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Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate

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ABSTRACT

The suitability of using more “sustainable” concrete for wind turbine foundations and other applications involving large quantities of concrete was investigated. The approach taken was to make material substitutions so that the environmental, energy and CO_2-impact of concrete could be reduced. This was accomplished by partial replacement of cement with large volumes of fly ash or blast furnace slag and by using recycled concrete aggregate.

Five basic concrete mixes were considered. These were: (1) conventional mix with no material substitutions, (2) 50% replacement of cement with fly ash, (3) 50% replacement of cement with blast furnace slag, (4) 70% replacement of cement with blast furnace slag and (5) 25% replacement of cement with fly ash and 25% replacement with blast furnace slag. Recycled concrete aggregate was investigated in conventional and slag-modified concretes. Properties investigated included compressive and tensile strengths, elastic modulus, coefficient of permeability and durability in chloride and sulphate solutions. It was determined that the mixes containing 50% slag gave the best overall performance. Slag was particularly beneficial for concrete with recycled aggregate and could reduce strength losses. Durability tests indicated slight increases in coefficient of permeability and chloride diffusion coefficient when using recycled concrete aggregate. However, values remained acceptable for durable concrete and the chloride diffusion coefficient was improved by incorporation of slag in the mix. Concrete with 50% fly ash had relatively poor performance for the materials and mix proportions used in this study and it is recommended that such mixes be thoroughly tested before use in construction projects.

1. Introduction

Minimising the environmental impact and energy- and CO_2-intensity of concrete used for construction is increasingly important as resources decline and the impact of greenhouse emissions becomes more evident. Thus, it is logical to use life cycle and sustainable engineering approaches to concrete mix design. This requires several elements: maximizing concrete durability, conservation of materials, use of waste and supplementary cementing materials, and recycling of concrete. Waste and supplementary cementing materials such as fly ash, blast furnace slag, silica fume, rice husk ash and metakaolin can be used as partial replacements for portland cement. These materials can improve concrete durability, reduce the risk of thermal cracking in mass concrete and are less energy- and CO_2-intensive than cement. Use of aggregate obtained from crushed concrete is an example of recycling and conservation of raw materials.

Examples of developments in sustainable philosophies for concrete have been published [1–6]. Much research has been performed on the use of high volumes of fly ash and other supplementary cementitious materials to produce more sustainable and durable concrete [7–10]. Recycled concrete is becoming of increasing interest for use as aggregate in structural concrete and recent research has examined its performance [11–22].

The objective of the research described in this paper was to assess the properties of concrete that combine both supplementary cementitious materials and recycled concrete aggregate. The application of particular interest was wind turbine foundations since these use large quantities of concrete. A target 28 day compressive strength of 40 MPa was sought, in addition to durability in sulphate- and chloride-bearing environments to which onshore and offshore concrete foundations may be exposed. The mixes contained relatively high amounts of fly ash, blast furnace slag and combinations of both. The mixes were tested for basic mechanical and hydraulic properties in addition to durability in marine environments.

2. Experimental procedure

2.1. Materials and concrete mix design

Concrete mixes containing either natural or recycled concrete aggregates were studied and compared. Five different mix designs were investigated for the concrete with natural aggregate. The first of these was a control mix and did not contain any

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Table 1
Chemical composition and physical properties of cement, fly ash and blast furnace slag.

	Cement	Fly ash	Slag
CaO (wt%)	63.25	5.54	39.84
SiO_2 (wt%)	20.80	47.58	38.00
Al_2O_3 (wt%)	4.61	26.42	7.52
Fe_2O_3 (wt%)	2.59	12.19	0.31
MgO (wt%)	4.17	0.90	10.54
Na_2O (wt%)	0.16	1.5	0.32
K_2O (wt%)	0.50	1.9	0.38
SO_3 (wt%)	2.70	1.08	0.16
LOI (wt%)	0.90	2.20	1.42
Blaine fineness (m^2/kg)	364	341	554
Specific gravity	3.15	2.35	3.00

Table 2
Mix proportions of concrete with natural aggregate.

	100 OPC	50 FA	50 BFS	70 BFS	25 FA/25 BFS
Cement (kg/m^3)	390.4	190.3	195.4	117.3	191.0
Fly ash (kg/m^3)	0	190.3	0	0	95.5
BFS (kg/m^3)	0	0	195.4	273.6	95.5
Water (kg/m^3)	156.3	152.4	156.5	156.4	153.0
Sand (kg/m^3)	739.1	720.7	739.7	738.0	723.1
Aggregate (kg/m^3)	1118.2	1090.3	1119.1	1117.9	1094.0
Superplasticizer (l/m^3)	3.90	3.81	3.91	3.91	3.82
Yield (kg/m^3)	2405	2345	2407	2404	2353
Slump (mm)	75	170	65	60	130

fly ash or ground granulated blast furnace slag. Two of the mixes contained 50% replacement of cement with either fly ash or slag and one contained 70% slag. The final mix used 25% fly ash and 25% slag as cement replacement. The cement used was ASTM C 150 Type I portland cement. The fly ash was ASTM C 618 Class F and the blast furnace slag was Grade 120 (ASTM C 989). The chemical analysis and physical properties of the cement, fly ash and slag are presented in Table 1. The use of 50–70% slag as partial replacement for cement is well established for improving concrete durability [23]. Class F fly ash is usually added cement replacement levels of 15–25% [23]. The higher fly ash content of 50% studied was based on successful results at a similar level reported by others [7–10].

The silica sand used conformed to ASTM C 33 and the natural coarse aggregate was round, smooth siliceous stone sieved between 6.35 and 12.7 mm. Both the fine and coarse aggregates were oven dried at 105 °C prior to use. Sodium naphthalene sulphonate superplasticizer (Rheobuild 1000) was used to improve concrete workability. All mixes had a water/cementitious material ratio of 0.4. The mix proportions, yield and slump are presented in Table 2.

Selected experiments were performed on concrete mixes that used recycled concrete as coarse aggregate. The recycled concrete was obtained from a 20-year-old concrete residential patio slab that had been broken up with a jackhammer. The original concrete mix design was unknown. However, Schmidt hammer tests indicated an approximate compressive strength of 25–30 MPa. No further crushing or treatment was undertaken. The concrete had not been exposed to deicing salts. The original aggregate in the concrete patio was round siliceous stone with nominal maximum diameter of 38 mm. The recycled concrete was sieved into three size fractions: 6.35–12.7 mm, 12.7–19.0 mm, and 19–25.4 mm. The recycled concrete aggregate (RCA) consisted of a combination of relatively smooth pieces of unfractured stone, angular pieces of either mortar adhering to stone or mortar itself, and angular pieces of fractured stone. The smallest size fraction tended to have a greater proportion of mortar and lower proportion of unfractured stone than the larger size fractions. Fig. 1 shows the different aggregates and morphologies. The specific gravity and absorption of the recycled concrete and natural aggregates were measured in accordance with ASTM C 127 and the results are presented in Table 3.

Fly ash was excluded from mixes containing RCA due to relatively poor performance in concrete with natural aggregate. Initial mix trials with RCA in oven dried condition produced concrete that was very stiff and exhibited zero slump. These

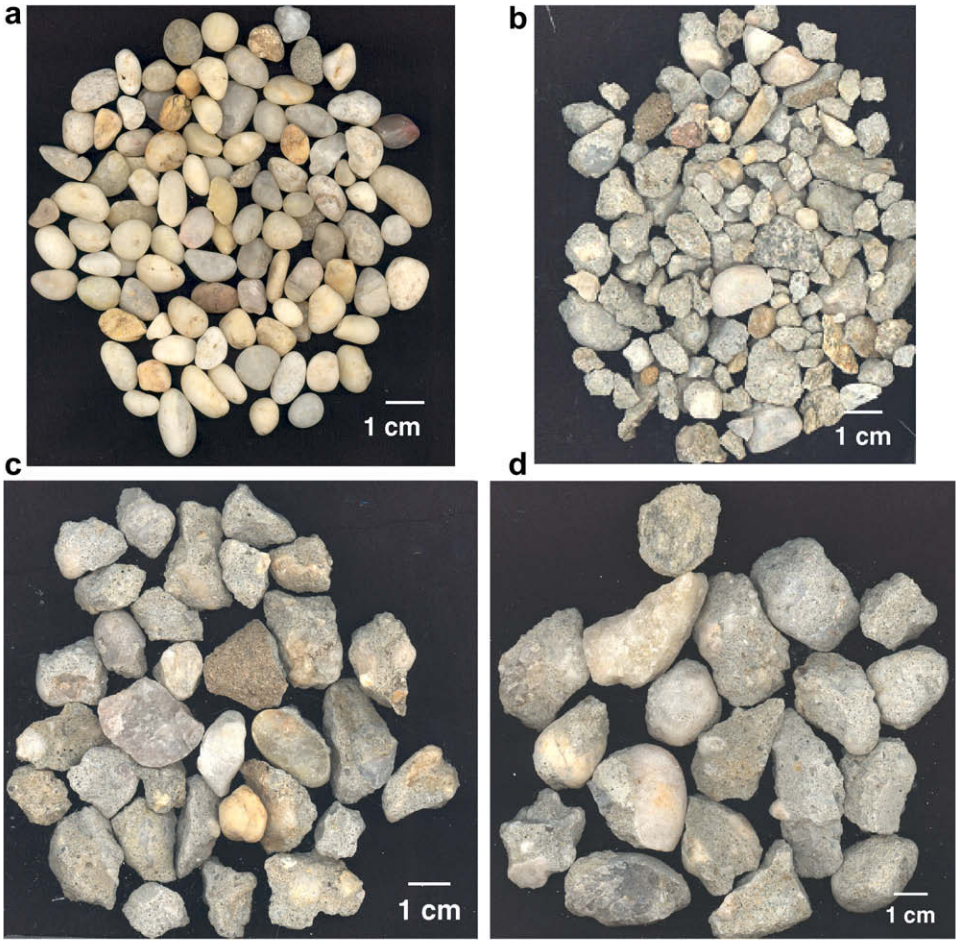

Fig. 1. Different aggregates used: (a) 6.35–12.7 mm natural siliceous stone; (b) 6.35 –12.7 mm recycled concrete; (c) 12.7–19.0 mm recycled concrete; and (d) 19–25.4 mm recycled concrete.

Table 3
Specific gravity and absorption data for aggregates (SSD = saturated surface dry).

Aggregate type	Bulk specific gravity (SSD)	Bulk specific gravity (dry)	Apparent specific gravity	Absorption (%)
6.35–12.7 mm natural	2.67	2.65	2.69	0.6
6.35–12.7 mm RCS	2.43	2.29	2.65	5.9
12.7–19.0 mm RCA	2.42	2.31	2.59	4.7
19.0–25.4 mm RCA	2.46	2.36	2.61	4.1

concrete mixes had rapid workability loss due to absorption of mix water by the aggregate and were difficult to compact. Therefore, in subsequent mixes the RCA was pre-soaked for 24 h and used in a saturated surface dry (SSD) condition. Three types of RCA mixes were investigated. The first contained 100% Portland cement, the second contained 50% cement and 50% blast furnace slag and the third contained 30% cement and 70% slag. The complete proportions for the mixes containing recycled concrete as aggregate are given in Table 4. The aggregate mass refers to the saturated surface dry condition. The water content refers to the added water and does not include that present in the recycled concrete aggregate after soaking. Mixes containing 6.35–12.7 mm RCA are designated by the suffix "RCS" and mixes with 12.7–19 mm and 19–25.4 mm RCA are designated by the suffix "RCA".

2.2. Mixing and casting procedure

The concrete was mixed in a laboratory pan mixer. The coarse and fine aggregates were first dry blended for 1 min. Cement and any fly ash and/or slag were then added and dry blended for a further minute. Two thirds of the water–superplasticizer mix was added and mixing continued for another minute. The remaining water and superplasticizer were then added and the total mixing time was 5 min. Concrete was cast and consolidated in accordance with ASTM C 192 and vibrated on a vibrating table until large bubbles ceased to appear on the top surface.

2.3. Curing

All concrete specimens were demoulded after 24 h and cured in water at 23 °C. The curing period for different tests varied as discussed below.

2.4. Mechanical properties

The mechanical properties of the concrete investigated included compressive and tensile strengths and elastic modulus. The development of compressive strength in the concrete mixes was investigated. Concrete specimens were cast as cylinders, 102 mm diameter and 204 mm high, for compressive strength tests. The specimens were cured for periods of 7, 14, 28 and 84 days. After curing, the specimens were capped and tested in accordance with ASTM C 39 using a Forney compression tester. Six specimens per mix were tested at each age.

Cylindrical specimens, 152 mm in diameter and 305 mm high, were used in a series of splitting tensile strength tests following ASTM C 496. The materials tested included either natural or large recycled concrete aggregate. All cylinders were cured in water at 23 °C for 28 days and six specimens per mix were tested.

The dynamic elastic modulus was measured on concrete with natural and large recycled concrete aggregate. Three beams per mix were tested using the method described in ASTM C 215. The beams were 76 mm by 102 mm by 406 mm and were cured in water at 23 °C for 28 days.

Table 4
Mix proportions of concrete with recycled concrete aggregate (SSD = saturated surface dry).

	100 OPC-RCS	50 BFS-RCS	100 OPC-RCA	50 BFS-RCA	70 BFS-RCA
Cement (kg/m^3)	370.4	184.5	394.8	196.1	117.7
BFS (kg/m^3)	0	184.5	0	196.1	274.4
Water (kg/m^3)	148.2	147.6	157.9	156.7	156.9
Sand (kg/m^3)	700.1	697.6	748.0	743.4	741.6
6.35–12.7 mm SSD aggregate (kg/m^3)	1122.9	1118.9	0	0	0
12.7–19.0 mm SSD aggregate (kg/m^3)	0	0	350.5	348.2	347.8
19.0–25.4 mm SSD aggregate (kg/m^3)	0	0	708.5	704.8	705.3
Superplasticizer (l/m^3)	3.70	3.69	3.95	3.92	3.92
Yield (kg/m^3)	2279	2271	2316	2302	2300
Slump (mm)	65	70	85	85	80

2.5. Coefficient of permeability (hydraulic conductivity)

The water permeability (hydraulic conductivity) of different concrete mixes under saturated conditions was measured in a flexible wall triaxial cell permeameter on cylindrical specimens 102 mm diameter and 90 mm long. The permeant was de-aired tap water at room temperature. The applied pressure gradient was 207 kPa over the length of the specimen. The confining pressure applied to seal a latex membrane to the side surface of the concrete specimen was 414 kPa. The experimental set-up followed that given in ASTM D 5084. Tests commenced after a curing period of 84 days. The specimens were vacuum saturated with de-aired water prior to measurement. Volumetric flow rates in and out of the specimens were monitored and measurements commenced when equilibrium was reached after approximately 24–48 h. The test duration after achievement of equal flow rates was 48–72 h.

2.6. Chloride diffusion coefficient

The durability of different concrete mixes exposed to artificial seawater was investigated. The primary initial interest was for offshore wind turbine foundations and the results are applicable to other marine applications. The chloride diffusion coefficient was determined as a measure of durability as this property determines the time to corrosion initiation of embedded reinforcement. The method used was similar to that given by ASTM C 1556 except that seawater was used instead of a 165 g/l NaCl solution. The composition of the seawater was based on ASTM D 1141 and is given in Table 5. Cylinders 152 mm diameter and 305 mm high were cast and cured for 28 days. Three specimens per mix were cast. After curing the cylinders were coated on all surfaces except the top with an epoxy coating to ensure one dimensional chloride ingress. The cylinders were then immersed in a tank containing the artificial seawater at 23 °C. The seawater was replaced with a fresh solution every month. The total exposure period was 1 year after which the concrete was analysed for chloride profile by grinding successive layers of concrete as per ASTM C 1556 and analysing for acid soluble chloride by potentiometric titration as described in ASTM C 1152. The apparent diffusion coefficient was calculated using the method given in ASTM C 1556.

2.7. Exposure to sulphate solution

Degradation of concrete due to sulphates present in soil, groundwater or seawater is a potential durability concern for many applications using concrete, including onshore and offshore wind turbine foundations. Therefore, the resistance of concrete with natural or recycled concrete aggregate to sulphate attack was determined by exposing beams to alternating wet–dry cycles in a 50 g/l (0.35 M) solution of Na_2SO_4 at 23 °C. The selected sulphate concentration was based on ASTM C 1012. The beams were 76 mm by 102 mm by 406 mm and were cured for 28 days prior to exposure to the Na_2SO_4. The sulphate solution was changed on a monthly basis and the total test duration was 12 months. The dynamic elastic modulus of the beams was measured once per month in order to monitor degradation. All measurements were taken when the beams were in a wet condition.

3. Results and discussion

3.1. Workability

Other than the trial concrete mixes containing dry RCA, all mixes exhibited good workability and were readily consolidated under laboratory conditions. Fly ash gave the most significant improvement in workability and required a shorter vibration time. This was reflected in the slump measurements presented in Table 2. Workability was similar for the mixes with different sized RCA and the slump values were 65–85 mm as shown in Table 4. In addition, the workability of mixes with natural and recycled aggregate was similar for the same level of slag replacement. Although the RCA mixes were expected to be less workable due to the rougher surface texture of crushed particles and greater angularity com-

Table 5
Composition of artificial seawater.

Component	Concentration (g/l)
NaCl	24.72
KCl	0.67
$CaCl_2 \cdot 2H_2O$	1.36
$MgCl_2 \cdot 6H_2O$	4.66
$MgSO_4 \cdot 7H_2O$	6.29
$NaHCO_3$	0.18

pared with the smooth, rounded natural stone, this seemed to be compensated by using the RCA in saturated surface dry condition.

3.2. Morphology

Figs. 2 and 3 show the macrostructure of slag-modified concrete cross-sections with natural and small recycled concrete aggregate. The different subsets of aggregate within the recycled concrete aggregate are indicated in Fig. 3. The figures also show the different shape of the aggregates ranging from near-spherical for the natural stone to elongated and angular for the mortar component of the recycled material.

3.3. Compressive strength

The results of the compressive strength tests are presented in Figs. 4–6. The mean and standard deviation for six specimens per mix are given. The compressive strength results for concrete containing natural aggregate in Fig. 4 show that partial replacement

Fig. 2. Cross-section of 50 BFS concrete with 6.35–12.7 mm natural stone aggregate.

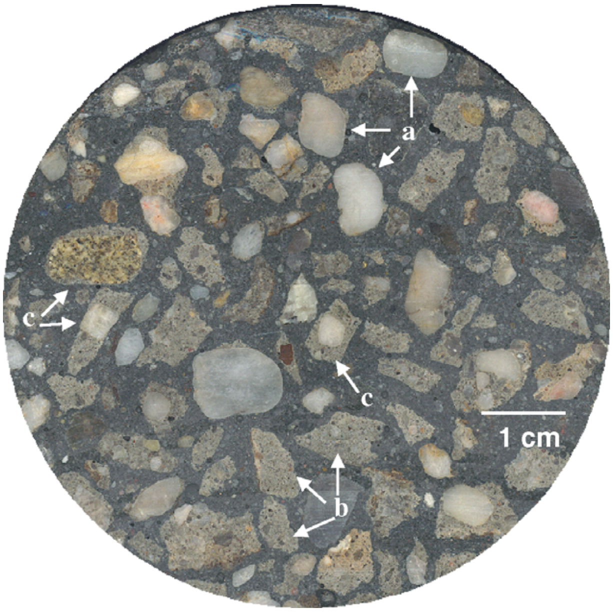

Fig. 3. Cross-section of 50 BFS concrete with 6.35–12.7 mm recycled concrete aggregate showing examples of: (a) clean stone; (b) mortar; and (c) stone with surrounding mortar.

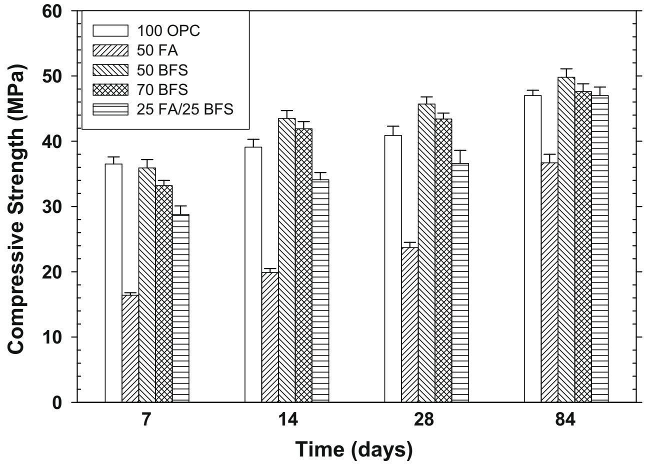

Fig. 4. Compressive strength of concrete with natural aggregate versus time.

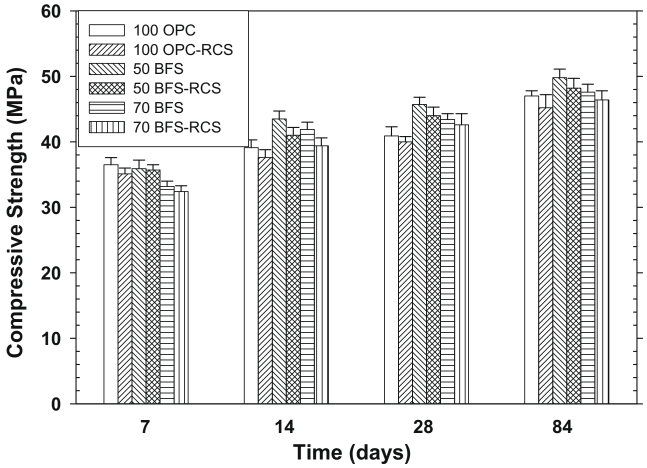

Fig. 5. Compressive strength of concrete with natural aggregate and small recycled aggregate (RCS) versus time.

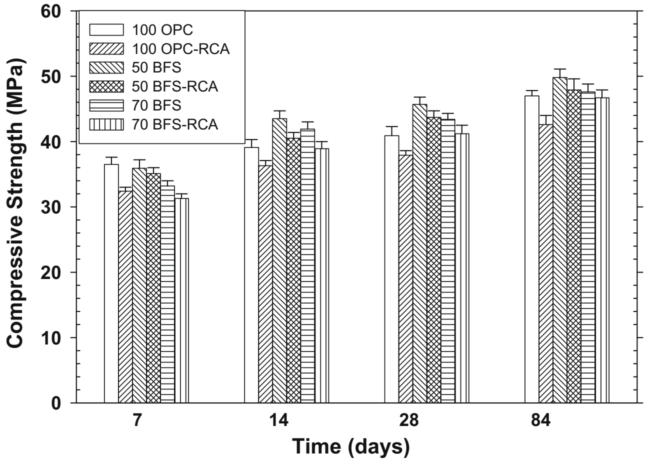

Fig. 6. Compressive strength of concrete with natural aggregate and large recycled aggregate (RCA) versus time.

of cement with 50% fly ash results in decreased strength, particularly at 7 days. The 7 day compressive strengths ranged from 16.4 MPa for the 50 FA mix to 36.5 MPa for the 100% OPC mix. The mixes with slag showed slightly reduced 7 day strength compared with the 100% OPC mix of 33.2 MPa (70% slag) and 35.9 MPa (50% slag).

Reduction of early compressive strength for concrete containing high levels of fly ash is established and efforts have been made to overcome this [24]. Although the strength of the 50% fly ash mix did improve with curing, its strength at 84 days was less than 40 MPa and it remained the weakest of all mixes tested. For this reason, fly ash was omitted from the mixes containing RCA. It is apparent that 50% replacement of cement with the fly ash used in this study was detrimental to strength up to 84 days and that more detailed investigation would enable determination of an optimal level. It is noted that fly ash has variable chemical and physical properties depending on the source [24,25] and that performance of high volume fly ash mixes using different sources of materials may vary accordingly. In contrast, blast furnace slag tends to be more uniform in chemical composition and physical characteristics [23] and is therefore more likely to give more consistent results.

The results for the 50% fly ash concretes can be compared with other research [7] in which different sources of US fly ashes were used at replacement levels of 58%. In general, higher strengths were obtained for a variety of fly ash chemistries than those measured in this work. However, it is noted that Bilodeau et al. [7] used a significantly lower water/cementitious material ratio of 0.33 versus 0.40, although the total cementitious content was somewhat lower (362 kg/m^3 versus 390.8 kg/m^3). The 7, 28 and 91 day compressive strengths reported by Bilodeau et al. [7] were 18.2–27.6, 26.9–43.4 and 39.7–50.9 MPa, respectively. This compares with 7, 28 and 84 day compressive strengths of 16.4, 23.7 and 36.7 MPa, respectively, in this study for 50% fly ash. These results are similar in magnitude to the lower range obtained by Bilodeau [7] and perhaps not so low considering the higher water/cementitious material ratio used in this study. It is noteworthy that significant differences in compressive strengths for high volume fly ash concretes with different brands of ASTM Type I cement were obtained by Bilodeau et al. [7]. The low-alkali cement with lower tricalcium aluminate content gave lower compressive strengths. Another possible explanation for the poor performance of the 50% fly ash mixes in terms of strength and other properties discussed below is that there was some incompatibility between the fly ash, cement and/or dosage of superplasticiser used in this work. Such issues have been reported previously [26]. Alternatively, the fly ash may have had deleterious surface deposits or other issues affecting reactivity [25].

Inclusion of 50% blast furnace slag in the natural aggregate mixes was beneficial, giving the highest strength at 28 and 84 days of all the mixes studied with values of 45.7 and 49.8 MPa, respectively. Blending 25% fly ash and 25% slag resulted in improved strengths at all ages compared with the 50% fly ash mix, particularly at 84 days. Increasing the cement replacement level to 70% slag resulted in slightly reduced strength compared with concrete containing 50% slag. The maximum mean strength difference was 2.7 MPa at 7 days. The results demonstrate that 40 MPa compressive strength can be readily achieved at 28 days with a mix design containing 50 or 70% slag as partial replacement of cement and that long term strength under wet curing conditions can also be achieved with mixes containing 25% fly ash/25% slag.

Fig. 5 shows the compressive strength development for mixes with small recycled concrete aggregate. At 7 days the strengths for the 100% OPC and 50% slag mixes with and without small RCA were similar, while the 70% slag concretes had slightly lower strengths. By 14 days there was a distinction in that the 50% slag mix with small RCA had significantly higher compressive strength than the mix without slag. At 28 days both the 50% and 70% slag mixes had improved compressive strength compared with the 100% OPC mix. Mixes with small RCA tended to have lower compressive strength than those with natural aggregate for the same binder at all ages. However, this difference was generally limited to less than 2 MPa and all mixes reached the 28 day target strength of 40 MPa.

The strength development of the mixes with large RCA is indicated in Fig. 6 and also compared with that for concrete with natural aggregate. In general, lower compressive strengths were obtained for the concrete incorporating the blend of larger sized RCA than the smaller natural or recycled aggregate. The results showed that slag was beneficial for the RCA mixes at all ages and that the difference in mean strength between natural and RCA concretes was lower for mixes containing slag. The 50% and 70% slag mixes had 28 day mean compressive strengths of 43.7 and 41.2 MPa, respectively, compared with 37.9 MPa for the 100% OPC mix. Prolonged wet curing increased the compressive strength further with the 50% slag mix achieving a mean compressive strength of 47.9 MPa at 84 days. Comparison between Figs. 5 and 6 suggests that, in the absence of slag, notably higher compressive strengths were achieved with smaller sized RCA.

Recent research on RCA concrete has generally shown that compressive strength is reduced by RCA as compared to natural aggregate [13–15,20]. However, equivalent strength [16,21] and higher strengths [14] have also been reported. The effect of RCA on compressive strength appears to be highly dependent on original concrete quality and mix proportions, in addition to water/cement ratio, and workability. For the type of aggregates and mix proportions studied in the present research it was evident that strength decrease associated with RCA could be mitigated with slag and that adequate strengths could be achieved. It has been shown [21,27] that the microstructural characteristics of the interfacial transition zone between RCA and cement paste is important in influencing concrete strength. Therefore, it is hypothesized that incorporation of slag improved interfacial bonding between paste and RCA, thus resulting in higher strength. Slag has been shown to densify the microstructure and increase the microhardness of the interfacial transition zone for concrete with natural aggregate [28] and this may possibly explain improvements achieved for RCA concrete with slag. Further work will examine the interfacial microstructure to ascertain the reasons for this improvement.

3.4. Tensile strength

The splitting tensile strengths of the concrete mixes are compared in Fig. 7. As shown, the splitting tensile strength of the natural aggregate mixes was increased by incorporation of 50% and 70% slag and decreased by incorporation of 50% fly ash. The 28 day mean splitting tensile strength ranged from 1.69 to 2.83 MPa for the 50% fly ash and 50% slag mixes with natural aggregate, respectively. The FA/BFS blend had a mean strength in between that of the mixes with either 50% slag or 50% fly ash with a value of 2.41 MPa.

The mean tensile strengths of the RCA mixes were 0.02–0.32 MPa lower than those of the equivalent natural aggregate formulations. Replacement of 50% cement with slag led to improved tensile strength for the RCA formulations and the mean value was 2.68 MPa compared with 2.29 MPa and 2.23 MPa for 100% OPC and 70% slag, respectively. The results were consistent with the achievement of enhanced compressive strength for slag-modified RCA mixes. Increased compressive and splitting tensile strengths of RCA concrete using slag cement (65% Portland cement/35% blast furnace slag) have also been measured by others [16].

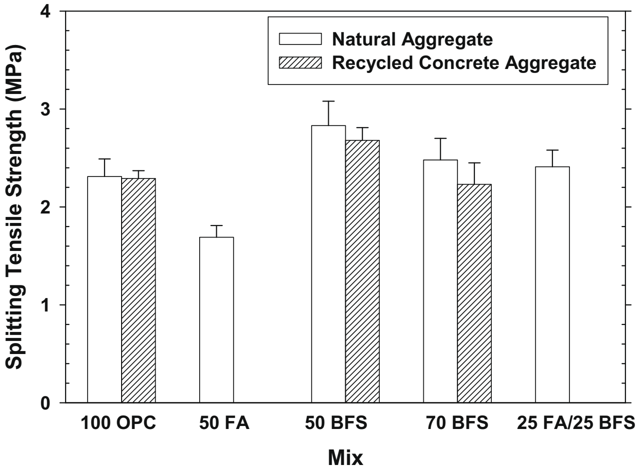

Fig. 7. Splitting tensile strength of natural and recycled aggregate (RCA) concrete mixes at 28 days.

3.5. Fracture surfaces

Figs. 8 and 9 compare the fracture surfaces of split specimens with natural and large recycled concrete aggregate. Examination of the fracture surface in Fig. 8 indicated that, in addition to the matrix itself, fracture was primarily at the stone/matrix interface and through stone for the natural aggregate mixes. The RCA mixes (Fig. 9) primarily exhibited fracture through old mortar particles and through stone. Fracture at relatively bare stone/matrix interfaces occurred to a lesser degree. The interfaces between old mortar and new matrix generally remained intact and this observation implies good interfacial bonding.

3.6. Elastic modulus

The dynamic elastic modulus data for the different concrete mixes at 28 days are presented in Fig. 10. The 28 day dynamic elastic moduli of the 100% OPC and 50% slag mixes were essentially equivalent and were 47.2 and 47.4 GPa, respectively. Addition of fly ash to the concrete caused the modulus to decrease, particularly for the 50 FA mix which had a modulus of 37.7 GPa. Replacing the cement with 70% slag caused slight reduction in the dynamic modulus to 45.6 GPa. Elastic modulus was significantly decreased for concrete containing RCA and the values ranged from 36.2 GPa for the 70% slag mix to 40.1 GPa for the 100% OPC mix. Decrease in elastic modulus when RCA is used is consistent with other findings [17,19,20]. The lower modulus for the RCA mix may have an impact on the structural response of this type of concrete. For example, a lower stiffness material may be less susceptible to cracking.

3.7. Coefficient of permeability

The results in Fig. 11 show that the coefficients of permeability of the 100% OPC, 50% slag, 70% slag and 25% fly ash/25% slag after 84 days of wet curing were very similar and ranged between 1.0

Fig. 8. Fracture surface of 50 BFS concrete with natural aggregate showing examples of: (a) unfractured stone; (b) stone pullout; and (c) fractured stone.

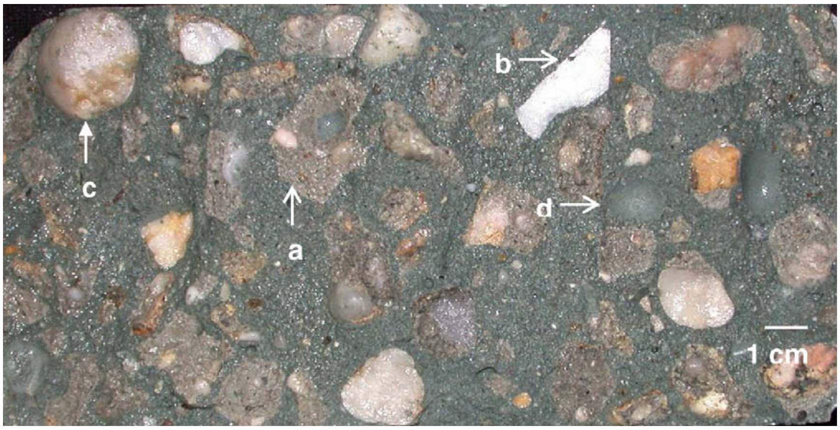

Fig. 9. Fracture surface of 50 BFS concrete with recycled concrete aggregate showing examples of: (a) fractured old mortar; (b) fractured stone; (c) unfractured stone and (d) stone pullout.

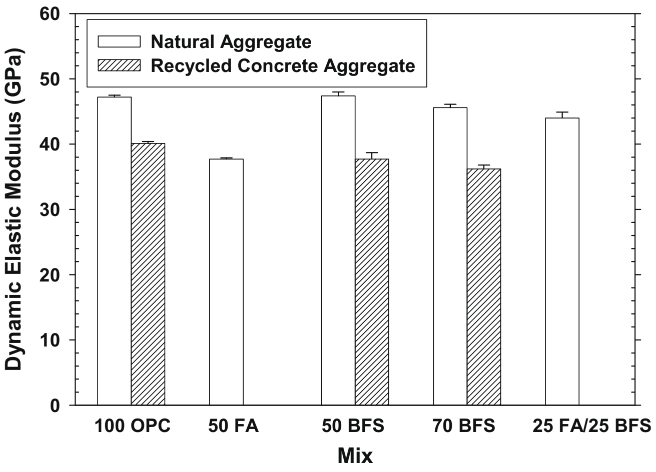

Fig. 10. Dynamic elastic modulus of concrete with natural aggregate and large recycled concrete aggregate at 28 days.

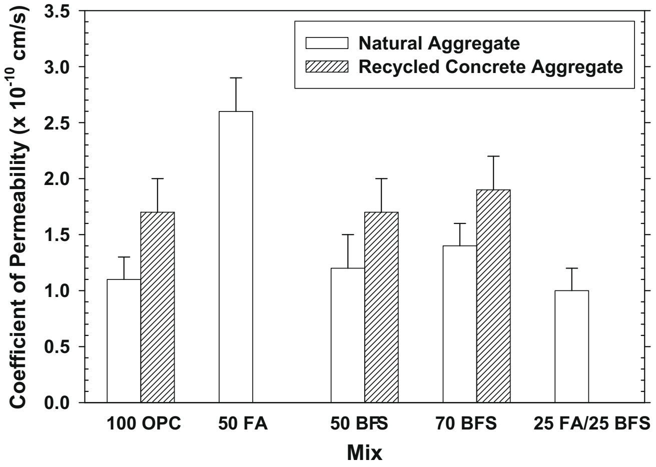

Fig. 11. Coefficient of permeability for different concrete mixes after 84 days curing.

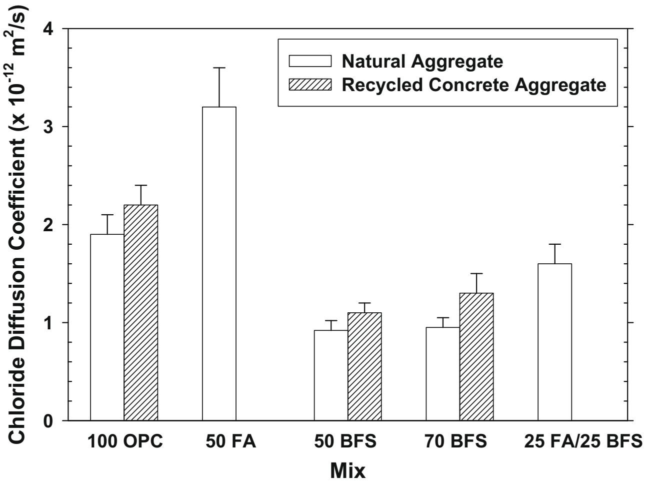

Fig. 12. Chloride diffusion coefficient for different concrete mixes with natural and large recycled aggregate after 1 year in artificial seawater.

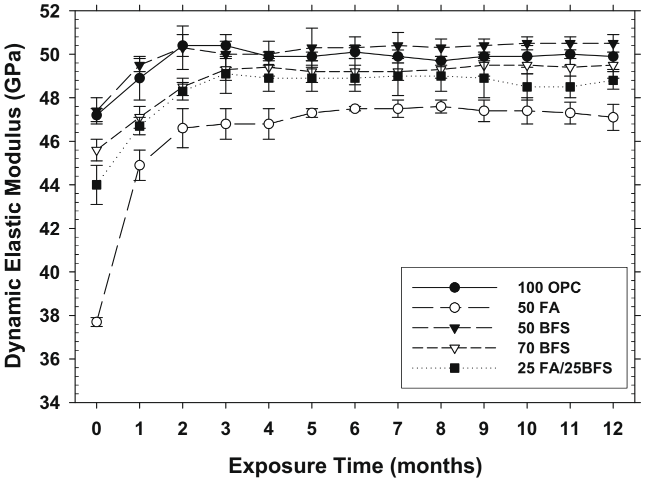

Fig. 13. Dynamic elastic modulus versus exposure time for concrete with natural aggregate exposed to sodium sulphate solution.

and 1.4 × 10^{-10} cm/s. Partial replacement of cement with 50% fly ash led to a significant increase in permeability (2.6 × 10^{-10} cm/s). Use of RCA also resulted in increased permeability of 1.7–1.9 × 10^{-10} cm/s, although the impact was not as great as that of 50% fly ash. The higher permeability of the RCA mixes is probably associated with the mortar in the RCA. Residual mortar in RCA has previously been suggested as a conduit for water transport [14]. In all cases the coefficient of permeability was less than 3 × 10^{-10} cm/s and this is acceptable for durable concrete.

3.8. Chloride diffusion coefficient

Fig. 12 indicates that the chloride diffusion coefficients after exposure to artificial seawater for 1 year were generally of the order of 10^{-13}–10^{-12} m^2/s. This is indicative of durable concrete that would provide suitable protection to embedded steel reinforcement from chloride-induced corrosion. The mean diffusion coefficients were similar for the 50% and 70% slag mixes and were 9.2 and 7.8 × 10^{-13} m^2/s, respectively. This compared with 1.9 × 10^{-12} m^2/s for 100% OPC and 3.2 × 10^{-12} m^2/s for 50% fly ash mixes. Hence, incorporation of slag resulted in reduced chloride diffusion coefficients. The findings are similar to results reported previously for concrete with 70% and 75% slag showing reduced diffusion coefficients [29,30] but are in conflict with other results for fly ash-modified concrete [24,29].

Substitution of recycled concrete aggregate for natural stone caused an increase in chloride diffusion coefficient. This degree of increase was mitigated by the use of slag.

The results can be compared with previous studied on resistance to chloride penetration. Gonçalves et al. [22] found increased diffusion coefficients for concrete containing recycled concrete aggregate although the difference was reduced at higher cementitious contents. Otsuki et al. [21] reported that the depth of chloride penetration of concrete exposed to 3% NaCl solution for 28 days increased when recycled concrete was substituted for natural aggregate, although the difference was less pronounced at low and high water/cement ratios (0.25 and 0.70, respectively).

3.9. Sulphate resistance

Figs. 13 and 14 show the mean dynamic elastic modulus versus exposure time of the natural aggregate and RCA beams exposed to the 5% sodium sulphate solution. The initial increase in dynamic modulus between 1 and 3 months for all mixes was attributed to ongoing hydration. After 12 months of exposure the 100% OPC

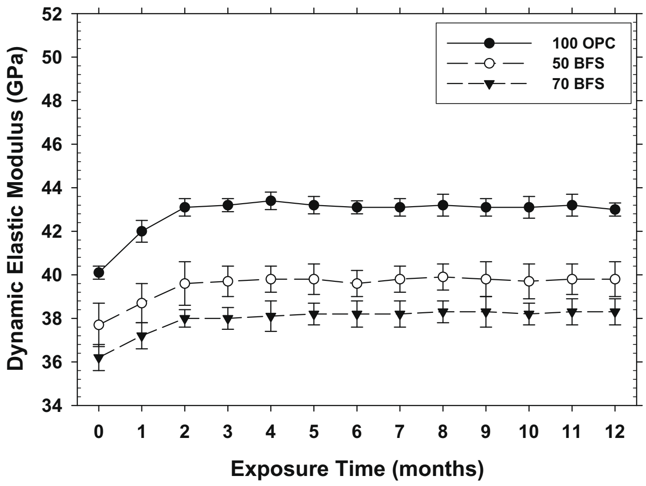

Fig. 14. Dynamic elastic modulus versus exposure time for concrete with recycled concrete aggregate exposed to sodium sulphate solution.

and 50% fly ash mixes showed slight expansive cracking and softening on the edges of the beam for both types of aggregate. This did not cause changes to the dynamic modulus since the deterioration was limited to the surface. Similar behaviour has been observed for mortars exposed to a magnesium sulphate solution for 5 years where surface attack did not cause decrease in modulus [31]. The RCA mixes continued to have lower dynamic modulus than the natural aggregate counterpart but showed the same visual features. Longer term exposure is necessary to obtain more realistic indications of durability for extended service life. However, initial indications showed the superior performance of mixes containing slag and this is consistent with prior research on sulphate resistance [32].

4. Conclusions

The combined effects of partial cement replacement and use of recycled concrete aggregate to improve the sustainability of new concrete was investigated. The results indicated that concrete mixes containing 50% replacement of cement with blast furnace slag gave the best results in terms of mechanical properties and durability when either natural or recycled concrete aggregate was used. Recycled concrete aggregate was not significantly detrimental to strength, particularly when the concrete also contained slag. Hence, it was possible to produce concrete with a target 28 day compressive strength of 40 MPa suitable for many structural applications, including wind turbine foundations. Coefficient of permeability and chloride diffusion coefficient were increased to a small degree by fly ash or recycled concrete aggregate, although the values remained satisfactory for durable concrete. Elastic modulus was decreased when either fly ash or recycled concrete aggregate were incorporated in concrete. There appeared to be some incompatibility or possible contamination issues with the fly ash used in the research project which resulted in relatively poor performance of the mixes with 50% fly ash. This finding demonstrated that it cannot be assumed that all sources fly ash will necessarily improve the properties of concrete at high replacement levels and that detailed testing of specific materials and mix proportions is recommended before use in construction projects.

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