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Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement

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ABSTRACT

Milled waste glass was used as secondary cementitious material towards production of recycled aggregate concrete with improved strength and durability attributes. Experimental investigation of the novel concept of using milled waste glass, as partial replacement for cement, to overcome the drawbacks of recycled aggregate and the resulting concrete showed that waste glass, when milled to micro-scale particle size, is estimated to undergo pozzolanic reactions with cement hydrates, forming secondary calcium silicate hydrate (C–S–H). These reactions bring about favorable changes in the structure of the hydrated cement paste and the interfacial transition zones in recycled aggregate concrete.

Use of milled waste glass, as partial replacement of cement, is estimated to produce significant gains in strength and durability of recycled aggregate concrete. Milled waste glass was also found to suppress alkali-silica reactions. The encouraging test results are viewed to facilitate broad-based use of recycled aggregate and diversion of large quantities of landfill-bound mixed-color waste glass for a value-added use to produce recycled aggregate concrete incorporating milled waste glass.

1. Introduction

The growing environmental concerns, increasing scarcity of landfills, rapidly depleting sources of quality (virgin) aggregate in some regions coupled with the increasing haulage and growing landfill costs are the driving forces promoting the recycling of concrete demolition waste in new concrete. The recycling of construction waste, including concrete, and the landfill-bound constituents of the municipal solid waste stream, including glass which occurs largely as mixed-color waste glass with limited market value, are considered important steps towards sustainable construction practices.

Out of the over 2 billion tons of aggregate consumed each year in the US, only 5% comes from recycled sources such as demolished concrete [1]. About 300 million tons of construction and demolition (C&D) waste is generated in the US each year. About 50% of this is recovered for recycling, and the rest is landfilled [2–4]. A considerable proportion of recycled aggregate is used as roadfill. According to Mehta [5], the global concrete industry consumes close to 10 billion tons of sand and rocks (2002 data), and produces over 1 billion tons of C&D waste annually. Since aggregates constitute approximately 70% of concrete volume, the utilization of waste concrete as recycled aggregate can yield significant environmental impact. This encourages urgent steps towards increasing the recycling rate of demolished concrete as aggregate in new concrete construction.

The broad use of recycled aggregate in concrete is hindered by its higher water absorption (two to three times that of normal aggregate) and the increased shrinkage of the resulting recycled aggregate concrete. These drawbacks result largely from the old mortar/cement paste clinging to the surface of recycled aggregates as shown schematically in Fig. 1. According to Hansen and Narud [6], the volume percentage of the old mortar attached to the surface of aggregate varies between 25% and 35% when concrete with natural gravel is reduced to 16–32 mm particle size, about 40% in the case of recycled aggregate with 8–16 mm particle size, and near 60% in recycled aggregate with 4–8 mm particle size. Hasaba et al. [7] reported that 35.5% of old mortar is attached to natural gravel in recycled aggregate with 5–25 mm particle size produced from concrete with 24 MPa compressive strength. For the same size of recycled aggregate, the attached mortar fraction increased to 36.7% and 38.4% when the recycled aggregate was produced by crushing concretes with compressive strengths of 41 MPa and 51 MPa, respectively. According to Japanese studies [8], approximately 20% of cement paste is attached to the recycled aggregate with 20–30 mm particle size. Nixon [9] has concluded that the most significant difference between recycled aggregate and virgin aggregate is the markedly higher water absorption of the recycled aggregate. Tavakoli and Soroushian [10] found that the water absorption capacity of recycled aggregate reflects on the amount of cement paste adhering to the surface of the aggregate particles.

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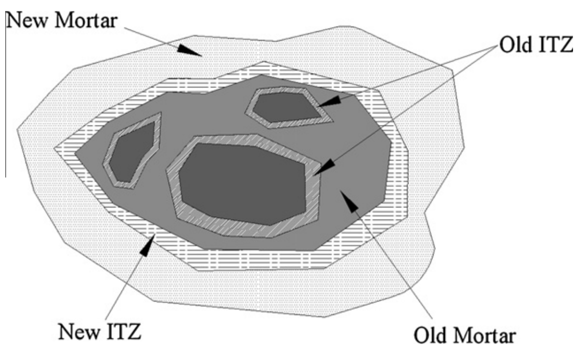

Fig. 1. A recycled aggregate within new mortar.

With increased quantity of the clinging paste, the drying shrinkage of the resulting concrete increased accordingly. They further reported that recycled aggregate concrete shows higher drying shrinkage than normal concrete, and the magnitude of the increase in drying shrinkage depends on the properties of the parent concrete from which the recycled aggregate was obtained. Recycled aggregate is a valuable resource; value-added consumption of recycled aggregate, as replacement for virgin aggregate in concrete, can yield significant energy and environmental benefits. Production and transport of virgin aggregates generate emissions representing 0.0046 million tons of carbon equivalent for each ton of virgin aggregate, compared to only 0.0024 million tons of carbon equivalent per ton of recycled aggregates [11]. Considering the global consumption of 10 billion tons/year of aggregate for concrete production, the net emission reductions resulting from the replacement of virgin aggregates with recycled aggregates can yield major environmental benefits. These benefits are bound to get more pronounced over time as the depletion of the sources of virgin aggregates force shipments over longer distances, while recycled aggregates is generally available locally. Large-volume use of recycled aggregate concrete requires resolution of the problems with increased water absorption and drying shrinkage of the resulting concrete.

The waste glass generated in the US in 2008 was about 12.2 million tons, 77% of which was disposed of in landfills [12]. The bulk of waste glass can be collected in mixed colors, and has limited markets. It is realized that mixed-color waste glass offers desired chemical composition and reactivity for use as a supplementary cementitious material (SCM) for enhancing the chemical stability, pore system characteristics (pore refinement, discontinuity, and pore filling), moisture resistance and durability of concrete. To achieve these benefits, waste glass needs to be milled to micro-scale particle size for accelerating its beneficial chemical reactions in concrete. These beneficial effects of milled waste glass can enhance the residual cement (which forms the interface in new concrete) occurring on the surface of recycled aggregates and are thus expected to improve the performance characteristics of recycled aggregate concrete.

An important factor that determines the ease with which a material can be recycled is the extent to which its composition varies. Traditional SCMs such as coal fly ash are subject to wide variations of material composition. Glass, however, has a minor variation in chemical composition. An in-depth study of the waste glass occurring in the solid waste stream has shown that the waste glass composition is highly consistent [13] which makes it a material of choice for recycling.

Earlier researchers have investigated the use of glass in normal concrete [13–19]. Polley et al. [20] investigated glass aggregate as substitute for fine aggregate. They observed that the long term compressive strength of concrete containing glass was higher than that of control mix. Dyer and Dhir [21] reported occurrence of pozzolanic reaction involving ground glass which resulted in higher C–S–H level in mixes containing ground glass when compared with control mix. Shayan and Xu [14] concluded that waste glass has a potential of being used as aggregate and pozzolan in concrete that could potentially replace traditional pozzolans such as fly ash and silica fume in concrete.

This research looks at the synergistic use of two waste materials, i.e., waste glass and demolished concrete (as recycled aggregate) and emphasizes the novel concept of using milled waste glass to over come the limitations of recycled aggregate and consequently recycled aggregate concrete. When milled waste glass is used in recycled aggregate concrete as partial replacement of cement, it interacts with calcium hydroxide available in the attached mortar/paste clinging to aggregate surface to form calcium silicate hydrate (C–S–H) which is the key binder among cement hydrates. This reaction can enhance the quality of the remnant cement paste on recycled aggregates, thus benefiting the strength, durability and dimensional stability of recycled aggregate concrete.

2. Materials and methods

2.1. Materials

Concrete mixes incorporating various percentages of recycled aggregate and control concrete mix designs incorporating 100% virgin aggregate were produced following the provisions of ACI 211.1-91 (weight-based batching) with either 100% Portland cement or with 20% replacement of cement with milled waste glass. Type I Portland cement, conforming to ASTM C 150 and mixed-color milled waste glass with an average particle size of 13 µm were used. Fig. 2 shows the scanning electron micrograph while Fig. 3 shows the particle size gradation curve of milled glass used in the experimental program. Crushed limestone virgin aggregate with a maximum size of 19 mm obtained from local quarry was used as coarse aggregate. The recycled aggregate having maximum particle size of 19 mm was obtained from a local C&D waste facility. The record showed that the parent concrete from which recycled aggregate was produced had a designed compressive strength of 28 MPa (4000 psi). It had been manufactured using Type I Portland cement, normal sand and crushed limestone aggregate. During the 30 years life of this concrete, it had not shown any signs of durability related problems including freeze thaw, sulfate attack and chloride attack. Normal sand was used as fine aggregate in all concrete materials. Table 1 shows physical properties of the virgin and recycled coarse aggregates as well as that of sand. The physical properties and chemical composition of the milled waste glass used in the experimental work are shown in Tables 2 and 3, respectively. Each type of mix design was produced with two different levels of water/cementitious (w/cm) ratios: 0.38 and 0.50. The water content of concrete mixes was adjusted to compensate for the difference in water absorption capacities of recycled and virgin aggregates. Water-reducing and air-entraining admixtures were also used in all mixtures. Surfactant based air entraining agent (with brand name of CATEXOL™ A.E. 260, manufactured by Axim) was used at a rate of 2.43 ml/kg of the cementitious material in all mixes. The water reducing agent (non-ionic surfactant based admixture known by brand name CATEXOL™ 1000 NP, manufactured by Axim) was used at a rate of 2.43 ml/kg in low w/cm mixes, and at a rate of 1.98 ml/kg in high w/cm mixes. Table 4 shows the concrete mix de-

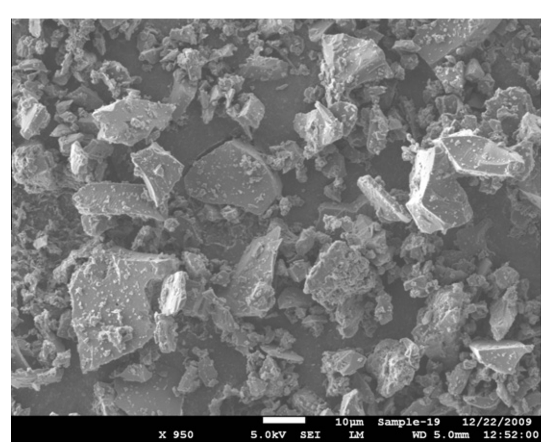

Fig. 2. SEM micrograph of milled waste glass.

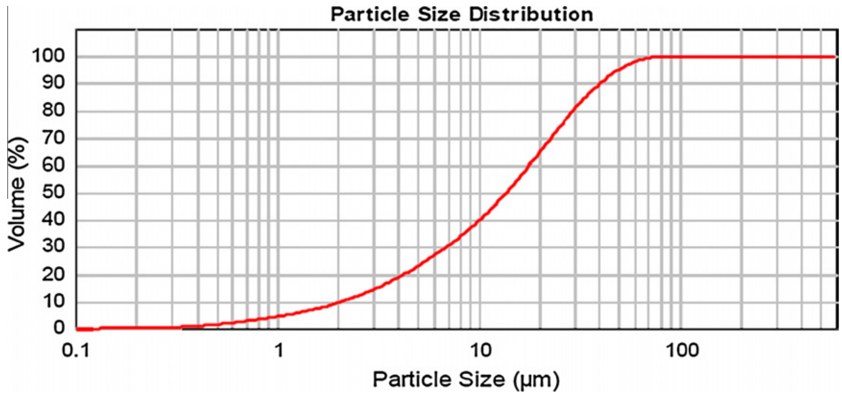

Fig. 3. Size gradation curve of milled waste glass.

Table 1
Physical properties of aggregates.

Aggregate type	Dry density (kg/m^3)	Bulk specific gravity	Bulk specific gravity (SSD)	Absorption (%)	Loss on abrasion (%)
Virgin	1743	2.57	2.65	2.28	22.8
Recycled	1446	2.30	2.40	4.35	31.6
Sand	2.86 (F.M.)	2.65	–	0.97	--

Table 2
Physical properties of milled waste glass.

Parameter	Value
% Passing # 325 mesh	97%
Specific gravity	2.46 gm/cc
Median particle size	13 µm
Moisture content	0.1%
Brightness	80%
Specific surface area	1.31 m^2/gm
Loss on ignition	0.4%

Table 3
Chemical composition of glass.

Compound	wt.% age
Silica (SiO_2)	68
Sodium oxide (Na_2O)	12
Calcium oxide (CaO)	11
Alumina (Al_2O_3)	7
Magnesium oxide (MgO)	1
Potassium oxide (K_2O)	<1
Iron oxide (Fe_2O_3)	<1
All other oxides combined	<1

Table 4
Mix designs of low w/cm concrete mixes.

	M1[a]	M2	M3	M4	M5
Virgin coarse aggregate (kg/m^3)	952	476	476	–	–
Recycled coarse aggregate (kg/m^3)	–	399[b]	399[b]	797[c]	797[c]
Sand (kg/m^3)	651	651	651	651	651
w/cm ratio	0.38	0.38	0.38	0.38	0.38
Cement content (kg/m^3)	468	468	375	468	375
Water content (kg/m^3)	178	178	178	178	178
Milled waste glass (kg/m^3)	–	–	94[d]	–	94[d]

[a] control mix.
[b] 50% replacement of virgin aggregate.
[c] 100% replacement of virgin aggregate.
[d] 20% by weight of cement.

signs involving different percentages of recycled aggregate and 100% normal aggregate for the low w/cm ratio mixes where as Table 5 shows the corresponding mixes for the high w/cm ratio mixes.

Table 5
Mix designs of high w/cm concrete mixes.

	M6[a]	M7	M8	M9	M10
Virgin coarse aggregate (kg/m^3)	952	476	476	–	–
Recycled coarse aggregate (kg/m^3)	–	399[b]	399[b]	797[c]	797[c]
Sand (kg/m^3)	651	651	651	651	651
w/cm ratio	0.50	0.50	0.50	0.50	0.50
Cement content (kg/m^3)	468	468	375	468	375
Water content (kg/m^3)	234	234	234	234	234
Milled waste glass (kg/m^3)	–	–	94[d]	–	94[d]

[a] control mix.
[b] 50% replacement of virgin aggregate.
[c] 100% replacement of virgin aggregate.
[d] 20% by weight of cement.

2.2. Mixing and test procedures

Both, virgin and recycled aggregate were oven dried to constant weight first. The aggregates were then mixed with water equivalent to their respective absorption capacity for 5 min in a laboratory rotating drum mixer before mixing with other ingredients and estimated water based on the actual w/cm ratio. Mixing water was added to mixer in three parts, each time mixing the ingredients for 2–3 min before addition of a part of water. All tests were carried out according to the provisions of relevant ASTM standards. Table 6 lists various tests and the relevant ASTM standards followed in this experimental program.

2.3. Test specimens

Concrete cylinders with 200 mm height and 100 mm diameter were produced and cured in lime-saturated water until different testing ages in accordance with ASTM C 192 for each of the mix designs described in Tables 4 and 5 for compressive strength. Flexural strength and the residual flexural strength tests of aged specimens were carried out on prismatic beam specimens with 100 mm × 100 mm cross-section and length of 350 mm. Concrete disc specimens with thickness (height) of 50 mm and diameter of 100 mm were used for sorption and chloride permeability tests.

2.4. Statistical analysis

Each mix design was prepared in three replications, with three specimens prepared and tested for each replicate. Statistical analysis of the raw test data of the three replications was carried out using statistical software. A general linear model was fit to each response variable (parameter tested). Model included fixed effects as well as 2- and 3-way interactions. Post-hoc pairwise comparisons were then performed. Statistical significance was considered at 0.05 level of confidence. Test results in various figures show estimated least square means and standard errors.

3. Experimental results and discussion

3.1. Fresh concrete properties

Table 7 shows the fresh concrete properties of the low and high w/cm mixes. Slump is observed to slightly increase with the introduction of milled waste glass. This could be attributed to the low water absorption of glass. The slump of recycled aggregate concrete mixes (at both levels of w/cm ratio) is higher than that of corresponding control mixes. The lower density of recycled aggregate in comparison to virgin aggregate and higher natural air content of fresh recycled aggregate concrete than that of control concrete could be the cause of higher slump. Density of the fresh concrete slightly dropped due to the addition of milled waste glass as partial replacement for cement. The lower specific gravity of milled waste glass when compared with that of Portland cement could be cause in this case. No appreciable effect of milled waste glass on air content of the mixes was observed.

3.2. Compressive strength

Fig. 4 shows the compressive strength test results at 14 and 56 days of age for low w/cm ratio mixes produced with 100% virgin and various percentages of recycled aggregate replacing virgin aggregates, with and without milled waste glass. Fig. 5 shows the compressive strength test results of the corresponding high w/cm ratio mixes. Among the low w/cm ratio mixes, the compressive strengths of concrete mixes with milled waste glass used as partial replacement for cement were lower than those of the corresponding concrete mixes without milled waste glass at 14 days of age. At the age of 56 days, this trend was reversed when partial replacement of cement with milled waste glass benefited the compressive strength of concrete. Statistical analysis of test results indicated the significant benefits of milled waste glass (as partial replacement for cement) to the compressive strength of concrete. At the age of 56 days the compressive strength of M3 (mix produced with 50% replacement of virgin aggregate with recycled aggregate and 20% cement replaced with milled glass) is 8% higher than that of M2 (corresponding mix produced with 100% cement). Similarly, the compressive strength of M5 (mix with 100% replacement of virgin aggregate with recycled aggregate and 20% cement replaced with milled glass) is 12% higher than M4 (mix with 100% replacement of virgin aggregate with recycled aggregate and 100% cement). When compared with control (M1), the compressive strength of M3 is comparable with that of M1 at 56 days of age.

The compressive strength test results for the high w/cm ratio mixes (Fig. 5) follow trends similar to those for the low w/cm ratio mixes. In this case too, the compressive strength of M10 is 5% higher than the corresponding mix (M9) at 56 days of concrete age. Where as, the compressive strengths of M7 and M8 mixes are found to be comparable. Comparison between 56 days compressive strength of M8 and M6 (control mix) shows insignificant difference.

Significant improvement in strength at 56 days of age is an indirect measure of the pozzolanic activity of milled waste glass when used as partial replacement for cement. The increase in strength is estimated to be the result of formation of a denser microstrcuture.

3.3. Flexural strength

Fig. 6 shows the flexural strength test results at 14 and 56 days of age for low w/cm ratio mixes produced with 100% virgin and

Table 6
ASTM specifications followed in the experimental work.

Test description	Specification
Concrete mixing and curing	ASTM C 192
Slump	ASTM C 143
Density (fresh concrete)	ASTM C 138
Compressive strength	ASTM C 39
Flexural strength	ASTM C 78
Density (hardened concrete), water absorption and porosity	ASTM C 642
Sorption	ASTM C 1585
Chloride permeability	ASTM C 1202
Freeze–thaw resistance	ASTM C 666
Alkali-silica reaction	ASTM C 1260

Table 7
Fresh concrete properties of low and high w/cm mixes with and without glass.

Mix design	Slump (mm)	Density (kg/m^3)	Air content (%)
M1	70	2299	4.5
M2	83	2219	5
M3	92	2209	5
M4	95	2213	6
M5	97	2193	6
M6	178	2208	7
M7	190	2121	8
M8	204	2118	7
M9	196	2084	8
M10	206	2096	7.5

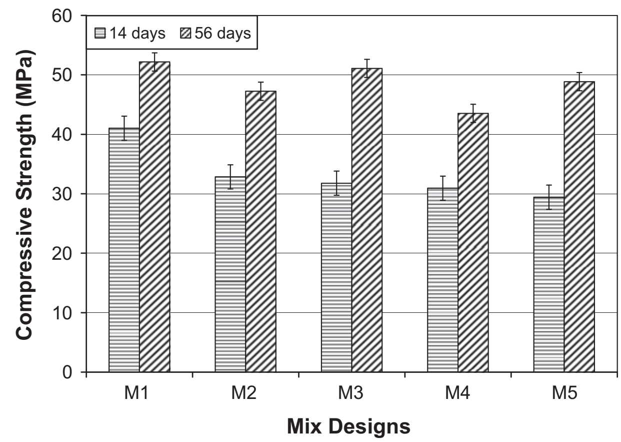

Fig. 4. Compressive strength of low w/cm concrete mixes (means and standard errors).

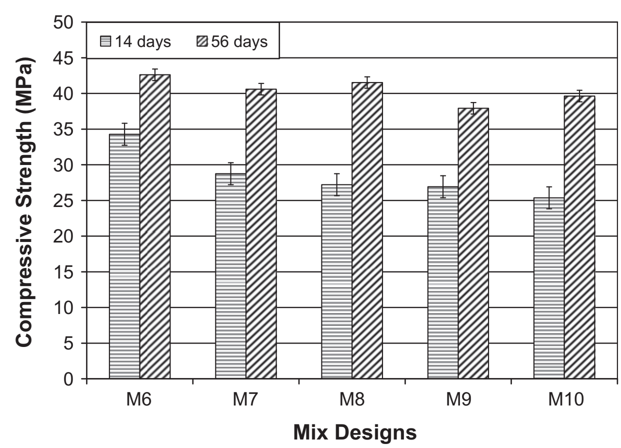

Fig. 5. Compressive strength of high w/cm concrete mixes (means and standard errors).

various percentages of recycled aggregate replacing virgin aggregates, with and without milled waste glass. Fig. 7 presents the corresponding test results for the high w/cm ratio concrete mixes. Flexural strength test results of the low and high w/cm ratio concrete mixes follow trends similar to those of compressive strength test results. In the case of low w/cm ratio concrete mixes, the flexural strengths with milled waste glass at 14 days of age are lower than those without milled waste glass. At 56 days of age, however, the use of milled waste glass as partial replacement for cement increases the flexural strength of concrete. An 11% (comparison of M2 and M3 mixes) and 14% (comparison of M4 and M5 mixes) increase is observed in 56 days flexural strength.

The flexural strength of high w/cm ratio concrete materials followed trends similar to those of low w/cm ratio concrete materials. At 14 days of age, the mean flexural strengths of high w/cm ratio concrete mixes incorporating milled waste glass were less than those of the corresponding concrete materials without milled waste glass. At 56 days of age, high w/cm ratio concrete mixes with milled waste glass (M8 and M10) provided 8% and 10% higher flexural strength than the corresponding concrete mixes without milled waste glass (M7 and M9), respectively. Statistical analysis of test results indicated that the effect of milled waste glass on the flexural strengths of high w/cm ratio concrete materials was significant at 56 days of age.

The significant increase in the later-age flexural strength of concrete mixes with incorporation of milled waste glass as partial replacement for cement is expected to be the result of the improvements in the interfacial transition zone (ITZ) and the cementitious paste in concrete realized by the pozzolanic reactions of milled waste glass with calcium hydroxide (CH) resulting in its conversion into C–S–H.

3.4. Density, water absorption and porosity

Water absorption and porosity are important indicators of the durability of hardened concrete. Reduction of water absorption and porosity can greatly enhance the long-term performance and service life of concrete in aggressive service environments. Decreased porosity also benefits the compressive and flexural strengths of concrete, as a fundamental inverse relationship exists between porosity and strength of solids. Table 8 shows the results of the bulk density (dry), bulk density (after immersion) and volume of voids test results for hardened concretes with and without milled waste glass at 56 days of age. Partial replacement of cement with milled waste glass is observed to produce an increase in the bulk density (dry) and the bulk density (after immersion) of concrete. This could be attributed to the conversion of CH to C–S–H

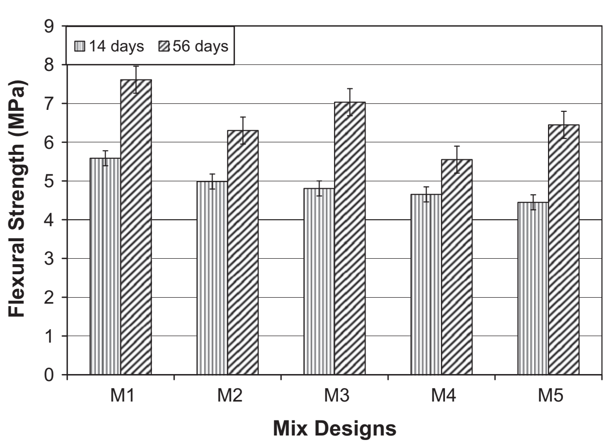

Fig. 6. Flexural strength of low w/cm concrete mixes (means and standard errors).

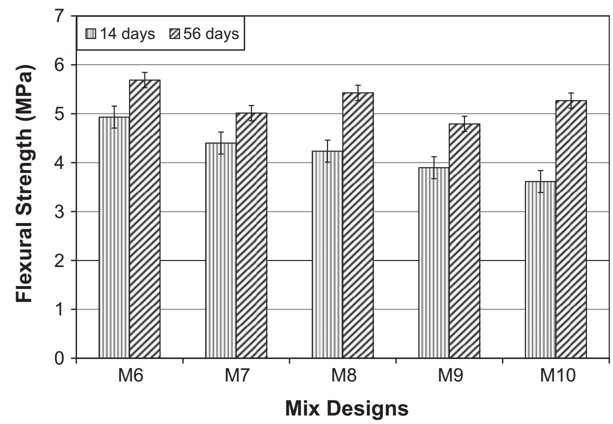

Fig. 7. Flexural strength of high w/cm concrete mixes (means and standard errors).

by the pozzolanic reaction of milled waste glass in concrete, noting that the specific gravity of the resulting C–S–H (that falls on the lower end of the 2.3–2.6 range) is somewhat higher than that of CH (2.24) [22]. Furthermore, the filling effect of very small milled waste glass particles results in improved particle packing, resulting in denser and hence less permeable microstrcuture. Water absorption of concrete is observed to be significantly reduced with introduction of milled waste glass as partial replacement for cement in both low and high w/cm ratio mixes. Use of milled waste glass as partial replacement for cement also results in lowering the volume of voids in concrete. Statistical analysis indicated the significant effect of milled waste glass towards reduction of water absorption and reduction of the volume of voids. It should be noted that the void content test used here measures the volumes of both continuous and discontinuous pores in concrete. Unlike continuous pores, the presence of discontinuous pores in hydrated cement paste is not detrimental to the water absorption and thus durability of concrete. Such pores, however, results in reduction of concrete strength.

3.5. Sorption

The entry of moisture into porous materials is one of the most common physical phenomena encountered in everyday life. This phenomenon is of great interest in many scientific fields. A great deal of fundamental work concerning the flow of water in unsaturated porous materials has been conducted in the field of soil physics [23–26].

Out of the three modes: (i) capillary absorption (sorption); (ii) diffusion; and (iii) permeation [27–31], sorption is the most important mode of moisture transport in concrete due to the fact that through out its service life concrete is mostly unsaturated. The concept of sorptivity/sorption was first introduced by Philips [32] in 1957 in the context of hydrology and soil physics who defined sorptivity as the most important single quantity governing the unsaturated flow in porous media. In the modern context, sorption has been defined as the absorption of water by capillary pores, and its transport by the capillary action [33,34]. Capillarity, referred to the action of liquids in fine tubes [23], forms a basis for sorption in porous materials.

The old clinging mortar (with a strong presence of the old ITZ) plays a significant role in increasing the moisture absorption capacity of recycled aggregate concrete. Improvements in the clinging (residual) mortar constituent of recycled aggregate (including the old ITZ) can bring about important gains in the moisture resistance and thus the dimensional stability and durability of recycled aggregate concrete. Milled waste glass can have a

Table 8
Density (hardened concrete), water absorption and porosity.

Mix design	Bulk density dry (Mg/m^3)	Bulk density after immersion (Mg/m^3)	Absorption (%)	Volume of voids (%)
M1	2.22	2.36	5.93	13
M2	2.19	2.32	6.26	14.25
M3	2.12	2.33	5.15	13.10
M4	2.07	2.22	7.50	15.50
M5	2.10	2.26	5.85	13.15
M6	2.11	2.24	6.48	13.68
M7	2.05	2.20	6.95	14.65
M8	2.07	2.22	6.12	13.70
M9	1.99	2.14	8.15	15.75
M10	2.01	2.18	6.52	13.75

particularly beneficial effect on the microstructure of recycled aggregate concrete. This is due to the strong presence of the old ITZ within cement hydrates clinging to recycled aggregates, which is highly porous and includes a relatively large concentration of calcium hydroxide. These conditions provide for pronounced pozzolanic reactions of milled waste glass, yielding beneficial effects by refining the capillary pores. Important gains in the structure and performance of the clinging mortar in recycled aggregates can thus be expected, which is key to improvement of the recycled aggregate quality for use in new concrete.

Sorption tests were carried out in accordance with ASTM C 1585-04 [35]. Specimens were subjected to two different conditioning methods, referred to as oven drying and air drying. In oven drying, the disc specimens were dried in oven at 50 °C until a constant mass was achieved. This required on average 23 days (different time for low and high w/cm mixes) of continuous oven drying. In air drying, specimens were dried in the laboratory environment at 20 °C and 28% RH over an average period of 7 months until constant mass was achieved. Specimens were sealed on sides and top with epoxy to produce one-dimensional sorption during the test. Each mix design had three replicate specimens. Fig. 8 shows view of some of the sorption test specimens inside the test setup.

Fig. 8. View of sorption test setup.

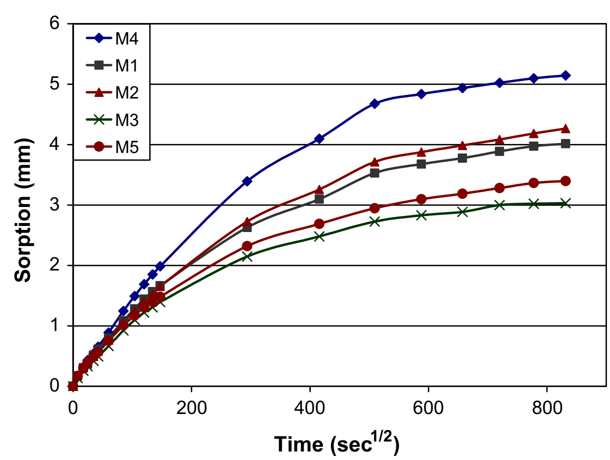

Fig. 9. Sorption plot of oven dried low w/cm concrete mixes.

3.5.1. Oven dried specimens

Fig. 9 shows the, *i* (sorption per unit area per unit density of water) vs. time$^{1/2}$ plots, which are herein, referred to as sorption plot of oven-dried, low w/cm ratio concrete mixes. Fig. 10 shows the corresponding sorption plot of the high w/cm ratio, oven-dried specimens. As can be seen in these plots, partial replacement of cement with milled waste glass results in significant reduction of water sorption of the concretes produced with recycled aggregates. Figs. 11 and 12 shows the cumulative sorption of concrete mixes after 8 days of continuous exposure to water, for the low and high w/cm ratio mixes, respectively. Analysis showed statistically significant effects of glass towards reduction in cumulative sorption of recycled aggregate concrete mixes. Concrete mixes at both levels of w/cm ratio showed significantly lower rate and cumulative sorption when compared with corresponding control mixes.

The reduction in rate of absorption and cumulative sorption of recycled aggregate concrete as a result of partial replacement of cement with milled waste glass may be attributed to the availability of more CH at the old ITZ of recycled aggregate to undergo pozzolanic reaction, producing more C–S–H and hence greater pore refinement effects. The formation of denser and less permeable microstrcuture (Section 3.4) may be another cause of significant reduction in rate of sorption and cumulative sorption.

3.5.2. Air dried specimens

Results of the sorption tests on air-dried specimens of low and high w/cm concrete mixes are shown in Figs. 13 and 14, respectively. The test results on air-dried specimens exhibit similar trends as those on oven-dried specimens; that is, concrete mixes with milled waste glass as partial replacement of cement showed significant reductions in the rates of absorption and cumulative water sorption when compared with similar mixes without milled waste glass.

3.6. Chloride permeability

In this test, the specimens are sandwiched between NaOH (Sodium Hydroxide) and NaCl (Sodium chloride) solutions (Fig. 15). The driving force for permeation of chloride ions was a 60-V potential applied between the opposite surfaces of the concrete disc specimen. The conductivity of saturated specimens was measured through monitoring of electric conductivity (Coulombs passed)

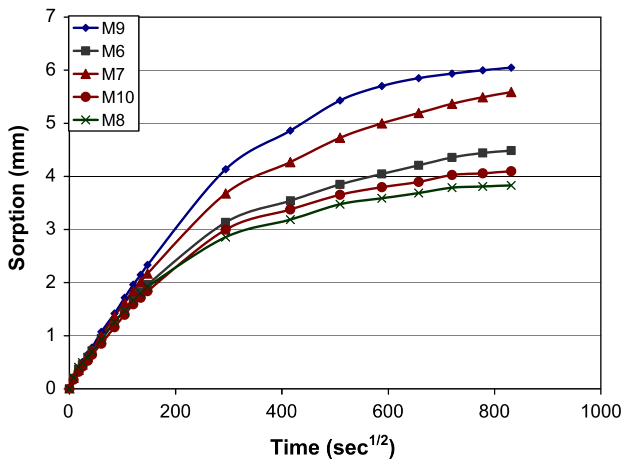

Fig. 10. Sorption plot of oven dried high w/cm concrete mixes.

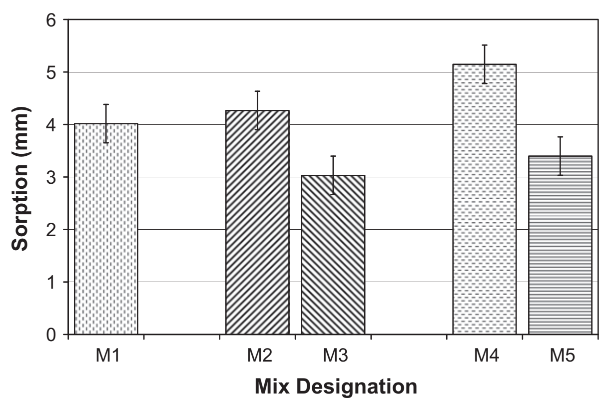

Fig. 11. Eight days cumulative sorption of oven dried low w/cm concrete mixes.

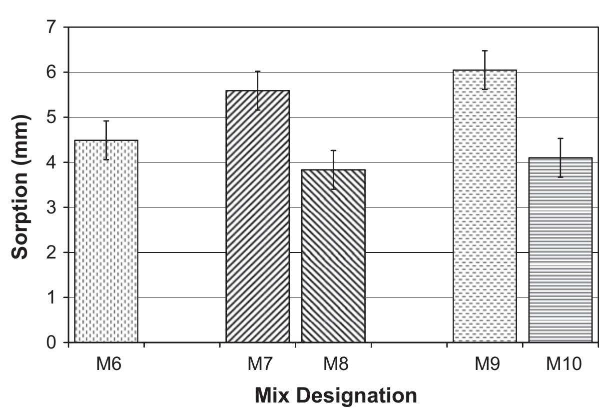

Fig. 12. Eight days cumulative sorption of oven dried high w/cm concrete mixes.

over the 6-h test period, with the total charge passed at the end of the test recorded as the primary test result.

Fig. 16 shows the rapid chloride permeability test results (charge passed through specimens) for concrete materials of low w/cm ratio with and without milled waste glass as partial replacement of cement. Fig. 17 shows the corresponding chloride permeability test results for concrete materials of high w/cm ratio with and with milled waste glass as partial replacement of cement.

In the case of low and high w/cm ratio concrete materials, the inclusion of milled waste glass enhances the resistance of concrete to chloride permeation; the number of coulombs passed through the concrete specimens containing milled waste glass is thus reduced significantly. Statistical analysis confirmed the significant effect of milled waste glass towards enhancement of concrete resistance to chloride permeation. According to ASTM C 1202, if the number of coulombs passed lies between 2000 and 4000, the chloride permeability of concrete is considered low, and it is considered very low for the 100–1000 range. All low w/cm ratio concrete materials (with the exception of recycled aggregate concrete) provided low chloride permeability levels. The recycled aggregate concrete mix containing milled waste glass had the number of coulombs passed slightly over 2000. Nevertheless, inclusion of milled waste glass resulted in 54% reduction of the number of coulombs passed through concrete specimens containing 100% recycled aggregate when compared with corresponding concrete specimens without milled waste glass. A similar reduction in the charge passed through other recycled aggregate concrete mix containing 50% of recycled aggregate was 56%. Concrete mixes with high w/cm ratio followed the trend of low w/cm mixes, wherein 46% and 53% reduction in number of coulombs passed was observed in concrete mixes with 100% and 50% recycled aggregate concrete, respectively, as a result of the inclusion of milled waste glass.

The enhanced resistance to chloride ion permeation (number of coulombs passed) is estimated to be brought about by the pore refinement and pore blocking and filling effects of milled waste glass pozzolanic reactions, noting that the current flow through concrete is a function of pore fluid conductivity. The high resistance to chloride ion permeation offered by concrete materials incorporating milled waste glass as partial replacement for cement makes them an ideal choice for construction of bridge decks, pavements and parking lots which are frequently exposed to the deleterious effects of deicer slats.

3.7. Freeze–thaw resistance

Freeze–thaw test results were carried out on high w/cm ratio concrete mixes with and without milled waste glass. Following the provisions of ASTM C 666 (Procedure B), after 42 days of curing, three specimens from each mix were subjected to 310 freeze–thaw cycles. Specimens were frozen in air and thawed in water as per the requirement of the Procedure B. Fig. 18 shows the plot of time vs. temperature for the freeze–thaw cycle to which the specimens were exposed inside the freeze–thaw chamber. Specimens were weighed before the start of the test, and the weight change under freeze–thaw cycles was recorded at the end of the test. The residual flexural strength of the aged specimens was also measured at the conclusion of the test following the provisions of ASTM C 78.

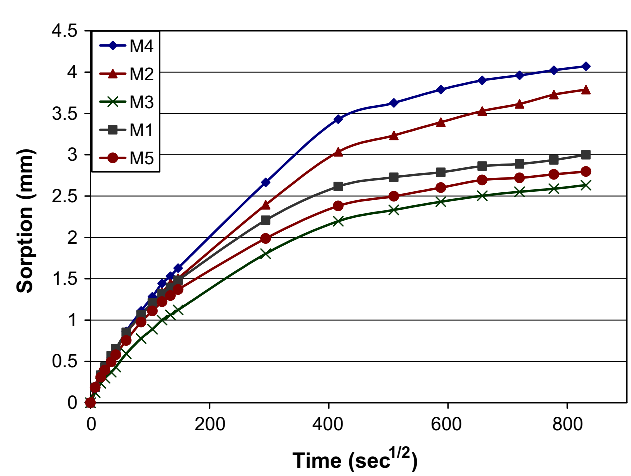

Fig. 13. Sorption plot of air dried low w/cm concrete mixes.

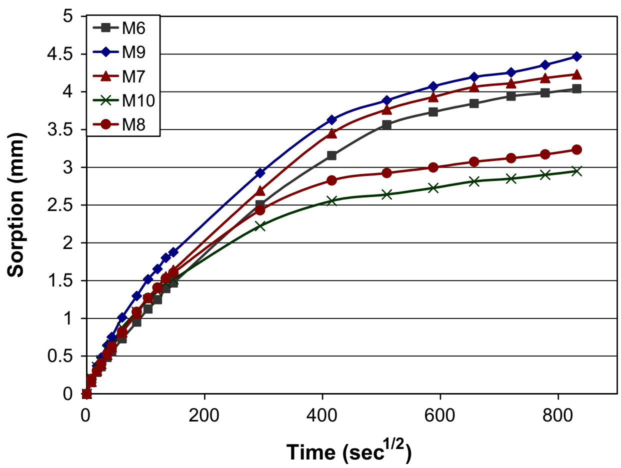

Fig. 14. Sorption plot of air dried high w/cm concrete mixes.

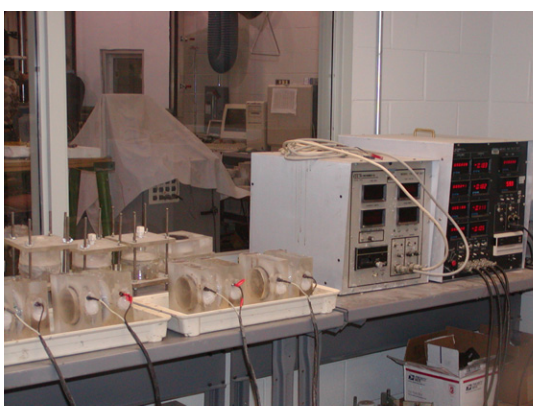

Fig. 15. The rapid chloride permeability test setup.

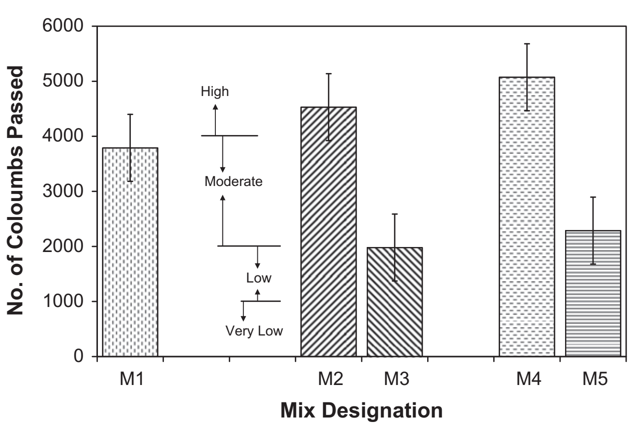

Fig. 16. Rapid chloride permeability test results for low w/c ratio concrete materials with and without milled waste glass (means & standard errors).

Increase in weight due to water absorption is an indication of the extent of deterioration of concrete due to cracking under freeze–thaw cycles. Table 9 shows the recorded values of weight gain for concrete materials (high w/cm ratio) with and without milled waste glass. There is a 29% decrease in cumulative weight gain after 310 freeze–thaw cycles in recycled aggregate concrete (compare the cumulative weight gains of M9 and M10) as a result of introducing milled waste glass. The corresponding drops in cumulative weight gain for M8 mix was 23%. Table 10 shows the

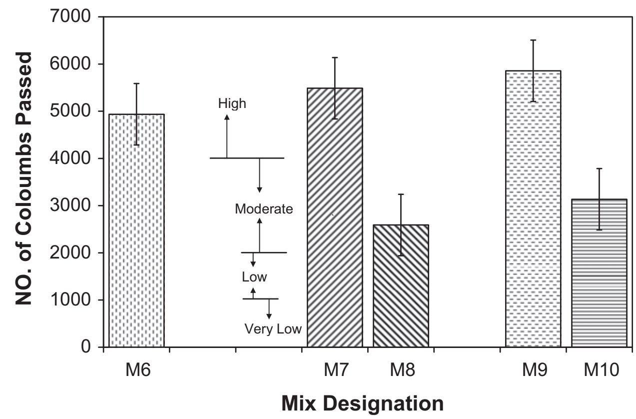

Fig. 17. Rapid chloride permeability test results for high w/c ratio concrete materials with and without milled waste glass (means & standard errors).

damage index values of concrete materials with and without milled waste. A damage index value of '1' corresponds to very little damage, whereas a value of '5' represents the worst damage caused due to the freeze–thaw cycles. A damage index value was assigned to each concrete mix based on the extent of visually observed surface damage (cracks, surface flaking, aggregate pop outs and corner chipping) and cumulative weight increase at the end of 310 freeze–thaw cycles.

Fig. 19 shows the flexural strength test results of the aged and unaged concrete mixes with and without milled waste glass. The introduction of milled waste glass is observed to produce a significant increase in residual flexural strength (aged flexural strength) of concrete materials made with different proportions of recycled aggregate. Statistical analysis of the test results indicated that the differences in flexural strengths of aged specimens with and without milled waste glass were significant in favor of concrete materials incorporating milled waste glass.

The superior freeze–thaw resistance of concrete mixes incorporating milled waste glass is a possible effect of the improvements in the microstructure resulting from the pozzolanic reactions of milled waste glass. The beneficial effects of pore size refinement and pore discontinuity associated with such reactions enhance the freeze–thaw durability of concrete.

3.8. Alkali-silica reaction

Some of earlier researchers have reported the occurrence of Alkali-silica reaction (ASR) in concrete between the highly alkaline

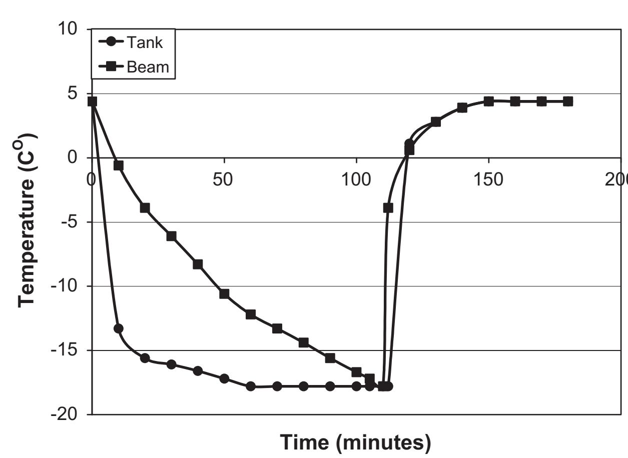

Fig. 18. The time–temperature plot of a freeze–thaw cycle.

Table 9
Weight gained by high w/cm ratio specimens during freeze–thaw cycles.

Mix designs	M6	M7	M8	M9	M10
Weight gained (%)	0.40	0.47	0.36	0.55	0.39

Table 10
Damage index of high w/cm mixes with and without glass.

Mix designs	M6	M7	M8	M9	M10
Damage index	3	4	2	5	2

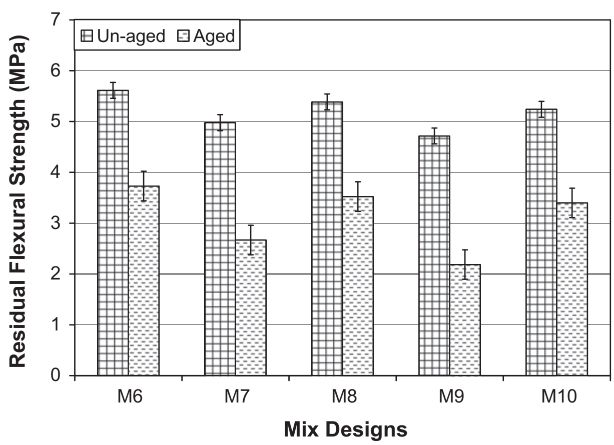

Fig. 19. Flexural strength of aged and unaged concrete mixes with and without milled waste glass (means and standard errors).

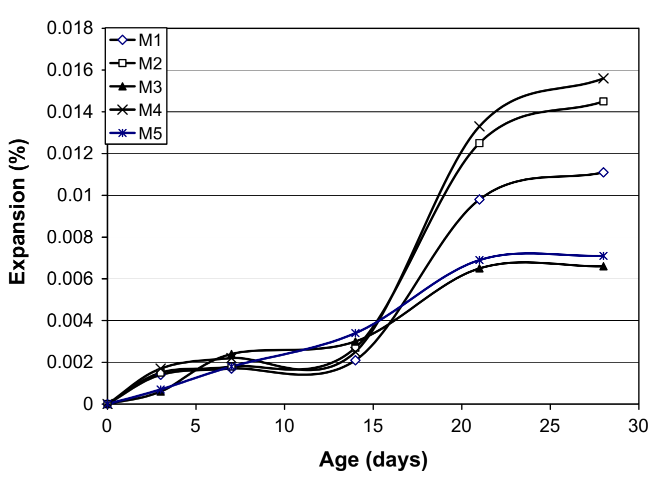

Fig. 20. Alkali silica test results of low w/cm mixes.

pore solution of cement paste and glass [13,19,36–40]. However in most of the cases glass was used as replacement for fine aggregate with coarser particle size [13,36,39,41,42]. When using glass, the key factor is to mill it to powder size to expose its higher surface higher to cause timely occurrence of pozzolanic reaction.

Fig. 20 shows the results of the ASR test carried out on low w/cm ratio mixes. Prismatic specimens were tested in accordance with the provision of ASTM C 1260 by aging them in a sodium hydroxide (NaOH) solution at 80 °C (176°F) continuously for 28 days with intermittent readings of the length change of bars taken during the course of the test. These experiments were prolonged for 28 days (exceeding the standard test period) in order to investigate the ASR-related expansions over longer time periods. According to ASTM C 1260, ASR related expansions less than 0.10% at 16 days after casting are indicative of innocuous behavior, while those between 0.10% and 0.20% at the same age are indicative of both innocuous and deleterious behavior in field performance, and expansions more than 0.20% at 16 days of age are indicative of potentially deleterious expansion. Although all concrete mixes showed expansion below 0.1% at 16 days of concrete age, the one's containing milled waste glass had significantly lower cumulative expansion at 28 days of concrete age. When compared with corresponding recycled aggregate concrete mixes without milled waste glass, it is observed that the presence of milled waste glass acts to suppress the ASR related expansion. This beneficial effect of milled waste glass has also been observed by earlier researchers who studied the use of milled waste glass in normal concrete [14]. It is estimated that the fine particles of milled waste glass change the kinetics of the chemical reaction in favor of pozzolanic reaction and utilize the alkalis in pore solution towards pozzolanic reaction before the formation of deleterious ASR gel.

4. Conclusions

The use of milled waste glass as partial replacement for cement is estimated to effectively overcome the limitations of recycled aggregate (higher water absorption and weak clinging mortar/paste) paving the way for its broad-based use towards production of recycled aggregate concrete.

When glass is used in fine particle size (~13 μm) as partial replacement for cement in concrete, it is estimated to undergo pozzolanic reaction that results in improved microstrcuture of recycled aggregate concrete through improvement in the quality of remnant mortar/paste attached to the surface of recycled aggregate that subsequently forms interface between recycled aggregate and new mortar in recycled aggregate concrete.

The filling effect of sub-micron sized milled glass particles is expected to result in improved particle packing, forming a denser and hence less permeable microstructure of recycled aggregate concrete.

The use of milled waste glass as partial replacement of cement in recycled aggregate concrete results in enhanced durability characteristic such as sorption, chloride permeability, and freeze–thaw resistance through improvement in pore system characteristics, filling effect of glass particles, and conversion of CH to C–S–H available in the old mortar/cement paste attached to the surface of recycled aggregate.

Significant increase in the later age strength is achieved through the formation of denser and less permeable microstructure which is expected to be the result of the filling effect of sub-micron sized glass particles. Improvement in 56 days strength provides an indirect measure of the pozzolanic activity of milled waste glass.

Milling of waste glass to sub-micron particle size is key to benefit from its pozzolanic reaction. The high surface area of milled waste glass changes the kinetics of chemical reaction towards beneficial pozzolanic reaction utilizing the available alkalis before production of a potential ASR gel.

Acknowledgments

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