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Performance of concrete made with commercially produced coarse recycled concrete aggregate

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Abstract

Performance tests have been carried out for fresh and hardened properties of concrete made with commercially produced coarse recycled concrete aggregate and natural fine sand. Test results indicate that the difference between the characteristics of fresh and hardened recycled aggregate concrete and natural aggregate concrete is perhaps relatively narrower than reported for laboratory-crushed recycled aggregate concrete mixtures. For concrete without blast furnace slag having similar volumetric mixture proportions and workability, there was no difference at the 5% significance level in concrete compressive and tensile strengths of recycled concrete and control normal concrete made from natural basalt aggregate and fine sand. Water absorption rates and carbonation of recycled concrete and reference concrete were comparable for most applications. However, the abrasion loss of recycled aggregate concrete made with ordinary portland cement increased by about 12% compared to normal concrete, while the corresponding drying shrinkage was about 25% higher at 1 year. The ratio of splitting tensile strength to compressive strength was found to be in good agreement with established values derived for equivalent grade concretes made with normal-weight natural aggregates. One-year test results indicate that incremental improvements in durability characteristics can further be achieved with the use of blast furnace slag cement. Enhanced fresh and hardened concrete properties of the investigated recycled concrete aggregate as compared to aggregate derived from laboratory-crushed concrete arise primarily from improved aggregate grading and quality achievable in plant crushing operations.

Keywords: Aggregate; Blast furnace slag; Compressive strength; Drying shrinkage; Durability; Performance; Recycled concrete

1. Introduction

In recent years, the recycling of concrete to produce aggregates suitable for nonstructural concrete applications is emerging as a commercially viable and technically feasible operation. This situation has arisen following well over two decades of intensive research, predominantly centered on laboratory-crushed concrete [1–3]. Hence, the potential now exists for demolished concrete to serve as a source of quality aggregate feedstock in a variety of nonstructural applications, particularly in modern urban centers removed from quarry sites. Such recycling operations have the added benefit of reducing landfill disposal, while conserving primary resources and reducing transport costs.

Recent advances in aggregate–production technologies in the areas of rubble screening and aggregate washing, and tighter regulation of the recycling industry [4–6], have contributed to significant improvements in aggregate quality. Accordingly, the performance characteristics of concrete incorporating commercially graded recycled concrete aggregate, hereafter, referred to as recycled concrete, require reassessment in relation to natural aggregate concrete.

Literature reports [1,6] confirm that the cement mortar attached to the aggregate particles primarily determines the performance of concrete made with laboratory-crushed recycled concrete aggregate. This residual mortar alters aggregate absorption and density and can have adverse effects on concrete performance. As widely reported [2,7], typical reductions of the order of 10% in compressive strength and up to a 70% increase in drying shrinkage are not uncommon.

While studies on the engineering properties of concrete made with laboratory-crushed recycled concrete aggregate

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Table 1
Sieve analysis of coarse recycled concrete aggregate and basalt aggregate

Coarse aggregates	Percentage of mass passing through sieve, mm						
Maximum size	19 mm	13.5 mm	9.5 mm	6.7 mm	4.75 mm	2.36 mm	150 μm
Recycled concrete aggregate	100	91.4	28.7	7.6	5.4	0.2	0.5
Basalt	100	84.0	43.7	5.6	2.1	1.0	0.2

abound [8,9], only limited data are available on commercial-grade recycled concrete aggregate, including concrete mixture proportions, fresh concrete performance, and durability characteristics. Thus, this paper evaluates aspects of concrete rheology and performance of N25 (25 MPa)-grade concrete containing commercially crushed and graded recycled concrete aggregate.

2. Experimental program

2.1. Aggregates

A single source of commercially graded unwashed coarse recycled concrete aggregate and natural fines was used in all concrete mixtures. The natural coarse aggregate used was a nominal 14-mm crushed basalt. The grading of the basalt and the coarse recycled concrete aggregate conformed to the requirements of Australian Standard AS 2758.1 [10] as shown in Table 1.

This grading and a fine-to-coarse aggregate ratio of 46:54 were kept constant throughout the test program for all concrete mixtures. Based on visual inspection, the surface texture of the plant-crushed recycled concrete aggregate appeared characteristically grainy compared to the basalt. The recycled concrete aggregate was batched in the as-received state. Details of the physical properties of both aggregates are shown in Table 2.

Partly as a result of residual cement mortar attached to the commercial recycled concrete aggregate particles, marginally lower density and higher aggregate crushing values were observed compared to the basalt aggregate. As indicated in Table 2, recycled concrete aggregate also has a comparatively high water absorption value at 5.6%.

Table 2
Properties of recycled concrete aggregate and basalt aggregates

Property	Recycled concrete aggregate	Basalt
Aggregate crushing value, % (AS 1141.21)	23.1	15.7
Bulk density, kg/m^3 (AS 1141.6)	2394	2890
Water absorption, % (AS 1141.6)	5.6	1.0
Impurity level, % (AS 1141.32)	0.6	< 0.1
LOI, %	4.9	1.3

2.2. Binders

Ordinary portland cement, designated Type GP, and a blast furnace slag cement, Type GB, comprising 65/35 portland cement/blast furnace slag were used in the investigations. The slag blend was used partly to assess possible improvements in fresh concrete cohesion, workability, and concrete performance.

2.3. Concrete mixtures

Several preliminary trial mixtures were proportioned to evaluate water requirements for a nominal 25-MPa concrete. Mixture proportion data are given in Table 3. The unit water content of the concrete was corrected for free moisture in the aggregates. However, the recycled aggregate was presaturated for 10 min in the mixer and brought to room temperature prior to mixing the concrete. The mixtures were proportioned to have a nominal binder content of 240 kg/m^3 for C0912A, C0912B, and C1212A, while mix C1212B contained an additional 5% cement to assess the effect of increased cement content. Slag cement was used in mix C1212A.

The water–binder ratio of all mixtures was adjusted to achieve comparable consistency, and hence equal nominal slump of 80 ± 15 mm. A reduction in the water requirement was attained by using a lignosulfonate-based water-reducing admixture at nominal doses recommended by the manufacturer. The recycled concrete mixtures contained 100% recycled aggregate and natural fine sand, while the normal concrete mixtures contained all natural coarse and fine aggregates.

2.4. Specimens and testing

Specimens were cast from each mixture to assess compressive strength, drying shrinkage, expansion, splitting tensile strength, and abrasion resistance. The concrete durability-related tests involved accelerated carbonation and water absorption. Unless otherwise specified, all specimens, upon their removal from the molds, were stored under standard moist curing conditions at 23°C/>95% RH until required for testing. Hardened concrete testing was performed in accordance with the requirements of AS 1012

Table 3
Mix designation and mixture details of concrete specimens

Mix designation	Binder loading, kg/m^3	Binder type	Water–binder ratio	Slump, mm	Wet density, kg/m^3	Entrapped air content, %	Coarse aggregate
C0912A	242	Type GP	0.76	90	2466	2.4	basalt
C0912B	240	Type GP	0.73	75	2335	2.4	recycled
C1212A	238	Type GB	0.74	95	2321	1.8	recycled
C1212B	254	Type GP	0.70	80	2335	2.3	recycled

[11], with the exception of water absorption and abrasion resistance measurements that were respectively tested to ASTM C 642-1997 [12] and AS/NZS 4456.9:1997 [13].

3. Results and discussion

3.1. Fresh concrete properties

The workability, expressed in terms of slump, varied within a 20-mm band. As summarized in Table 3, the entrapped air content of concrete was similar for mixtures made with portland (Type GP) cement, varying within $2.4 \pm 0.2\%$ compared to the low value of 1.8% obtained for mix C1212A made with slag cement. Although the water absorption of the recycled aggregate is relatively high compared to the reference basalt aggregate, there was no difficulty in achieving the desired consistency and subsequent compaction of concrete. As suggested by Hansen and Narud [8], the observed marginal difference in measured wet density between recycled concrete and normal concrete can be attributed to the presence of lower-density residual cement mortar attached to aggregate particles.

3.2. Compressive strength

Compressive strengths were determined on concrete cylinders continuously stored under moist conditions for up to 365 days. As shown by the mean compressive strength results plotted in Fig. 1, there is no significant difference between the strength of portland cement concretes, as a function of aggregate type, for the grade of concrete investigated. The observed equivalence in strength between recycled and normal concretes contrasts the corresponding 10% reduction in strength typical of laboratory-crushed recycled concrete [6,9].

As expected, the slag cement concrete with similar water–cement ratios achieves much higher later-age strength owing to the hydraulic properties of the slag. The increase in strength gain of the slag cement concrete from 20.2 to 32.6 MPa between 7 and 28 days is significantly higher than the equivalent nominal 6 MPa average increase for the portland cement concretes. As noted in Fig. 1, the strength gain for recycled concrete made with portland cement remains virtually unchanged at the 5% significance level beyond 28 days.

3.3. Splitting tensile strength

Results of the tests for indirect tensile strength, as measured by the splitting tensile test, are shown in Fig. 2 for recycled concrete and the reference basalt mixtures. The general trend in the tensile strength development appears to depend mainly on binder rather than aggregate type. Hence, the tensile strength of the slag cement concrete improves with curing, while the tensile strengths of portland cement concretes remain practically unchanged beyond 28 days for the duration of the measurements.

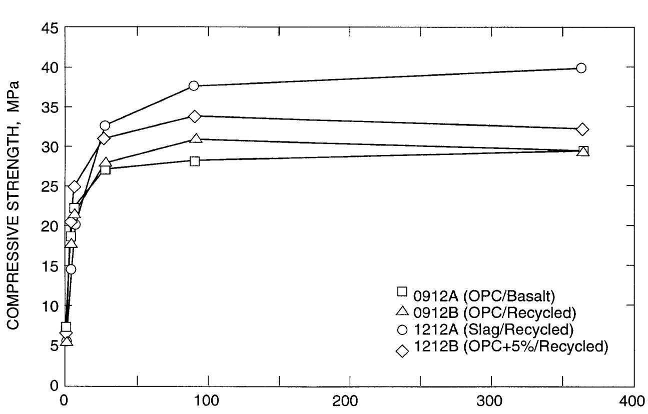

Fig. 1. Development of concrete compressive strength with age.

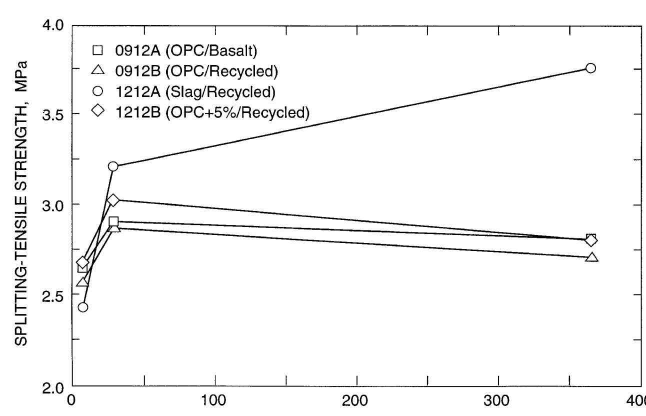

Fig. 2. Relationship between splitting tensile strength of recycled concrete and reference basalt concrete with time.

Table 4
Ratios of splitting tensile (f_t) and compressive strength (f_c) of concretes

	f_t/f_c		
Concrete mix	7 days	28 days	365 days
C0912A (OPC/basalt)	1.19	1.07	0.99
C0912B (OPC/recycled)	1.19	1.20	0.94
C1212A (slag/recycled)	1.21	0.98	0.96
C1212B (OPC + 5%/recycled)	1.08	0.97	0.89

OPC: Ordinary portland cement.

At one year, the tensile strengths of the slag cement samples were of the order of 25% above the portland cement samples compared to an equivalent 15% difference at 28 days. By contrast, the tensile resistance increases as the cement content of the concrete increases, as indicated by the difference shown between mixes C0912B and C1212B, respectively, with nominal and high portland cement contents. Generally, the pattern of behavior of the indirect tensile strength is similar to that of compressive strength. Compared with the development of compressive strength, however, the percentage compressive strength gain beyond 91 days is less pronounced except for the slag cement mixture.

The absence of any detrimental effect on recycled concrete tensile strength is partly indicative of good bond characteristics between aggregate and the mortar matrix. Thus, the corresponding mechanism of failure of recycled concrete specimens would be expected to be similar to that of the reference concrete.

As shown in Table 4, the splitting tensile-to-compressive strength ratio of recycled concretes are comparable to results obtained for conventional concretes made with natural aggregates. This ratio provides an indication of the resistance of a concrete to tensile strain and is dependent on type and size of coarse aggregate particles, voids in the concrete, curing conditions, and test conditions. Calculated splitting tensile-to-compressive strength ratio values ranged from 0.89 to 1.21 for recycled concrete, which is in close agreement with published values of between 0.8 and 1.4 for equivalent normal weight aggregate concretes [14].

3.4. Drying shrinkage

The variation of drying shrinkage strain with time for both recycled and reference concretes is shown in Fig. 3. Fig. 4 documents the corresponding expansion results of all concrete mixtures. The drying shrinkage of test specimens increased with time and stabilized at about 91 days, following similar trends reported by several researchers [1] for laboratory-crushed recycled concrete, although the absolute shrinkage values are slightly lower in the present case. While both natural and recycled aggregates display similar trends with regard to the rate of shrinkage, strains associated with recycled concrete made with slag cement at 365 days are over 35% higher than the reference mixture, and closer to typical published values of 30–70% [6,15]. In contrast, only a 15% increase in shrinkage strain is obtained for portland cement specimens for the same curing conditions. However, there appears to be a much less significant effect on drying shrinkage as a result of the 5% difference in cement content.

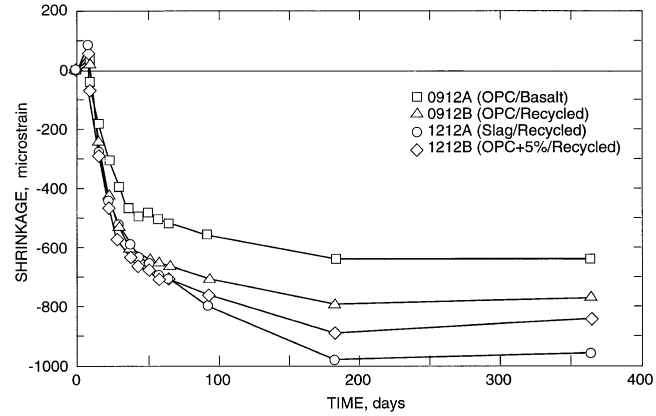

Fig. 3. Relationship between drying shrinkage strain of recycled concrete and reference concrete with time.

It is evident from Fig. 3 that recycled concrete concretes display higher drying shrinkage values compared to the reference normal concrete mixture, possibly partly due to the lower restraining capacity of recycled aggregate particles compared to basalt. Currently, the Australian Standard AS 3600 [16] recommends a basic shrinkage limit of 700 microstrain at 56 days.

Overall trends in the expansion profiles of recycled concrete mixtures shown in Fig. 4 are nearly identical to those observed in the drying shrinkage plots (Fig. 3). For portland cement concretes, a marginally lower expansion was obtained for recycled concrete compared with the control basalt concrete. The low expansion values obtained for the higher portland cement content mixture can be attributed to its lower water–cement ratio and improved paste quality of the matrix. Generally, it would be expected that shrinkage and swelling are similarly affected by the same parameters.

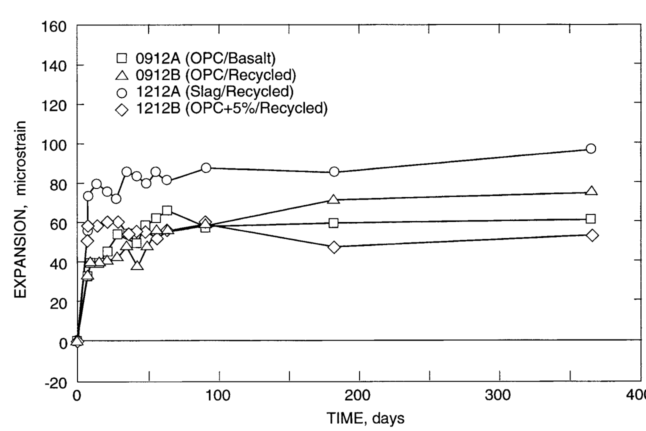

Fig. 4. Relationship between expansion of recycled concrete and reference concrete with age.

3.5. Abrasion resistance

The resistance to abrasion of the recycled concrete concretes was compared with the abrasion wear of the reference normal concrete. White fused aluminum oxide was used as the abrasive material and dispensed at a constant rate, to the point of contact between disc and the specimen surface. Fig. 5 shows the abraded volumes of concrete specimens tested. The abrasion resistance of recycled concrete specimens was generally similar. However, mix C0912B with nominal portland cement content showed slightly lower abrasion resistance. Reference to Fig. 5 further shows that the average abraded volume of the recycled concrete at 212 mm^3 was about 12% higher than that of the reference basalt concrete.

At the lower concrete strengths tested, the effect of aggregate hardness on abrasion resistance is likely to be more pronounced, given that the resistance to abrasion is influenced by concrete strength, aggregate properties, and quality of near-surface finish. As with normal and lightweight aggregates, the abrasion resistance of recycled concrete may be expected to increase with compressive strength [17].

3.6. Carbonation

The variation of depth of carbonation with time under accelerated exposure conditions is shown in Fig. 6 for all concretes. In general, a parabolic rate law applies to the recycled concrete as with the reference mixture. The slag cement mixture shows a slight deviation from this trend, suggesting the possibility of a different mechanism of carbonation. As expected, the rate of carbonation of the slag cement concrete is fractionally higher than the equivalent strength-grade concretes not containing slag. However, for portland cement specimens, recycled concrete carbonation rates appear to correlate well with cement content.

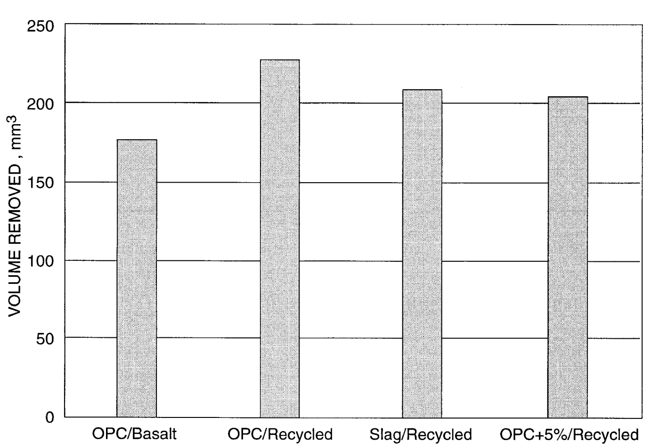

Fig. 5. Abrasion resistance of recycled concrete and reference concrete.

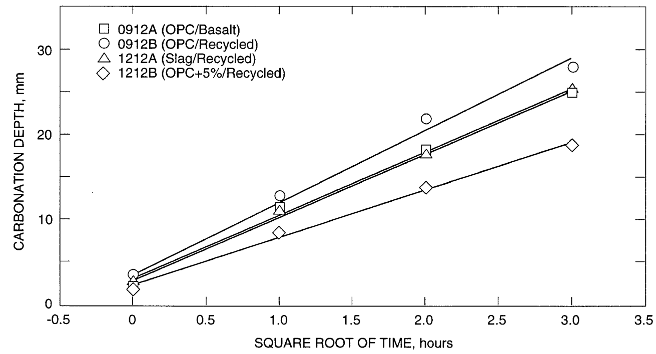

Fig. 6. Accelerated carbonation rates of concrete in 4% CO_2 atmosphere.

By excluding the slag cement concrete, some correspondence can be established between concrete strength and the rate of carbonation of the mixtures investigated for all remaining concretes. Hansen [1] cites earlier carbonation studies carried out in Japan under different experimental conditions that showed a 65% increase in carbonation rate relative to the control. This trend contrasts with the nominal 10% rise shown in Fig. 6 for plant-crushed and graded recycled aggregate.

3.7. Water absorption

Fig. 7 shows percent water absorption for specimens subjected to 6 days of moist curing after demolding and 21 days of drying at 50% RH and 23°C. The measured absorption of water indicates the relative quality of near-surface concrete properties.

Reference to Fig. 7 shows that under the curing regime employed, the lower porosity of the basalt aggregates in the normal concrete mixture restricts the rate of water absorption compared to the recycled concrete mixtures that have an average 25% higher absorption. The residual mortar attached to recycled concrete particles serves as a potential conduit for

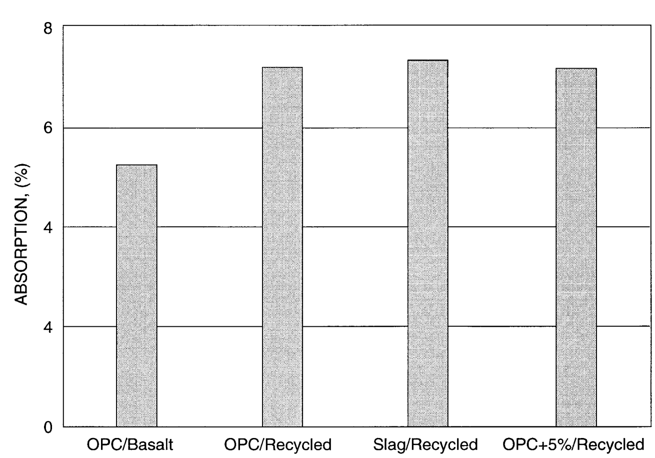

Fig. 7. Water absorption rates of recycled concrete and reference normal concrete.

moisture transport, especially under limited curing conditions for which the maturity of concrete matrix strength and aggregate:matrix bond properties remains critical.

As exemplified by the carbonation results, some correlation between the quality of the matrix and the transport of fluids or the degree of permeability is to be expected for fully cured specimens. Thus, for moist-curing conditions the contribution of aggregates to concrete permeability may be much less pronounced and thus provide a better indicator of recycled concrete durability under service conditions.

4. Conclusions

1. Plant processing of recycled aggregate produces relatively smoother spherical particles, which leads to improved concrete workability in comparison with natural basalt aggregate concrete with equivalent grading and ratio of fine to coarse aggregate.

2. For mixtures with similar volumetric mixture proportions and workability, there was no significant difference at the 5% confidence level in the 28-day compressive strengths of concrete made with commercial recycled aggregate and strength obtained for normal weight natural basalt aggregate concrete. Higher drying shrinkage values are however observed.

3. Tensile strength of recycled concretes as measured by the splitting tensile method on specimens cured for periods up to 365 days, showed no statistically significant reduction in strength in the period from 91 to 365 days.

4. Concrete containing recycled aggregate as the coarse aggregate fraction reduced the abrasion resistance by about 12% compared to the reference concrete made with basalt aggregates.

5. Examination of water absorption and carbonation rates have shown little difference between commercially produced recycled concrete and the reference concrete having a cement content of 242 kg/m^3.

6. Ratios of splitting tensile strength/compressive strength were found to be in good agreement with conventional values derived for concretes made with normal-weight natural aggregates.

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