas permeability can also be used to inform decisions of the choice of concrete where carbonation-induced corrosion is a key deterioration mechanism [6].

Brederjem et al. [7] found that concretes with recycled concrete aggregates had higher gas permeability coefficients when compared to control mixes. A maximum increase of 300% was observed when 100% fRCA was used and a maximum increase of 411% was observed when 100% fRCA and cRCA was used. However, as stated in section 2.1, w/b was increased with an increase in the replacement level of fRCA. This, along with the associated increase in overall porosity and the increase in porosity associated with fRCA particles in comparison to natural fine aggregates, caused the increase in gas permeability.

However, Tam and Tam [15] observed a 51.81% reduction in gas permeability at 20% fRCA substitution after 56 days of curing where the two-stage mix approach is used. In this mix approach, cement slurry layer is formed around the fRCA particles during the first stage such that cracks and voids on the surface of fRCA particles may be filled and, therefore, leading to an improvement in the new interfacial transition zone.

2.2.1. Summary and relevance

Studies on the effect of fRCA replacement on gas permeability are limited and have opposing results. This may be due to the mixing methods used, the quality, composition, and properties type of fRCA used. Further studies are required. However, the use of the two-stage mixing approach was shown to improve gas permeability performance of fRCA concrete.

2.3 Accelerated carbonation
The carbonation of concrete is a process by which gaseous carbon dioxide (CO₂) reacts with concrete pore solution to form a weak carbonic acid (H₂CO₃). This then reacts with calcium hydroxide (Ca(OH)₂) to form calcium carbonate (CaCO₃) in the concrete pores. This process results in the decrease of the concrete pH from 12.5 to 8.4 once carbonation is complete [4]. The rate of carbonation is a function of the pore structure and pore solution chemistry of the concrete [4]. Once the carbonation front reaches the reinforcing steel, the passive oxide layer which protects the steel from corrosion is disrupted and, under favourable conditions, i.e. in the presence of oxygen and moisture, the steel reinforcement may begin to corrode.

Carbonation can be tested under accelerated conditions where carbon dioxide concentrations are increased to 2% [16]. Results can be used to model the carbonation of structures using relationships between test results and field performance [4].

Dhir et al. [13] measured carbonation resistance of concrete up to 20 weeks. fRCA concrete was compared to natural aggregate concrete of equal strength. Equal strength was obtained by altering the w/b. It was found that carbonation resistance improved with the addition of up to 100% fRCA and up to 50% fRCA. This is linked to the decrease in w/b and the associated refining of the concrete pore structure, along with the presence of additional Ca(OH)₂ in the hardened cement paste phases of fRCA. An improvement was observed for all sources of parent concrete used. The degree of improvement is further dependent on the carbonation of the parent concrete. Ca(OH)₂ can be found in these hardened cement paste phases where parent concrete was not carbonated. Ca(OH)₂ present in fRCA samples can undergo carbonation along with Ca(OH)₂ present in the new hardened cement paste matrix. The former would not be present in concrete made with natural aggregates. The presence of additional carbonateable material would decrease the rate of carbonation and, therefore, improve carbonation resistance.

Levy and Helene [17] also compared the carbonation of fRCA and natural fine aggregate concrete of equivalent strength. Results support that of Dhir et al. [13] in that there is a decrease in carbonation depth observed with fRCA replacement up to 100% fRCA replacement.

Sim and Park [18] observed a stabilisation of carbonation results between 0% and 30% replacement levels, and a decrease in carbonation depth at 60% and 100% replacement. Concrete tested here, unlike in the previous two studies, had a constant w/b of 0.35.

Zega and di Maio [14] investigated the effect of replacement levels up to 30% on carbonation depth at a constant w/b of 0.45. It was found that samples of all replacement levels had a carbonation depth of approximately 2 mm. This was explained by the absorption of free water by the fRCA particles and resultant lowering of the effective w/b to 0.43 and 0.41 at 20% and 30% replacement respectively.

However, Geng and Sun [19] observed an increase in carbonation depth with an increase in replacement level at a constant w/b of 0.4. The rate of depth change increases further beyond a 40% replacement level. No chemical analysis of the fRCA was done, but this difference in result may be because Ca(OH)₂ that was present had been carbonated already, or because the fRCA sample is predominantly made of crushed aggregate particles. Furthermore, the carbonation depth increases as maximum particle size is reduced from 0.36 mm to 0.16 mm. This is due to an increase in the presence of porous hardened cement paste phases.

Additionally, Evangelista and de Brito observed an increase of 110% [8] and 60% [9] at 100% replacement in 2010 and 2016 respectively. Variability in results may be due to differences in w/b, as discussed in section 2.1, or differences in the chemical properties of fRCA. Mineralogical properties of fRCA used showed a high proportion of hardened cement paste phases in the fRCA sample, all of which were fully carbonated [9]. A 40% increase in carbonation depth at 30% replacement was also observed [9].

### 2.3.1. Summary and relevance

Studies show that carbonation resistance increases with the use of uncarbonated fRCA, due to the presence of Ca(OH)₂ in the hardened cement paste phases. Concrete with fRCA replacement levels of up to 100% showed an improvement in performance. In practice, this may lead to better protection against carbonation-induced corrosion and the associated serviceability issues.

### 2.4 Chloride penetration

In marine environments, reinforced concrete is vulnerable to the ingress of chloride ions by diffusion. Where sufficient free chlorides are present at the level of the reinforcing steel, localised depassivation and subsequent corrosion of the reinforcement is likely to occur [4].

Results of chloride penetration tests can be correlated to chloride diffusion coefficients of concrete. These can be used as an input parameter in service life models.

At 28 days, Evangelista and de Brito [9] found that the chloride diffusion coefficient increased linearly with an increase in fRCA replacement ratio. At 100% replacement levels, the chloride diffusion coefficient was 43.8% greater than the control concrete with natural aggregates. This may be associated with an increase in porosity linked to the increase in w/b, as discussed in section 2.1, as well as the increased porosity of fRCA particles in relation to natural aggregate particles. At 120 days, however, the chloride diffusion coefficient decreased at 10% replacement level and then increased to approximately the same value as the control at 30% replacement. Therefore,
at low substitution levels, the presence of fRCA has a limited effect on chloride penetration results. This may be due to the fine filler effect of fine fRCA particles or the presence of limited unhydrated cement particles present in the fRCA sample undergoing hydration. At 100% replacement levels, the chloride diffusion coefficient was 51.9% greater than the control, but lower than the 100% replacement level result at 28 days. At higher substitution levels, the factors improving performance below 30% replacement are outweighed by the presence of excess porous fRCA particles and free water increasing overall concrete porosity. The improvement of chloride penetration results with time shows an improvement of the concrete microstructure with time due to ongoing hydration. Free water absorbed by fRCA may be facilitating this hydration of anhydrous cement particles present in the concrete matrix.

Evangelista and de Brito [8] found that the chloride diffusion coefficient increases by 11.9% at 30% replacement and increases by 33.8% and 100% replacement. As w/b is altered by Cartuxo et al. [12], as outlined in section 2.1, chloride diffusion coefficient without superplasticizer increases up to 33%, chloride diffusion coefficient with normal superplasticizer decreased up to 38%, and chloride diffusion coefficient with high performance superplasticizer decreased up to 46%. The maximum recommended fRCA replacement levels for normal and high-performance superplasticizer concrete are 30% and 100% respectively.

Sim and Park [18] investigated the influence on fRCA replacement level and the addition of fly ash as a supplementary cementitious material on chloride ion penetration. Chloride ion penetration was found to decrease with time to below 2000 Coulombs at all replacement levels at 21 days and below 500 Coulombs at all replacement levels at 56 days. An improvement of performance with time is expected due to ongoing hydration reactions. Little change was observed as replacement levels were varied between 0% fRCA and 100% fRCA. Total charge passed decreased by 50% when 30% fly ash replacement was used. This is due to the refinement of the pore microstructure. Additionally, binders containing supplementary cementitious materials such as fly ash and slag have been shown to have a high chloride binding capacity and, therefore, reduce the free chlorides present and reduce the rate of chloride penetration [4]. Therefore, the use of fly ash as a supplementary cementitious was found to have a greater influence on chloride ingress than fRCA replacement level.

2.4.1. Summary and relevance

In general, an increase in chloride penetration is observed with an increase in fRCA replacement level. However, findings suggest that a substitution level up to 30% has a limited effect on fRCA concrete chloride penetration performance. In practice, this may show acceptable protection against chloride-induced corrosion and the associated serviceability issues at 30% fRCA replacement levels. Where fRCA is used in such scenarios, concrete performance can be optimised. The performance of fRCA concrete in chloride penetration was found to be dependent on the overall porosity and pore structure of the concrete which, in turn, is linked to the w/b used. As in conventional concrete, w/b can be optimised through the use of normal and high-performance superplasticizers. Performance was also found to be linked to the use of supplementary cementitious materials such as fly ash.

3 Conclusions

Based on the analysis of the findings outlined in section 2, the following conclusions were drawn:

- The effect of fRCA on durability properties is, as expected, strongly tied to the w/b used and, therefore, the pore structure of the concrete. Results are also dependent on the quality of the parent concrete used, the phases present in fRCA samples, and the physical and chemical properties of fRCA used.

- In general, water absorption, gas permeability, and chloride ingress were found to increase with an increase in fRCA replacement level. A maximum replacement level of 30% may be advisable for the optimal performance of the aforementioned properties.

- Where uncarbonated fRCA was used, carbonation resistance increased with fRCA replacement. The effect of fRCA replacement on carbonation depth is dependent on the degree of carbonation of the parent concrete used, with uncarbonated concrete exhibiting good performance.

- The use of the two-stage mixing approach, supplementary cementitious materials, and normal or high-performance superplasticizers may allow the enhancement of durability performance of fRCA concrete. Further studies in this regard are required.

- There are limited studies available on fRCA concrete durability and the durability properties studied are not comprehensive.

References