Glass powder as replacement of cement for concrete – An investigative study

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Abstract

Cement production involves extensive energy absorption and emits huge quantities of CO₂ in the atmosphere. The production rates are increasing annually to meet the ever increasing demand with increased energy absorption and CO₂ emission. Hence, it is imperative to use materials which can replace use of cement to some extent. Conversely, waste glass is being dumped in the landfills. This practice is environmentally unsustainable since glass is non-biodegradable. Recently it's revealed that glass when grinded to a particular fineness exhibits cementitious properties due to pozzolanic reaction. This paper investigates the fresh, mechanical and durability properties of concretes made with cement replaced by coarse glass powder (<150 µm) at various replacement levels and employing different curing conditions. The replacement levels employed were 0%, 15%, 30% and 50% by weight of cement, while the curing regimes followed were ambient, Elevated Temperature Curing (ETC) @ 40°C and water. Scanning electron microscopy (SEM) and X-ray fluorescence (XRF) techniques were performed on cement and glass powder to investigate the microstructure and chemical composition of the materials. The initial findings show that 30% is the ideal replacement level as it exhibits quite comparable strengths, better workability and higher resistance to chloride ion penetration compared to the control mix.

Keywords: Waste glass powder, Cement, Pozzolanic activity, Compressive strength, Chloride penetration.

1. Introduction

Cement, the main ingredient in concrete which gives strength and serves the purpose of binding the other ingredients together is produced in enormous quantities. It is estimated that around 85.9 million metric tons of cement is produced in the United States alone, while the worldwide production is amounting to a staggering 4,200 million metric tons [1]. Manufacturing of cement is a highly polluting and energy-intensive process, which caters to around 12-15% of industrial energy consumption besides 5-7% of all carbon dioxide (CO₂) discharge [2]. To make matters worse, Szabó et. al [3] predicted that by the year 2030, there would be a 50% increase in the global CO₂ emissions from cement industry owing to rise in cement production to meet the ever increasing demand. This sharp rise in CO₂ outflow is believed to be responsible for the earth's climatic changes and the global warming [4]. Gopalakrishnan and Govindarajan [5] suggested replacing cement with either a solid waste material or an industrial by-product as a feasible option for reducing the cement consumption which eventually would result in environmental preservation. Employing industrial by-products like fly ash, silica fume, and blast furnace slag in place of cement depicted a value-added procedure to address the environmental issues. Hence, for sustainability and green construction, recycled waste materials are preferred in construction industry [6-11].

In recent years, focus has shifted to using waste glass in the construction industry [12-14]. Glass is being recycled in many countries since its physical and chemical properties do not alter even after multiple usage [15]. However, recycling of huge quantities of glass is not

possible owing to breaking, colour mixing and expensive recycling cost. The glass which is not recycled ends up in landfills and since glass is non-biodegradable, this practice is again environmentally unsustainable. In a recent report, it was stated that Australia generates around 1.1 million tons of glass waste annually with approximately 44% of it being dumped in the landfills [16]. The situation is more precarious in some other countries. Hence, waste glass has become a challenge for the waste management globally due to low recycling rate, limited landfill spaces and shortage in new spaces for landfills [17-18].

At first, waste glass was used as a fine aggregate replacement in concrete and it was observed that the mechanical and durability properties of the modified concrete were degraded due to the increased potential of Alkali-Silica Reaction (ASR) [19-21]. The main reason for this deterioration was due to high percentage of silica in glass culets which increased the chances of ASR in the concrete. According to the literature, ASR is a deleterious expansion occurring in concrete due to the reaction between siliceous minerals present in aggregate and the alkaline pore solution in concrete [22]. Later, investigations have shown that ASR occurrence in concrete is dependent on the particle size distribution of glass used - as the particle size decreases, the ASR probability reduces [15, 23]. The suppressive effect of glass powders on the ASR expansion in concrete was due to the pozzolanic characteristic of glass powder, similar to other pozzolanic materials such as fly ash, silica fume and metakaolin [24, 25]. These results, motivated the use of recycled glass powder with microscopic particle size distribution as cement replacement.

Experimental investigations have shown that glass when grinded to about 300 μm showed negligible ASR and these findings are in agreement with the maximum particle size of 300 μm for ASR occurrence [15, 26-28]. Mehta [29] stated that the glass particles start to behave as a pozzolanic material at approximately below 300 μm and when the fineness is reduced to about 100 μm the pozzolanicity of the glass exceeds that of fly ash at low cement replacement levels and after curing for 90 days. The pozzolanic property of glass increases with the fineness of the glass and, as the particle size distribution reduces, the pozzolanic ability of the glass increases. Studies as early as 2000, have been reported in the literature pertaining to the Glass Powder (GP) as cement replacement. In these studies, the size of the glass particle used ranged from 0-150 μm [23]. Of late, the researchers concentrated on finer glass particle size ranging from 0-100 μm and the maximum percentage of cement replacement is 60% [30-33]. Some of the studies pertaining to GP as binder replacement are listed in **Table 1**. There is no consensus about the ideal cement replacement percentage, as the performance of the glass powder concrete is dependent on various factors including the type of glass, particle size distribution and chemical composition of the glass.

Majority of the work done in the past, employed a finer GP (<100 μm) as binder replacement. The present study investigates the pozzolanic characteristics of a coarser GP (<150 μm) subjected to three different curing regimes. In addition to the standard compressive strength measurements, fresh and durable attributes of the GP mortars were assessed by measuring the slump and resistance to chloride ion penetration. Finally, the performance of the GP mixes exposed to distinct curing conditions are compared with a reference mix with 0% GP to obtain the optimum replacement level of the GP under investigation.

Table 1 GP as binder in concrete – A Literary Summary (Note: d_{50} is average particle size).

Size of the GP (μm)	Max rep (%)	Glass type	Experimental parameters	Properties tested	Reference
GP<100	30	Soda lime	% rep (10,20,30) @ w/b = 0.38	Creep, Elastic modulus & Compressive strength	34
GP<100	30	Bottle glass	% rep (10,20,30) @ w/b = 0.72	Mixing method on fresh & hardened properties	35
GP1<75 GP2<63 GP<75	20	-	% rep (5,10,15,20) @ w/b = 0.4	Fresh, Mechanical & Durability	36
GP<75	20	Plate glass	20% rep @ w/b = 0.35	Mechanical & Durability	37
0-100 (40% GP $\leq$ 10)	60	Soda lime	% rep (15,30,45,60) @ w/b = 0.49	Mechanical & Durability	33
Fine GP(<50) Coarse GP(125 – 200)	30	Soda lime	Fine and coarse GPs @ 30% rep, w/b = 0.4 (SEM-EDX , XRD, ASR), w/b = 0.5 (pore solution squeezes)	Solid phases, Pore solution & ASR	38
GP1 & GP2- (d_{50} =8.4)	20	Milled glass fibres	% rep (5,10,15,20) @ w/b = 0.5	Hydration & Microstructure	31
GP<75	25	-	% rep (5,10,15,20,25) @ w/b = 0.5 in control mix 1 % rep (5,10,15,20,25) @ w/b = 0.35 in control mix 2	Physical & Mechanical	39
GP<40(d_{50} =12)	30	-	Interior slabs (10% rep), Exterior slabs/sidewalks (20% rep), Exterior structural wall elements (10% & 30% rep) % rep (15,30,45) @ w/b = 0.45 in control mix	Fresh, Mechanical & Durability Sulfuric acid attack	32 40
0-100 (40% GP $\leq$ 10) GP1 & GP2- (d_{50} =8.4)	45 20	Bottle glass Industrial by product	% rep (5,10,15,20) @ w/b = 0.5	Mechanical & Durability	41
0-100 (40%GP $\leq$ 10)	30	Milled glass	% rep (5,10,15,20,25,30) @ w/b = 0.51 in control mix	Workability	42

(d ₅₀ =3.4)	60	Soda lime	% rep (15,30,45,60) @ w/b = 0.49 in control mix	Durability	30
Clear & Green glass(0-25)	25	Window & bottle glass	Pozzolanicity of clear & green glass at three diff curing temp (10,23 & 50 °C)	Hydration rate, Mechanical & Durability	43
(d ₅₀ =10)	60	Beer bottles	% rep (15,30,45,60) @ w/b = 0.49 in control mix	Particle size on ASR	28
(d ₅₀ =10)	20	Car wind screens	% rep (10,20) @ w/b = 0.5 in control mix	Fresh, Mechanical & Durability	44
(d ₅₀ =20)	20	Industrial by product	% rep (10,20) @ w/b = 0.4	Chloride transport test on microstructure	13
(d ₅₀ =45)	20	-	20% rep of cement, Influence of GP on expansion induced by ASR	ASR	22
10-15	30	Soda lime	% rep (20,30) @ w/b = 0.49 in control mix	Mechanical & Durability (Field conditions)	45
GP fine(40-700), GP dust(20%≤10) GP 4000(0-300), GP 6000(0-100)	20	Glass beads	GP fine (20% rep) , w/b = 0.465, GP dust (20% rep) , w/b = 0.471 GP 4000 (20% rep) , w/b = 0.480, GP 6000 (20% rep) , w/b = 0.485	Mechanical & ASR	46
75<GP1<150, 38<GP2<75, GP3<38	30	Soda lime	30% rep by volume of GP1, GP2 & GP3	Lime glass, Compressive strength & ASR	23

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2. Experimental program

2.1 Materials

The cement used in the current study was CEMIX general purpose cement, which complies with all the regulations and requirements highlighted in AS 3972 [47] for general purpose and blended cement. The GP utilised in this investigative study was provided by Envirosand, a company located in Brisbane, Australia. Envirosand creates GP by first collecting waste and sorting it using a shaker machine. The glass is then crushed into the appropriate sizes and stored in a controlled environment. GP furnished for the current study was of two different sizes, one with finer particle size distribution of 75 μm and the other with a coarser size of 150 μm . The fine aggregate used was EASY MIX double-washed river sand, which was provided by Griffith University. A sieve analysis was performed the results of which can be seen in **Figure 1**. The specific gravity, fineness modulus and water absorption of fine aggregate was 2.48, 2.5 and 1.5% respectively. The water used in this study was normal tap water from Griffith University. It was taken at room temperature of approximately 20°C.

Figure 1. Particle size distribution of fine aggregate.

Elemental composition of cement and GP is determined using X-ray fluorescence (XRF) technique, the results of which are given in **Table 2**. Since the sum of three oxides (SiO_2 , Al_2O_3 and Fe_2O_3) of GP is greater than 70%, it qualifies for the requirements of a cementitious material to be used as pozzolan (Class N/F/C) according to ASTM C618 [48]. Scanning Electron Microscopy (SEM) was carried on cement and GPs with different levels of magnifications, the results of which are illustrated in **Figure 1**.

Table 2 Chemical composition of cement and GP.

Composition	Cement	Glass Powder
SiO_2	21.00	69.77

Al_2O_3	5.50	1.42
Fe_2O_3	3.25	0.29
CaO	63.50	10.00
MgO	2.05	0.67
SO_3	2.15	0.19
Alkalies (Na_2O , K_2O)	0.85	12.53

Figure 2. SEM images at x200 and x500: (a) Cement; (b) Fine GP < 75 μm; and (c) Coarse GP < 150 μm.

2.2 Experimental parameters

The investigative experimental study was performed in two stages: first stage comprised of employing same mix design for the concrete with GPs of two different sizes and the second stage involved subjecting concrete specimens prepared with coarse GP to different curing regimes. A weight based mix design for the concrete was employed in both the stages and the replacement levels employed were 0%, 15%, 30% and 50% as shown in **Table 3**. For Stage 1, over 100 cylinders were cast for both the GPs. Each mix had 15 cylinders out of which 5 cylinders were tested at each curing age. While for Stage 2 about 180 cylinders were prepared, each mix had 45 cylinders, 15 specimens from each mix were subjected to three different curing conditions. Similar to Stage 1, the average of 5 samples was taken as the final value at every testing age for calculating the density, strength and chloride resistance. Overall, about 300 cylinders were cast in both stages for the investigative study.

Table 3 Mix proportions of mixes.

	Mix	GP (%)	Water (kg/m ³)	Cement (kg/m ³)	GP (kg/m ³)	S (kg/m ³)	W/(C+GP)
Stage 1 (GP < 75 & 150µm)	M1	0	240	600	0	630	0.40
	M2	15	240	510	90	630	0.40
	M3	30	240	420	180	630	0.40
	M4	50	240	300	300	630	0.40
Stage 2 (GP < 150µm)	M1	0	210	600	0	630	0.35
	M2	15	210	510	90	630	0.35
	M3	30	210	420	180	630	0.35
	M4	50	210	300	300	630	0.35

Three different curing conditions were employed to evaluate the pozzolanic behaviour of GP as shown in the **Figure 3**. For ambient curing, after 24 hours the cylinders were removed from the mould and kept in a room at a controlled temperature and humidity until the testing age. Elevated Temperature Curing (ETC) was done at 40°C, cylinders were kept in a chamber for 24 hours at a constant temperature of 40°C, and subsequently the samples were removed from the chamber and kept in the room under ambient conditions until the testing time. Water curing was done by immersing and keeping the cylinders submerged in limewater bath until testing time, this process of curing is compliant with the Australian standard AS 1012.8.1 [49].

Figure 3. Curing regimes employed: (a) ambient; (b) ETC@40°C; and (c) water.

2.3 Tests

Fresh and mechanical properties like workability and compressive strength were evaluated in the first stage while stage two had hardened density and resistance to chloride ion penetration evaluation besides the tests mentioned in stage one. The workability of the fresh concrete is determined by slump cone test in accordance with the standard AS 1012.3.1 [50]. AS 1012.12 [51] was used to measure the hardened density of cylindrical samples at 7, 28 and 91 days of curing. The compressive strength tests for all the concrete cylinders was performed at 7, 28 and 91 days of curing in accordance with AS 1012.9 [52]. An average of five cylinders was taken for each testing age in order to keep the standard deviation to a bare minimum.

Resistance to chloride ion penetration was evaluated by using Resipod which complies with the standard AASHTO TP 95 [53]. Resipod is a fully integrated 4-point Wenner probe used to measure the electrical resistivity of concrete cylinders non-destructively. Current is applied at the two outer probes and the resulting potential difference between the two inner probes is reported as the resistivity of the specimen, the ions in the pore liquid carry the applied current. This test method covers the laboratory evaluation of the electrical resistivity of concrete samples to provide a rapid indication of their resistance to chloride ion penetration. For each cylinder, an average of eight readings is taken and the final resistivity value is expressed in kΩcm. Based on the resistance value, the chloride ion permeability can be predicted from **Table 4**. As expected, higher the resistance lower would be the chloride permeability and vice versa. In majority of the cases, the resistivity results from the Resipod have shown a good correlation with chloride exposure tests, like ASTM C-1556, on cylinders cast from the same concrete mix [54]. In comparison with rapid chloride permeability test, the resistivity test is much quicker and easier for measuring the chloride permeability.

Table 4 Probability of chloride ion penetration based on measured resistivity [53].

Chloride Ion Penetrability	Resistivity (kΩcm)
High	<12
Moderate	12-21
Low	21-37
Very Low	37-254
Negligible	>254

2.4 Specimens

Concrete cylinders of dimension 100 mm (diameter) and 200 mm (height) were prepared in accordance with AS 1012.8.1 [49]. Cylindrical moulds were filled in two approximate equal layers and compaction was done by rodding 25 strokes per layer. Concrete cylinders were cured in a moist room at more than 95% relative humidity and at a temperature of $23 \pm 2^\circ\text{C}$ for 24 h, and then demolded, identified and subjected to the respective curing conditions until the testing age.

3. Results and discussions

Since the experimental work done in Stage 1 was to finalise the size of the GP to be used in Stage 2, and also for brevity, the results of Stage 1 are not discussed elaborately herein in this paper. Stage 2 results are presented in the following sections in some detail.

3.1 Stage 1 results

3.1.1 Workability – Stage 1

The workability of the mixes is given in Figure 4. It is clearly evident that as the GP content increases the slump value rises until 30% replacement and then the trend reverses in both the GPs employed. Out of the two GPs used, the coarse GP performed better than its finer counterpart at all replacement levels. The workability results of coarse GP were almost double that of the fine GP especially at substitution levels of 15% and 30%. GP replacement of 30% gave the maximum slump of 70 mm and 130 mm with fine and coarse GP respectively while the control mix at 0% GP could manage a modest workability of 50 mm. Based on the slump results, 30% is the ideal replacement level as it gave the maximum workability with both the GPs employed.

Figure 4. Workability of the mixes.

3.1.2 Compressive strength – Stage 1

The compressive strength results for both the GPs at different curing ages are illustrated in Figure 5. Both the GPs exhibited a similar trend of decrease in strength with the increase of the GP replacement level at all curing ages. There is a linear pattern in the strength reduction with 50% replacement giving the least strengths in both the GPs applied. The strength results of the control mix are same in both the GPs as it was done only once in order to avoid wastage of time and materials owing to repetition but is shown twice in the results for better comparison. All the mixes irrespective of the GP used and regardless of the replacement level showed an increase in strength with the curing age indicating progressive hydration reaction. The fine GP at 15% and 30% substitution reported maximum compressive strength of 39 MPa and 31 MPa respectively, while strengths of 38 MPa and 28 MPa were recorded by the coarse GP at same replacement level.

Figure 5. Compressive strength results – Stage 1.

3.1.3 Strength Activity Index (SAI) – Stage 1

The SAI values of the mixes is given in Figure 6. The pozzolanic performance of GP may be estimated with SAI, which is the ratio between the strength of mortar containing GP and the strength of equivalent control mortar at the same age. According to ASTM C618 [48], for a material to be qualified as a pozzolan, the SAI should be greater than 75%. GP replacement of 15%, 30% and 50% yielded maximum SAI values of 85%, 68% and 45% with fine GP while highest SAI of 82%, 61% and 35% were reported by coarse GP at same replacement levels respectively. These results specify that the performance of the fine GP was slightly better compared to its coarse counterpart. Similar findings in which the fine GP performed better than its coarse equivalent are reported in literature in several occasions [23, 36, & 46]. GP at 15% is the ideal replacement level since it showed the maximum SAI values of all the substitution percentages employed.

Figure 6. Strength activity index of Stage 1 GP mixes with different sizes.

As can be seen from **Figure 6**, the results for coarse GP were quite comparable with their fine counterparts, considering the fact that considerable amount of energy would be utilised in grinding the particles finer which would eventually increase the construction cost. Hence, to save the energy consumption and cost, the coarse GP was employed in stage two with varying curing conditions to optimise the replacement level and enhance the pozzolanic performance of the GP. In summary, Stage 2 results exhibited that the ideal replacement level increased from 15% to 30% and the SAI values were significantly improved from 61% to 89%. These results are discussed in some detail in the subsequent sections.

3.2 Stage 2 results

3.2.1 Workability – Stage 2

The workability of the mixes is shown in **Table 6**. The trend exhibited was similar to previous stage results, as the GP content increases the workability rises, however, the magnitude of slump was lower compared to prior due to lower water to binder ratio employed. It can be seen that mix with 30% GP recorded a maximum slump of 90 mm which is approximately double that of the control mix with 0% GP. Mix with 50% GP gave the least slump of 40 mm which is slightly below that of the control mix. GP substitution tends to increase the slump: this increase in workability is most likely due to the lower water absorption of the GP compared to the cement and increase in effective water to cement ratio in GP modified mixes. Another possible reason for this positive outcome may be due to the reduced specific surface area, since the GP used in the current study is coarser than the cement and hence a lower amount of water was consumed, which resulted in an increase in slump for the GP mixes. Zhen Chen and Chi Sun Poon [55] reported similar slump increase by employing milled GP at 10% and 20% replacement level, the median size of the used milled GP was 11.38 µm and a flow table technique was used to evaluate the workability of the mixes. It is a well-known fact that workability doesn't influence strength directly but this increased workability can be used to produce GP mixes with lower water to cement ratio for a given cement content,

thereby producing concrete with similar workability, improved strength and better durability than the control mix [42].

Table 5 Workability of the mixes.

Glass Powder (%)	Slump (mm)
0%	50
15%	70
30%	90
50%	40

3.2.2 Hardened density – Stage 2

Hardened densities of all the mixes subjected to various curing conditions are depicted in **Figure 7**. It is clearly evident that irrespective of the curing condition employed, the density values decreased with the addition of GP. It is interesting to note that, for ambient and Elevated Temperature (ET) cured samples the highest densities were recorded in either 7 or 28 days but for water cured cylinders, all mixes reached their maximum density at 91 days. This improvement in the densities in water cured specimens particularly at longer curing duration of 91 days may be due to the persistent hydration reaction. Mixes with 50% GP recorded the least densities of all the mixes regardless of the curing condition they were exposed to. In summary, compared to the control mix with 0% GP, 28-day densities of 50% GP mix reduced by 14%, 11% and 6% in ambient, ET and water curing conditions, respectively. The possible reason for this decrease is due to the lower specific gravity of GP (2.56) compared to that of cement (3.15) used in the study. Since, GP is resulting in a less dense concrete, it would be apt in places where light weight concreting is preferred. Shayan and Xu [45] reported density reductions of 5% and 3% at 20% and 30% GP replacement levels respectively at 28 days of curing, while the size of the used GP was 10-15 μm .

Figure 7. Hardened densities of mixes at 7 days, 28 days and 91 days of curing.

3.2.3 Compressive strength – Stage 2

The results for the compressive strengths of the mixes exposed to different curing conditions and at distinct curing ages are shown in **Figure 8**. There is a decrease in the strength with the increase in GP replacement, while the reduction is more prominent in the early curing period of seven days, the lessening effect is weakened at prolonged curing of 91 days, particularly with 15% and 30% GP mixes. This improved performance of GP mixes particularly at longer curing periods is due to the formation of secondary C-S-H gel formed due to reaction between amorphous silica present in GP and Ca^{2+} from lime in presence of water. At 91 days of ETC, the lowest reduction in strength of 4% was recorded by mix with 15% GP and at the same age ambient cured mix with 30% GP showed a strength reduction of only 13%. Mix with 50% GP did not show acceptable results as the earlier studies had shown that the pozzolanic reaction ceases beyond a replacement level of 30% due to absence of lime [35, 40]. In such cases, the additional GP would be acting as an inert filler. Considering the fact that the 0% GP or control mix was designed for 50 MPa, 15% and 30% GP substitution yielded 28-day compressive strengths of 45 and 39 MPa, respectively. Also, due to the secondary hydration caused by pozzolanic effect, the strengths increased to 49 and 45 MPa, respectively, at 91 days of curing. These results validate the pozzolanic attribute of the GP used in the current research.

As for the effect of different types of curing on the pozzolanic performance of the GP, as expected 7 day ET cured samples showed highest strength irrespective of the mix indicating the increment in rate of hydration due to enhanced temperature. However, at extended curing duration of 91 days, both ambient and water cured samples showed slightly better strength compared to the ET cured specimens at replacement percentage of 30%.

Figure 8. Compressive strength results – Stage 2.

3.2.4 SAI – Stage 2

The SAI values of all the mixes containing GP are depicted in **Figure 9**. The mixes with 15% and 30% GP had SAI values of greater than 75% for all curing conditions, validating the pozzolanic characteristic of the GP used in the current research. The highest SAI values of 81%, 92% and 96% were recorded for mixes with 15% GP at 7, 28 and 91 days, respectively, all being subjected to ETC, while 30% GP ambient cured samples have shown maximum SAI

values of 75%, 89% and 89% at similar age. Although, mixes with 15% GP showed higher SAI values, 30% GP is treated as the ideal replacement level since it is the highest possible GP substitution which exhibited almost similar SAI values compared to the mixes with 15% GP. Similar research findings were reported by another study employing fine GP (mean size 8 μm) at 30% replacement, the SAI recorded were 80% and 90% at 28 and 91 days of curing respectively [56]. Furthermore, Rahma et. al [57] reported slightly better SAI values of over 90% with a coarse GP (mean size 200 μm) at 15% replacement level.

Figure 9. Strength activity index of GP mixes.

3.2.5 Resistance to chloride ion penetration – Stage 2

Resistance to chloride ion penetration was measured by using Resipod as shown in **Figure 10**. Since ambient and ET cured samples exhibited the best pozzolanic performance as discussed in the previous section, cylinders subjected to ambient and ETC were evaluated for measuring the resistance using Resipod. The feasibility of chloride ion penetration depending on the resistance values is given in **Table 4**, based on the calculated resistivity the mixes fall in several categories of risk.

Figure 10. Resistivity measurements: (a) cylinder marking; (b) alignment; and (c) recording.

As shown in **Figure 11**, as the GP content increases, the resistivity values increase resulting in decrease in chloride ion penetration. At 28 days, ambient cured cylinders with 0%, 15%, 30% and 50% GP exhibited resistances of 13, 12, 12 and 18 k Ωcm , respectively, while the

corresponding ET cured specimens showed values of 14, 13, 15 and 16 kΩcm, respectively. Resistances of 18, 17, 20 and 82 kΩcm were recorded for ambient cured specimens with 0%, 15%, 30% and 50% GP, respectively, all at 91 days. The corresponding ET cured samples displayed resistances of 17, 18, 22 and 78 kΩcm.

ETC improved the resistances in all mixes and for both curing periods excepting with the mix with 50% GP, in which ambient cured specimens showed slightly better resistances for both curing ages. Mixes with 50% GP showed the highest resistances for both curing conditions and periods. A 50% substitution of GP increased the resistance from 13 to 18 kΩcm for 28-day ambient cured specimens likewise, for ET cured cylinders, the resistance changed from 14 to 16 kΩcm for the same duration. However, for 91 days of curing, mixes with 50% GP exhibited more stupendous rise in resistance being from 18 to 82 kΩcm and 17 to 78 kΩcm for ambient and ET cured cylinders, respectively.

This increments in resistances in GP replacement of 50%, particularly for longer curing ages, may be due to the combined effect of pozzolanic reaction, increased hydration and reduction in voids which resulted in microstructural refinements in GP mixes. Another study in which similar huge rise in chloride resistance by GP replacement was reported by Du and Tan [33], the technique adopted was Rapid Chloride Permeability Test (RCPT) and the size of the GP and maximum replacement level employed were 0-100 μm and 60% respectively. Similar technique was employed on concrete made with 30% GP at a curing age of 90 days resulting in very low chloride ion penetrability compared to the reference mix, however, the median size of the used GP was 8 μm, much finer than the one employed in the present study [56].

4. Research significance

As mentioned before, waste GP use as cement replacement can have a dual beneficial effect on the environment. Firstly, decrease in CO₂ emissions since GP use as cement replacement would lead to decrease in cement consumption thereby resulting in lowering cement production. Secondly, reduction in dumping a non-biodegradable material in landfill, resulting in saving the limited landfill spaces and lessening the unsustainable effect of discarding waste GP in the open spaces. According to a recent report, Australian cement production is about 9.7 million tons in 2015-2016 which generated around 5.3 million tons of CO₂ emissions in the atmosphere [58]. The investigative experimental study presented herein confirmed 30% as the ideal replacement level which if employed as cement replacement would lead to decrease in CO₂ emissions by 1.6 million tons per annum in Australia and globally the annual CO₂ discharge can be reduced by approximately 750 million tons. In addition to the positive environmental effects, employing waste GP in place of cement would lead to economical construction. Recycling a ton of GP consumes about 6.5 KW of electric power, 1 L of diesel and 0.27 L of gasoline. These data have been obtained from the company which supplied the GP for the current study. So, by summing up the costs of the fuels employed, recycling 1 ton of GP costed about AUD 200, while the present price of general purpose cement in local market is approximately AUD 300-330/ton. A 30% replacement of GP would result in savings of about AUD 800 million/annum in Australia, while globally the reduction in cost would be much higher.

Figure 11. Chloride resistance of GP mixes: (a) 28-days; and (b) 91-day

5. Conclusions

Unlike previous researches on use of GP as replacement of cement for concrete, the current investigative study employed a coarse GP as cement replacement. A thorough investigation into the overall performance of coarse GP has been carried out and the initial experimental results are very encouraging. The following conclusions can be drawn from these findings:

1. There is an increase in workability with the GP substitution, particularly mixes with 30% GP recorded the highest slump the value of which is almost double that for the control mix (0% GP).
2. Hardened density results indicate that GP replacements lead to lighter concrete thereby facilitating its use in places where light weight concreting is required.
3. Compared to a control mix with design strength of 50 MPa, GP mixes with 15% and 30% cement replacement resulted in compressive strengths of 49 MPa and 45 MPa, respectively at 91 days of curing.

4. As expected, ETC resulted in increases in the compressive strengths, particularly at early curing age of 7 days. However, this positive effect was subsided at longer curing regimes of 91 days and at higher replacement levels of 50%.
5. Mixes with 15% and 30% GP showed SAI values of greater than 75% irrespective of the curing condition and for all curing ages. This conforms to the requirements of ASTM C 618 and hence the confirmation of the use of GP as a pozzolanic material in concrete in the current investigative study.
6. GP utilised in the current research produced an incremental increase in the resistivity, especially mixes with 50% GP recorded a fourfold rise in resistance to chloride ion penetration compared to the control mix with 0% GP, thereby significantly reducing the probability of steel corrosion due to chloride ions in reinforced concrete members.
7. In order to get the maximum benefit, a higher percentage of GP substitution is preferred. Hence, 30% is considered as the ideal replacement level for the GP employed in the current experimental study since it showed better results compared to the other replacement levels for fresh, mechanical and durability properties of concrete made using these mixes.
8. Use of recycled waste GP as cement replacement in construction industry would have a dual beneficial effect environmentally and a significant valuable effect economically as discussed herein.

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