1876-4002/20

Send Orders for Reprints to reprints@benthamscience.net

The Open Waste Management Journal

Content list available at: https://openwastemanagementjournal.com

RESEARCH ARTICLE

Sustainable Use of Recycled Glass Powder as Cement Replacement in Concrete

Nafisa Tamanna[1,*] and Rabin Tuladhar[1]

[1]*College of Science and Engineering, James Cook University Townsville, QLD 4811, Australia*

Abstract:

Aims:

This paper introduces a sustainable way of using Recycled Glass Powder (RGP) as a cement replacement in concrete.

Background:

In Australia, almost one million tons of glass waste is collected annually for recycling purpose. However, the inconsistency in chemical composition and the presence of impurities make glass recycling process difficult. Besides, the lack of local recycling plants coupled with high transportation costs makes the recycling process expensive.

Objective:

For the successful use of recycled glass in concrete for industrial applications, it is therefore, important to characterize the physical and chemical properties of recycled glass collected by the local councils. Furthermore, the effects of replacement levels of cement with recycled glass on the strength and durability properties of concrete need to be assessed as well.

Methods:

Mechanical strength and durability properties of concrete with 10%, 20% and 30% of RGP as a partial cement replacement were tested and compared with typical concrete and fly ash blend concrete. The relative strength test of mortar was conducted to assess the reactivity of glass powder with the cement.

Results:

RGP concrete showed an improvement in strength over time like fly ash. Using RGP significantly improved the resistance against chloride penetration with increasing glass powder content. Furthermore, RGP also met the relative strength requirement as per Australian Standard requirement to be considered as a supplementary cementitious material.

Conclusion:

This research showed that the use of RGP as cement replacement is feasible for replacement level up to 10%. The outcome of this research aims to contribute towards sustainable development by reducing the consumption of cement, as well as reduction of glass waste going into landfill.

Keywords: Recycled glass powder, Sustainable concrete, Supplementary cementitious material, Pozzolanic reaction.

Article History	Received: November 02, 2019	Revised: February 02, 2020	Accepted: February 04, 2020

1. INTRODUCTION

The concrete manufacturing process produces substantial environmental impacts, mainly due to the carbon footprint associated with the cement manufacturing process. Cement, a key ingredient in concrete, is very energy-intensive to produce and is responsible for about 85 percent of the total embodied energy of concrete [1]. About 60% of the total CO_2 associated with the cement manufacturing process is emitted during the calcination of limestone ($CaCO_3$), and the remain-ing 40% of the emission comes from the burning of fossil fuel to generate energy during the cement manufacturing process. Cement production accounts for more than 8% of global CO_2 emissions [2]. One ton of cement production releases approxi-mately one ton of CO_2 into the atmosphere [3]. In 2012-2013, cement production in Australia was reported as 8.6 million tons, which

* Address correspondence to this author at the College of Science & Engineering (CSE), James Cook University, Townsville QLD 4811, 1 Australia;
Tel: 0469832349; E-mail: nafisa.tamanna@my.jcu.edu.au

contributed about 8.6 million tons of CO_2 to the environment [4]. Concrete industries around the world have long been using supplementary cementitious mater-ials such as fly ash, silica fume, and natural pozzolans as a partial cement replacement in concrete [1]. Recently, resea-rchers have also tried using recycled materials such as recycled glass powder as cement replacement in concrete [5 - 9].

In Australia, almost one million tons of glass waste is collected annually for recycling purposes [10]. However, the inconsistency in chemical composition and the presence of impurities make the glass recycling process difficult. Besides, the lack of local recycling plants coupled with high transportation costs makes the recycling process expensive. The use of waste glass in concrete and mortar has been tried in the past few years to replace coarse aggregate, sand, and cement. Several researchers have studied the use of waste glass with larger than 4.75 mm in size as coarse aggre-gate replacement in concrete since the 1960s. The use of coarse glass aggregate decreased the compressive strength with the increase in glass content, and mixed results were reported on the effect of glass aggregates on the workability of concrete [11 - 16]. Flat, smooth, and elongated nature of glass particles resulted in low strength and workability of concrete. Furthermore, Alkali-Silica Reaction (ASR) is another major issue encountered while using waste glass as a coarse aggr-egate replacement in concrete. ASR occurs between amor-phous silica in glass and alkali in cement producing expansive alkali-silica gel. In the presence of moisture, alkali-silica gel produced can absorb moisture from the surroundings and expand inside the micro-cracks on aggregates. ASR expansion leads to cracking in the concrete [17, 18], which makes the concrete more vulnerable to chloride attack. Cracking in concrete due to ASR expansion was found more pronounced when glass particle size greater than 19 mm was used in concrete [12]. Excessive cracking was also found in the study of using different forms of glass as coarse aggregate with cement [19]. Moreover, ASR expansion was found closely related to the proportion of glass particles in the mixture, for instance, a study by Shayan [20] found that the use of coarse glass aggregate greater than 30% resulted in an increase in ASR even with low alkali cement.

As deleterious cracks were noticed with the use of coarse glass aggregate, several studies have been conducted to investigate the potential of using recycled crushed glass as a fine aggregate replacement [21 - 24]. Glass sand concrete improved the fresh concrete properties due to the smooth surface and relatively low water absorption properties of glass [25]. However, mixed outcomes are reported on the mechanical and durability properties of hardened concrete with the change in glass size particles [23, 26, 27]. Minor cracks can form at the edge of glass aggregates during crushing operations and in the presence of moisture, ASR expansion gels may form on the cracked surface of aggregates leading ASR cracking of concrete [17]. An increase in glass content as the sand replacement was also found to increase ASR expansion [13, 23, 28 - 34]. Degirmenci [32] reported that concrete with 100% replacement of natural sand with recycled crushed glass exceeded the 0.10% ASR expansion limit at 21 days, which is considered as potentially deleterious expansion. ASR expansion was found to increase with the increase in the size of glass sand [23, 35]. The minimum and maximum expansion have occurred at a glass particle size of 0.150 mm and 2.36 mm, respectively. When glass size was smaller, the pozzolanic reaction occurs between glass particle and calcium hydroxide instead of deleterious ASR reaction.

Being amorphous and having prominent quantities of silica, crushed glass if finely ground, shows pozzolanic properties [36 - 38]. The pozzolanic properties of glass are found to be influenced by the particle sizes distribution of glass powder [39]. The silica (silicate ions) is detached from glass by hydroxyl ions in the pore solution and combines with calcium from portlandite to form calcium silicate hydrate. Furthermore, glass powder with particle size 300µm or smaller has been reported to reduce ASR expansion in concrete [40]. When finer glass particles are used in concrete results in a non-expansive pozzolanic reaction producing calcium silicate hydrate (C-S-H) with a low calcium-silicate ratio [9]. Pozzolanic properties of glass powder are reported to increase with reduced particle size and resulted in a delayed strength gain of concrete [8, 39 - 45]. The properties of recycled glass, and hence, its effects on concrete depend on the type of waste glass used. The nature of glass reactivity depends on the chemical composition of raw materials used and differs slightly for each glass type [46]. Borosilicate glass such as pyrex glass was found to be more reactive than soda-lime glass. Boro-silicate glass which was coming from pharmaceutical containers cullet had a tendency to expand. In addition, the amount of fluorescent lamp glass negatively influences the pozzolanic reaction. The high content of Na_2O_{eq} + PbO and the low content of CaO + MgO causes a high degree of sodium dissolution and involves in gel formation [47]. The ASR expansion of treated funnel glass was found relatively higher than crushed beverage glass due to the higher solubility of treated funnel glass [34]. A large amount of dissolved glass was available in the solution to form ASR gel [34, 48]. Besides, using lead glass in cement and concrete can leach out lead into the environment creating serious soil and groundwater pollution as it possesses high lead content in the glass. For the successful use of recycled glass in concrete for industrial applications, it is therefore, important to characterize the physical and chemical properties of recycled glass collected by the local councils. Furthermore, the effects of replacement levels of cement with recycled glass on the strength and durability properties of concrete need to be assessed as well. In this regard, this study investigates the feasibility of using colored soda-lime glass, collected by Cairns Regional Council, in North Australia as a partial cement replacement in concrete. Cairns Regional Council collects around 5000-5500 tonnes of glass waste annually. Around 50% of glass is recovered and recycled in different forms, while the remaining glass waste in the form of glass fines (around 2600 tonnes) cannot be recycled and is sent to landfills [37]. Besides, waste glass collected in Cairns Regional Council has to travel more than 2000 km to the southern parts of Australia to get recycled which makes the potential of alternative use of glass waste in concrete. In Singapore, 72300 tonnes of waste glass was produced, of which 57600 tonnes were disposed in 2016 [49]. About 51500 tonnes of waste glass was produced, and merely 19% of the total collected waste glass was recycled in 2018 [50].

According to the Environmental Protection Agency, the USA produced 11.5 million tonnes of waste glass in 2013, of which only 26% was recovered for recycling [51]. Although recycling of glass increased from 0.75 million tonnes in 1980 to more than 3 million tonnes in 2013, almost 74% of waste glass, predominantly soda-lime glass from container bottles, were disposed of in landfills. In 2010, 11530-kilo tonnes of waste glass were produced in the United States, out of which only 27.1% were recycled [52]. Being able to recycle a proportion of glass waste into concrete as a cement replacement, provides a whole new opportunity for recycling glass waste and reduces the amount of waste going to landfill. Furthermore, the use of recycled glass in concrete contributes towards sustainable development by reducing the consumption of cement.

In this study, material characterizations were conducted by using X-Ray Fluorescence (XRF), pPrticle Size Distribution (PSD), Scanning Electron Microscope (SEM) and X-Ray Diffraction analysis (XRD). Concrete was produced by replacing general-purpose cement with 10%, 20% and 30% of recycled glass powder. The results were compared with the control (100% Portland cement) and fly ash blend (30% fly ash) concrete. The effects of glass powder on compressive, flexural and tensile strength of concrete were evaluated. The relative strength of mortar was carried out to assess the reactivity of glass powder as a supplementary cementitious material. Furthermore, concrete resistance against chloride ion ingress was determined using a Rapid Chloride Penetration Test (RCPT).

2. EXPERIMENTAL PROGRAMS

2.1. Materials

General-purpose cement and fly ash blend cement (with 30% fly ash) were used in this research. A coarse aggregate with a nominal size of 20 mm from Edmonton Quarry was used in the study. Two different types of fine aggregates used were coarse sand and fine sand obtained from Barron River and Table **1** and regions, respectively. In this research, Recycled Glass Powder (RGP) was used in concrete as a partial cement replacement. The mixed soda-lime glass used in this study was collected from the kerb-side domestic waste collection by the Cairns Regional Council, Australia.

All collected recyclable materials are sorted and large items removed as it passes through the conveyor belt in the Materials Recovery Facility (MRF) unit. Vibrating conveyor belt separates light items, such as paper, cardboard, etc. Heavy items, for example, plastic bottles, glass bottles, and crushed glass are sent to the other conveyor belts to manually remove larger contaminants Fig. (**1a**). Glass items are then sent to glass crushing facility Fig. (**1b**). Glass crushing is performed at three phases as the waste glass goes through - imploder, shearing unit, and sanding unit. The imploder has rotating blades to crush glass. Glass particles are then moved to the shearing unit, where the glass particles are further crushed by shearing. Impurities such as paper, cardboard are removed before reaching the sanding unit. Rotating grinding shaft of the sanding unit Fig. (**1c**) crushes glass particles into two fineness levels - 5 mm (coarse glass) and 3 mm (fine glass). The 3 mm size glass particles Fig. (**2a**) are further pulverized to powder form (80% passing through 45 µm sieve) Fig. (**2b**) at ALS Minerals Geochemistry-Townsville Laboratory. At the moment, the council sends 5 mm size coarse glass particles to be used in road constructions as base course and subbase are sent to landfill. The use of recycled glass powder in concrete as partial cement replacement has the potential to create a high-value market for recycled glass.

2.2. Mix Proportion and Sample Preparation

This research was conducted in three phases. The first phase consists of material characterization to determine accurate chemical and physical characteristics of RGP. The second phase consists of an experimental investigation on the effects of RGP on fresh concrete (slump test, and fresh density test), hardened concrete properties (hardened density test, compressive strength, tensile strength, and flexural strength), and durability of concrete (rapid chloride penetration test). Five concrete mixes were investigated: GP cement concrete (control); fly ash blend (30% fly ash) concrete; and three concrete mixes containing RGP as cement substitution at 10%, 20% and 30% (noted as 10 RGP, 20 RGP and 30 RGP, respectively). To keep the concrete mix industry relevant, concrete mix supplied by Pioneer North Queensland (PNQ) Concrete as shown in Table **1** was used as the control mix in the study. SIKA RE Retarder was used in the mixture as an admixture to retard the setting time of the mixture. Testing was conducted on 7, 28 and 56 days of curing.

In the third phase, the relative strength test was conducted according to AS 3583.6 [53] on cement mortar to investigate the potential of RGP as a supplementary cementitious material. Five mortar mixes were prepared using standard sand (CEN-NORMSAND DIN EN 196-1). The amount of cement, sand, and water was used according to AS 3583.6 [53] as tabulated in Table **2**. The quantity of water used in each mix should provide a flow of 110 ± 5 for control mortar, as required by AS 2701 [54].

Concrete mixing was performed according to AS 1012.2 [55] and prepared for compressive, flexural, and indirect tensile strength and rapid chloride penetration test. All molded samples were then stored for initial setting. Samples were demolded after 24 hours and cured for a specific period in water, according to AS 1012.8.1 [56]. Mortar samples were prepared in accordance with AS 2350.12 [57].

2.3. Test Methods

The chemical compositions of cement, RGP and fly ash were found by X-Ray Fluorescence (XRF) using the ME-XRF26 method. The particle size distributions, including specific surface area, were determined using a laser-based particle size analyzer Malvern Mastersizer 2000. The morphology of materials was performed with a scanning electron microscope (Hitachi SU5000). The samples were coated with platinum to make the samples electrically conductive. Besides, X-Ray diffraction analysis was performed by using a D2 PHASER 2nd generation diffractometer (XRD), with a copper anode X-ray tube at 30 kV and 10 mA, in between 5° and 70° with a counting time of 160 s, at a step size 0.02.

Table 1. Materials content for 1 m^3 of concrete mix.

Material	Cement (g)	Recycled	Fine Aggregate			Coarse	Water	Admixture
-	(kg)	Glass Powder (kg)	Fine Sand	(kg)	Coarse Sand	Aggregate (kg) 20 mm	(L)	(mL)
Control	336	-	270		632	981	180	60
10 RGP	302.4	33.6	270		632	981	180	60
20 RGP	268.8	67.2	270		632	981	180	60
30 RGP	235.2	100.8	270		632	981	180	60
Fly Ash Blend (30% fly ash)	336	-	270		632	981	180	60

Fig. (1). Recyclable material sorting and crushing procedures as used by cairns regional council.

A slump test was conducted to measure the consistency of fresh concrete as per AS 1012.3.1 [58]. The slump cone was filled with fresh concrete in three layers. Each layer was compacted by rodding 25 times with a compaction rod. The amount of concrete subsided from the top of mold was measured; once the mold was removed. The fresh and hardened density of concrete was calculated after molding the cylinders (fresh density) and directly before testing (hardened density), by weighing and measuring samples, according to AS 1012.12.1 [59].

A compressive strength test was performed to determine the maximum compressive load that the sample can carry per unit area. Cylinders with a 100 mm diameter and 200 mm height were prepared according to AS 1012.8.1 [56]. A total of 32 cylinders was cast and cured: One cylinder was cast for each batch for the seven days test to estimate the early strength gain and three of each cylinder was prepared for the 28 and 56 days. During the compression test, a rubber cap was affixed on the rough end of the cylinder to allow smooth testing surfaces at either end. A steady load of 1.4 kN/sec was applied to the cylinder until the sample fails per AS 1012.9 [60]. A total number of 9 cylinders (150 mm diameter and 300 mm height) were prepared for the splitting tensile strength test following AS 1012.8.1 [56]. A loading rate of 1.2 kN/s was applied for the tensile test according to AS 1012.10 [61]. Concrete beams of size 100 mm × 100 mm × 360 mm were tested on a four-point bending test to determine the flexural strength of concrete at 28 days based on AS 1012.11 [62].

The test method for relative water requirement determines the amount of water needed for a specified flow. A flow table Fig. (**3a**) was used to determine a flow according to AS 2701 [54]. The flow mold was filled with mortar in a 25 mm thick layer until the mold was full. The mold was lifted away and allowed the flow table to drop 25 times in 15 seconds through a 12 mm height. The change in diameter of mortar was measured and the required flow was obtained by trial and error. The relative water requirement was calculated as the ratio of water of test mortar (with supplementary cementitious material) and control mortar (containing 100% Portland cement). The relative strength index is a test to assess the reactivity of supplementary cementitious material. It is the ratio of the strength of test mortar (containing supplementary cementitious material) and control mortar (with 100% Portland cement) expressed as a percentage.

According to AS 3582.1 [63], test mortar (supplementary cementitious material such as fly ash) should gain 75% of the control mortar strength to be considered as supplementary cementitious material. AS 2350.12 [57] was followed to prepare control and test mortar (mortar containing 10 RGP, 20 RGP, and 30 RGP). Three prismatic specimens 40 × 40 × 160 mm Fig. (**3b**) were cast and cured for 28 days for each batch. Compressive strength of the mortar bars was tested at the loading rate of 2.4 kN/s until failure according to AS 2350.11 [64]. The relative strength was calculated using Equation 1.

$$\text{Relative strength} = \frac{\text{Average compressive strength of test mortar at 28 days (in MPa)}}{\text{Average compressive strength of control mortar at 28 days (in MPa)}} X\ 100\% \quad \textbf{(1)}$$

A commonly used method to determine the concrete durability is the rapid chloride penetration test (RCPT). Concrete resistivity against chloride ions penetration in concrete was determined using RCPT according to ASTM C 1202-12 [65]. Concrete specimen of 50 mm thickness slice and 100 mm was cut from a 200 mm cylinder using a water-cooled diamond saw for the RCPT test. Three specimens were prepared for each batch for 28 and 56 days. The side surface of the concrete specimen was coated with epoxy. The coated concrete specimens were then subjected to vacuum saturation conditioning Figs. (**4a** and **4b**). The specimens were placed between two cells, where the positive cell contained 0.3 N NaOH solution, and the negative cell contained a 3.0% NaCl solution. A potential difference of 60 V direct current was applied between the two cells and the amount of total current passing through the concrete specimen was recorded every 30 minutes over a 6 hours duration. The amount of total charge passed was calculated by integrating the area below the current passed *vs* time graph.

3. RESULTS AND DISCUSSION

3.1. Characterization of Materials

The chemical compositions of cement, RGP, and fly ash are listed in Table **3**. As can be seen, RGP had the highest content of Silicon Dioxide (SiO_2), which is the basic requirement to consider as a pozzolanic material. The (SiO_2+Al_2O_3+Fe_2O_3) of RGP was found higher than the minimum requirement of 70%, according to ASTM C 618 [66]. The location of RGP in the CaO-Al_2O_3-SiO_2 ternary diagram, along with Portland cement and fly ash (Fig. **5**).

The particle size distribution of cement, fly ash and RGP all showed uniformly graded distribution curves (Fig. **6**). Cement with a specific surface area of 562 m^2/kg and fly ash having a specific surface area of 342 m^2/kg showed similar particle size distribution. However, cement exhibited a higher specific area due to the angular particle compared to the round-shaped fly ash. On the other hand, RGP showed finer particle size distribution than cement and fly ash with a specific surface area of 1169 m^2/kg. Table **3** shows that the effective size (D10, corresponding to 10% finer) of RGP was smaller than that of cement and fly ash. 50% of RGP was found to be smaller than 11.6 µm whereas 90% of RGP was finer than 51.8 µm. Whereas, cement and fly ash had 50% of particles finer than 21.4 µm and 20.1 µm, respectively. D90 (diameter corresponding to 90% finer) of cement and fly ash particles was greater than RGP.

The microstructures of these three materials are shown in Figs. (**7a**, **7b** & **7c**) using a scanning electron microscope. Cement and RGP showed angular shaped particles with the heterogeneous distribution. RGP consisted of sharp edges particles whereas, fly ash showed spherical shapes.

X-Ray diffraction analysis was performed to determine the X-Ray patterns of cement and RGP Fig. (**8**). X-Ray patterns of cement indicated a crystalline phase with a certain peak of major components, for instance, tri-calcium silicate, di-calcium silicate, calcium hydroxide and calcium silicate hydrate (C-S-H). RGP did not show a clear crystalline peak. In the amorphous phase, X-Rays are scattered in many directions leading to a large hump. RGP showed a large hump between 15 and 35 degrees due to the high silica compositions. It is evident that the RGP is a typical amorphous material, as no clear crystalline peak could be noticed.

3.2. Fresh Concrete Properties

3.2.1. Slump Test

The slump test was conducted to determine the consistency and workability of control concrete, concrete with RGP and fly ash (Table **4**). The target slump was in a range of 80 mm to 100 mm. The control concrete, 10 RGP, and 20 RGP mixtures achieved the desired slump; however, 30 RGP showed slump above 100 mm. The 10 RGP mixture exhibited less slump than that of the control mixture. However, as replacement level increased up to 30 RGP, slump drastically increased due to less water affinity of RGP. The real water to cement ratio increased in the mixture as the amount of RGP increased. The presence of more free water led to an increase in slump value. In addition, increasing RGP content could be a reason for cement dilution, which tends to reduce the formation of cement hydration products in the initial minutes of mixing, thereby causing insufficient products to bridge various particles together [8]. Fly ash concrete showed less workability with the same amount of water used in this study compared to control concrete and concrete with RGP. The reduced value of slump in fly ash concrete can be due to the porous nature of fly ash, which can absorb water from the mixture. A similar decrease pattern was observed by Akmal *et al*. [67].

3.2.2. Density

Table 4 shows that the fresh density of the control concrete was 2394 kg/m^3. A slight reduction in fresh density was observed with the addition of RGP due to the lower specific gravity of RGP. RGP had a specific gravity of 2.09 whereas cement had a specific gravity of 3.03. Fly ash concrete had a fresh density of 2410 kg/m^3 which was slightly higher than control concrete and concrete with RGP. The decrease in hardened density was noticed for the control, 10 RGP and fly ash concrete at 7 and 28 days. However, a significant increase in density was seen for the 10 RGP, 20 RGP and 30 RGP, as 2416 kg/m^3, 2364 kg/m^3 and 2338 kg/m^3, respectively, at 56 days. The addition of RGP exhibited an increase in hardened density with time. This can be attributed to the development of additional C-S-H gel which is formed during pozzolanic reaction of glass with calcium hydroxide. This can improve the interfacial transition zone and refine the capillary pores in concrete microstructure [44,68]. Fly ash concrete also supported this phenomenon and showed an increase in density at 56 days.

3.3. Hardened Concrete Properties

3.3.1. Variation of Compressive Strength

The compressive strength for control, RGP and fly ash concrete was tested at 7, 28 and 56 days Fig. (**9**). The control concrete showed better compressive strength than RGP and fly ash blend concrete at an early age (*i.e.*, 7 days). Compressive strength of concrete decreased as RGP replacement level increased, 20 RGP and 30 RGP showed 27% and 53% less strength than that of control concrete. RGP concrete had a negative impact on early-age strength due to the delay in pozzolanic reaction.

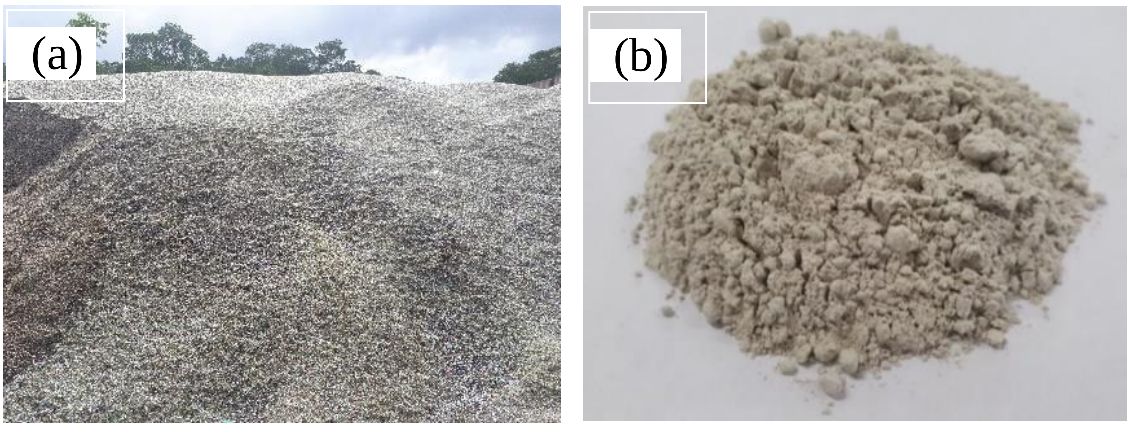

Fig. (2). (**a**) Crushed glass (3 mm size) at MRF site, (**b**) Glass powder (45 µm size).

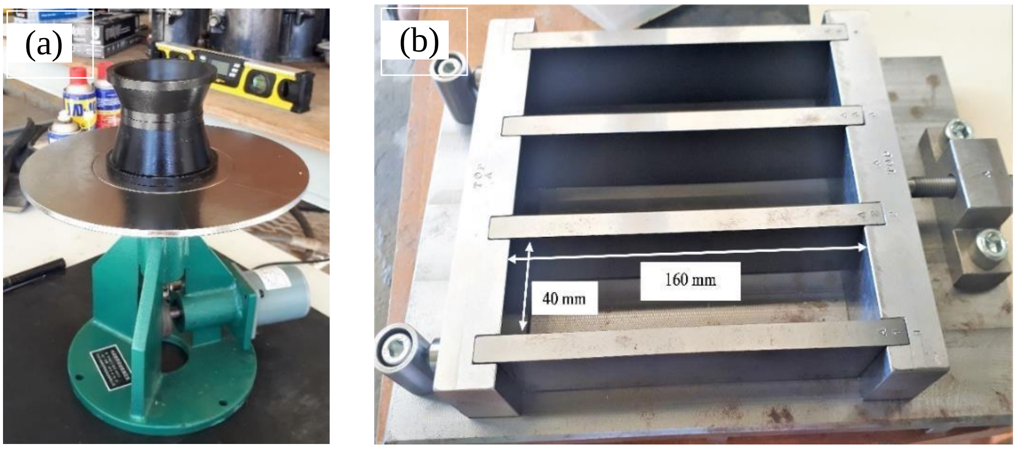

Fig. (3). (**a**) Flow table (**b**) Prismatic mold of 40 x 40 x 160 mm.

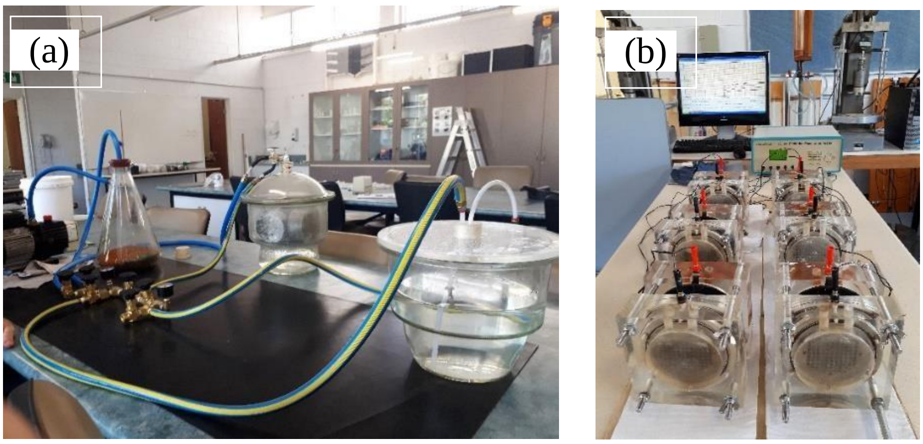

Fig. (4). (**a**) Vacuum saturation conditioning (**b**) RCPT Cells set up.

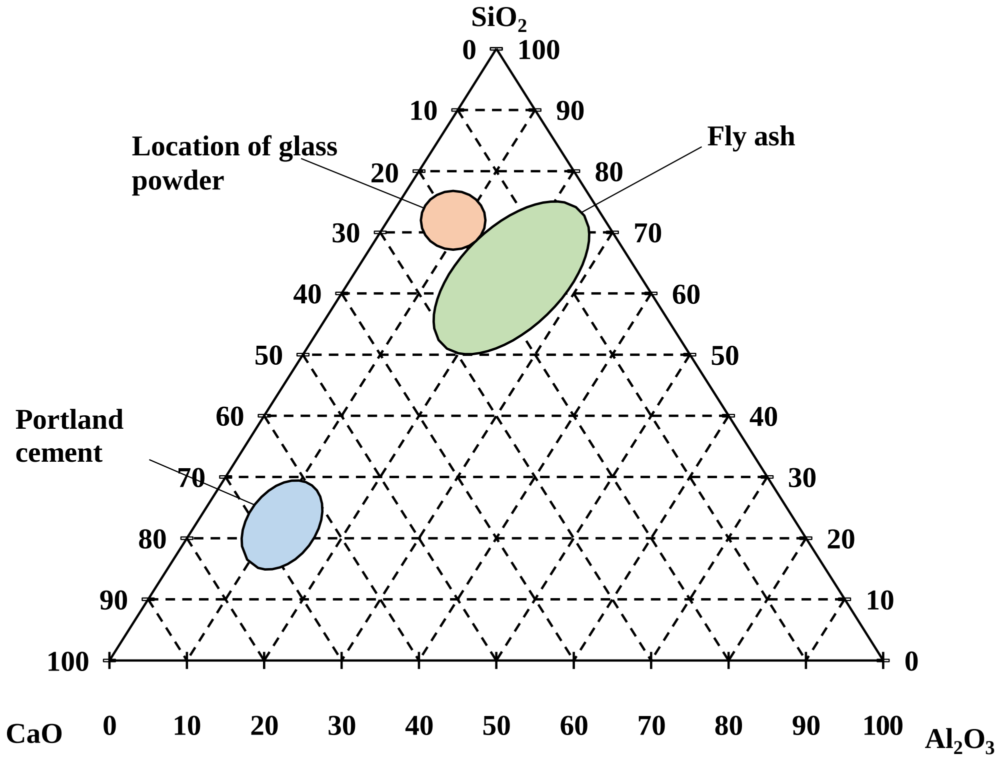

Fig. (5). CaO-Al_2O_3-SiO_2 ternary diagram of cement, fly ash and glass powder.

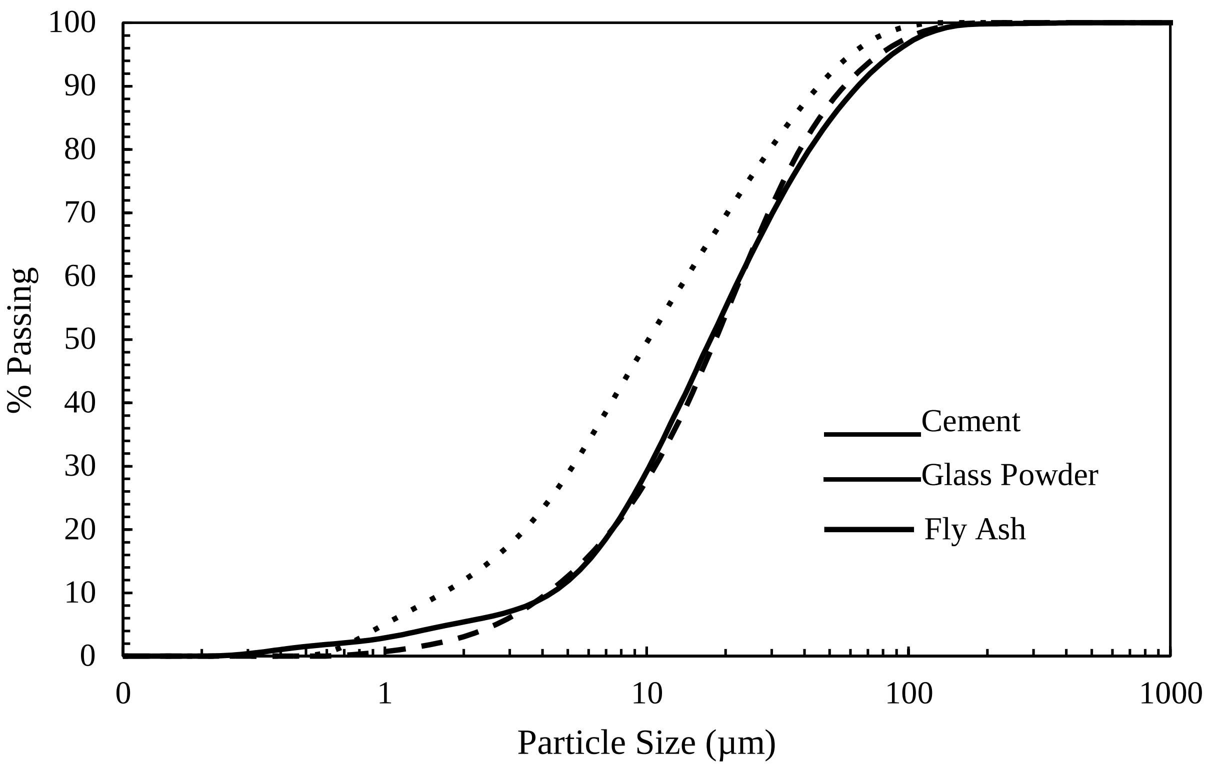

Fig. (6). Cumulative particle size distribution curve of cement, fly ash and glass powder.

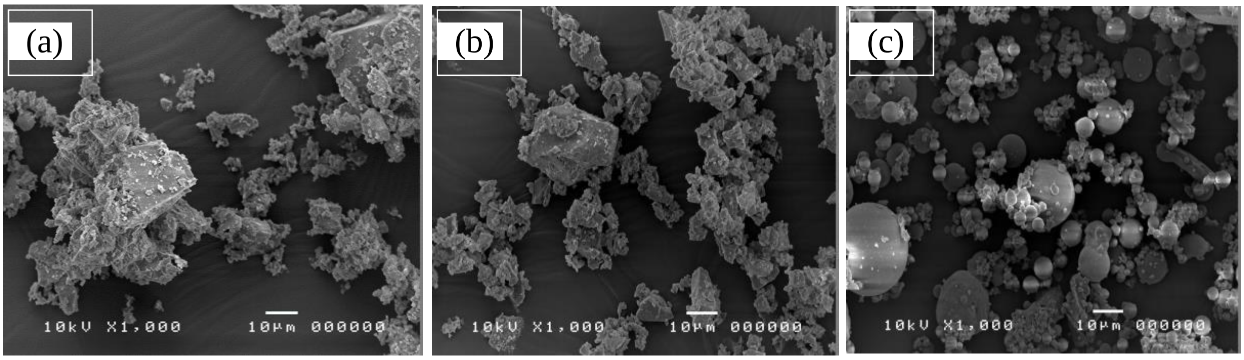

Fig. (7). Scanning electron microscope of (**a**) cement, (**b**) RGP, (**c**) fly ash.

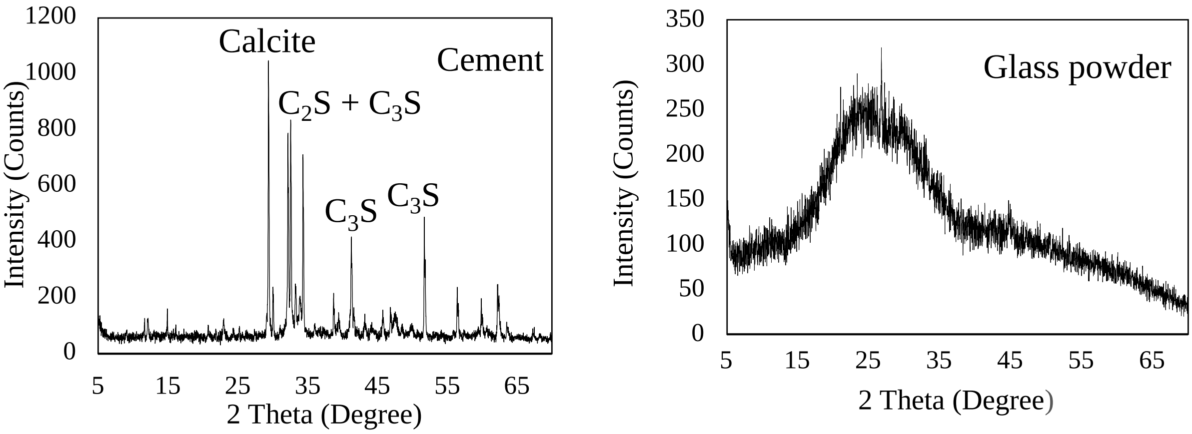

Fig. (8). XRD pattern for cement and RGP.

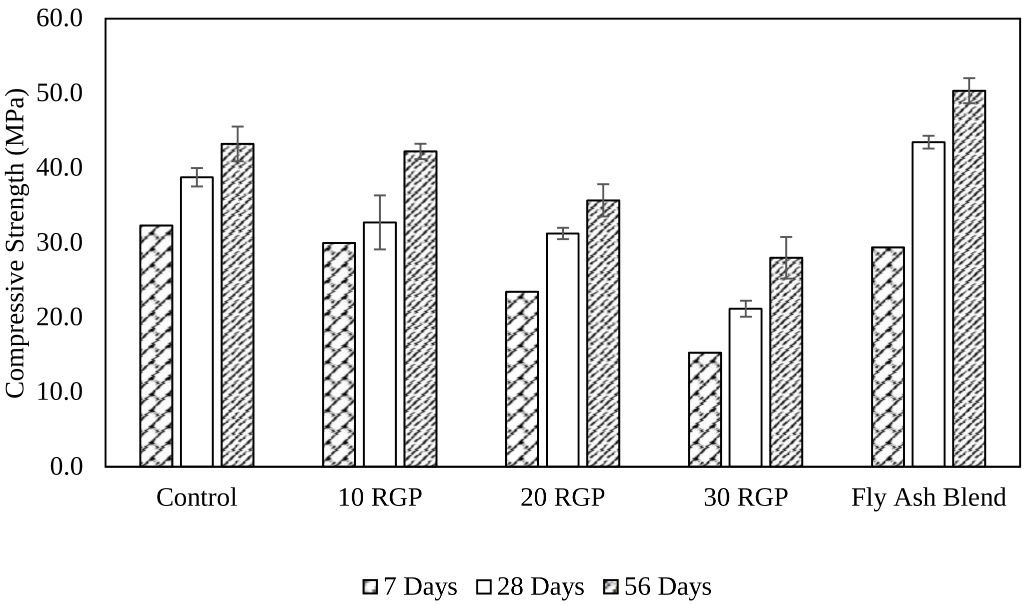

Fig. (9). Compressive strength of concrete with RGP and Fly Ash Blend.

Table 2. Mix proportion of mortar for three prism bars of 40 x 40 x 160 mm [53].

Material	Cement (g)	RGP (g)	Fine Sand (g)	Water (mL)
Control	450	-	1350	250
10 RGP	405	45	1350	250
20 RGP	360	90	1350	248
30 RGP	315	135	1350	247

Table 3. Chemical and physical characteristics of cement, fly ash and RGP.

	Cement	Fly Ash	RGP
Chemical Composition (%)			
SiO_2	18.99	56.86	72.02
Na_2O	0.16	1.02	12.85
CaO	63.94	4.08	11.25
Al_2O_3	4.99	21.62	1.47
MgO	0.78	4.12	0.57
Fe_2O_3	3.22	6.88	0.57
K_2O	0.35	1.97	0.35
SO_3	2.26	0.63	0.12
Physical properties	-	-	-
Specific Surface Area	562	342	1169
(m^2/kg)	-	-	-
D_{10} (μm)	4.85	4.92	1.90
D_{50} (μm)	21.4	20.1	11.6
D_{90} (μm)	70	75.3	51.8

Table 4. Slump and density of control, RGP and fly ash concrete.

Sample Name	Slump (mm)	Fresh Density	Hardened Density (kg/m3)		
		(kg/m^3)	7 days	28 Days	56 Days
Control	90	2394	2406	2399	2396
10 RGP	80	2381	2379	2373	2416
20 RGP	90	2312	2318	2329	2364
30 RGP	120	2254	2230	2250	2338
Fly Ash Blend	70	2410	2394	2376	2393

All concrete achieved the characteristic strength of 32 MPa at 28 days except 20 RGP (31.2 MPa) and 30 RGP (21.2 MPa). Fig. (**9**) shows that fly ash blend concrete produced the highest strength (43.5 MPa) at 28 days. However, 10 RGP and 20 RGP achieved compressive strength equivalent to 84% and 81% of control concrete. 30 RGP concrete showed lower strength gain than other concrete.

Control concrete achieved a strength of 43.22 MPa at 56 days. 10 RGP concrete achieved 96% strength of the control concrete, whereas 20 RGP and 30 RGP concrete obtained 82% and 64%, respectively. Besides, fly ash blend concrete had the maximum strength of 50.34 MPa at 56 days. Strength development exhibited a significant increase (41%, 52%, and 83% increase) for 10 RGP, 20 RGP, and 30 RGP concrete, respectively at 56 day. RGP and fly ash concrete gained further strength at later ages due to the formation of denser additional C-S-H at 56 days. The failure pattern of control and fly ash blend concrete was usually conic, shear-conic, and shear, and less dispersion with large distinct pieces. However, the addition of RGP displayed failure patterns most resembling conic and shear-conic modes; and smashed into many pieces.

3.3.2. Flexural and Tensile Strength of Concrete

The flexural and tensile strength of the concrete with RGP and fly ash as a partial cement substitute were conducted at 28 days Fig. (**10**). The addition of RGP did not show any significant effects on the flexural strength as all results obtained were within 10% of the control concrete. Recycled glass has the potential to reach long term effects. The long term effect can be attributed to the enhanced binding qualities of the calcium silicate hydrate which is formed during the pozzolanic reaction of glass with calcium hydroxide. However, tensile strength showed a decreasing trend as the RGP replacement level increased. The percentage of indirect tensile strength to compressive strength was in the range of 8-12%. Fly ash blend concrete exhibited 8% and 25% higher flexural and tensile strength than the control concrete, respectively at 28 days.

3.3.3. Rapid Chloride Permeability Test (RCPT)

RCPT was conducted on the concrete cylinder at 28 and 56 days to evaluate the resistance of concrete to chloride ion penetration (Fig. **11**). Control concrete showed the highest chloride penetration value compared to RGP and fly ash concrete both at 28 days and 56 days. The RCPT value of control concrete was 5234 coulombs at 28 days. According to ASTM C 1202, when the amount of charge passed (in coulombs) through the concrete is higher than 4000, the chloride ion permeability is considered as high. RGP and fly ash blend concrete showed lower chloride permeability compared to that of control concrete. The RCPT values of 10 RGP and 20 RGP were 5152 and 4840 coulombs, respectively at 28 days, still classified as high permeable concrete. As can be seen, RCPT values of 30 RGP and fly ash concrete were found to be 24% and 53% less permeable than that of control concrete which were between 2000- 4000 coulombs range, classified as moderately permeable concrete. A reduction of chloride ion permeability can be attributed to the formation of additional C-S-H gels which resulted in reduction in permeability of concrete.

A 19% reduction was noticed for control concrete at 56 days due to further hydration but still exhibited in a high permeable category. A total current passed through all the specimens decreased with an increase in curing time. The reduction rate in the permeability of concrete for RGP mixes was even more pronounced at 56 days due to an increase in density and due to the formation of additional C-S-H gel. Permeability of 10 RGP and 20 RGP concrete was moderate in category whereas 30 RGP showed very low permeable concrete. Fly ash concrete showed moderate to low permeability with an increase in curing time.

3.3.4. Relative Water Requirement

According to AS 3583.6 [53], the control mortar was prepared by using the amount of water required to give a flow of 110 ± 5. The test mortar with RGP was required to have sufficient water to achieve a flow within ±3 units of control mortar. 250 mL water was required for control mortar to gain a specified flow, as shown in Table **5**. RGP mortar showed flow values within three units of control mortar. Relative water requirement to control mortar was 100%, 99.2%, and 98.8% for 10 RGP, 20 RGP, and 30 RGP, respectively. Water requirement decreased as the RGP replacement level increased. This trend suggests that RGP does not absorb much water as cement does, and hence has a lower water requirement.

3.3.5. Relative Strength

A compressive strength test of mortar was conducted to assess the relative strength of RGP mortar bars at 28 days. Fig. (**12**) shows that 10 RGP mortar gained the highest relative strength which was about 75% of the control mortar. An increase in glass powder replacement affected negatively in relative strength. The 20 RGP and 30 RGP mortar achieved a relative strength of 61% and 59%, respectively. Relative strength was found to decrease with an increase in RGP quantity, and 40 RGP exhibited the least relative strength. The reason behind the reduction of strength in higher percentage can be due to inadequate cement paste available in the mixture to assist bonding within the mix, which is consequently forming the microscopic voids [69]. However, 10 RGP satisfied the requirements of AS 3582.1 [63] to be deliberated as supplementary cementitious material.

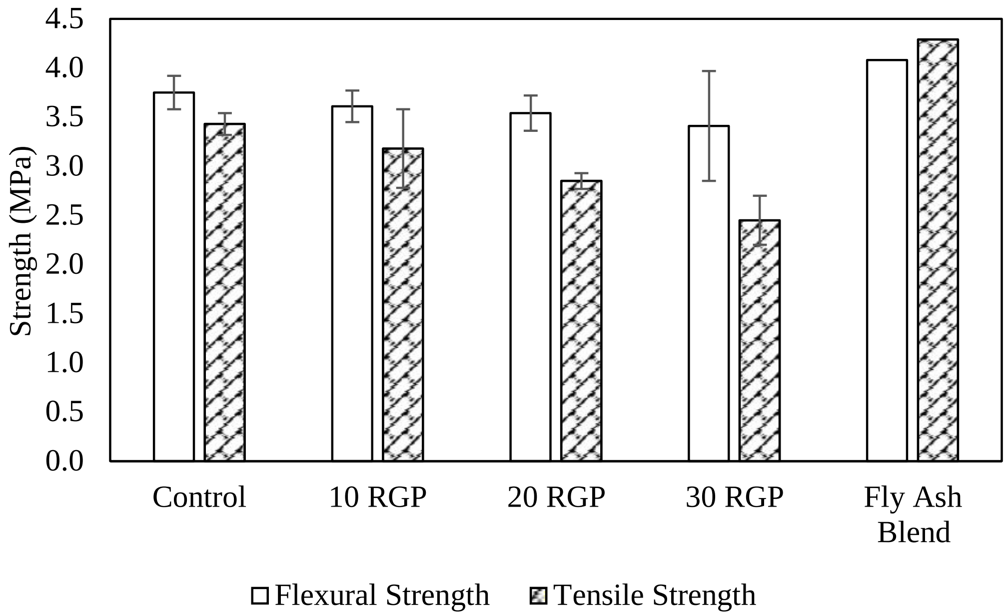

Fig. (10). Flexural strength of concrete with RGP and Fly Ash Blend.

Table 5. Relative water requirement of RGP.

Sample	Water Content (mL)	Flow (%)	Relative water requirement (%)
Control	250	110.9	-
10 RGP	250	112.8	100
20 RGP	248	110.7	99.2
30 RGP	247	109.8	98.8

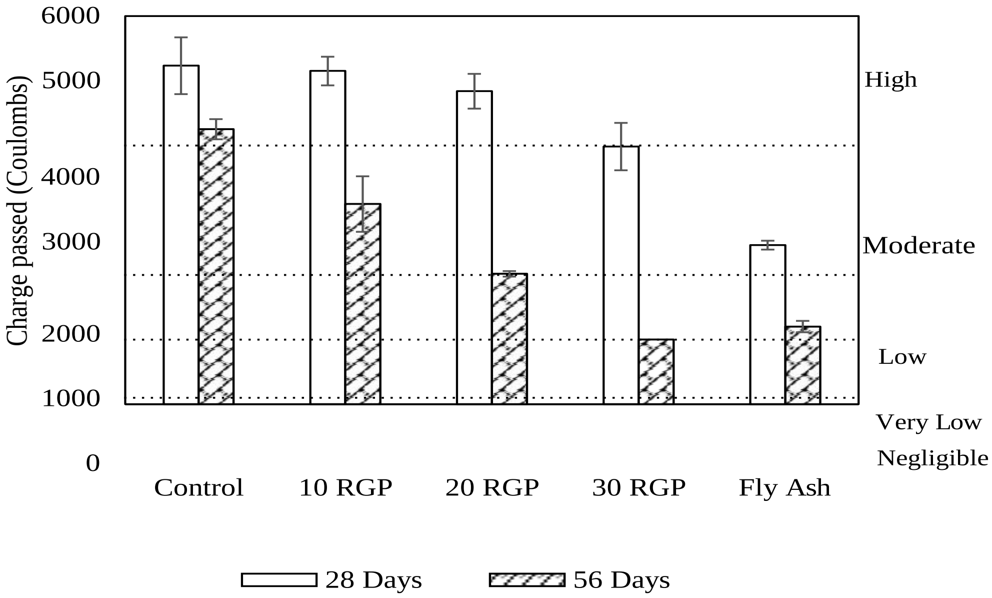

Fig. (11). RCPT results of concrete at 28 days and 56 days.

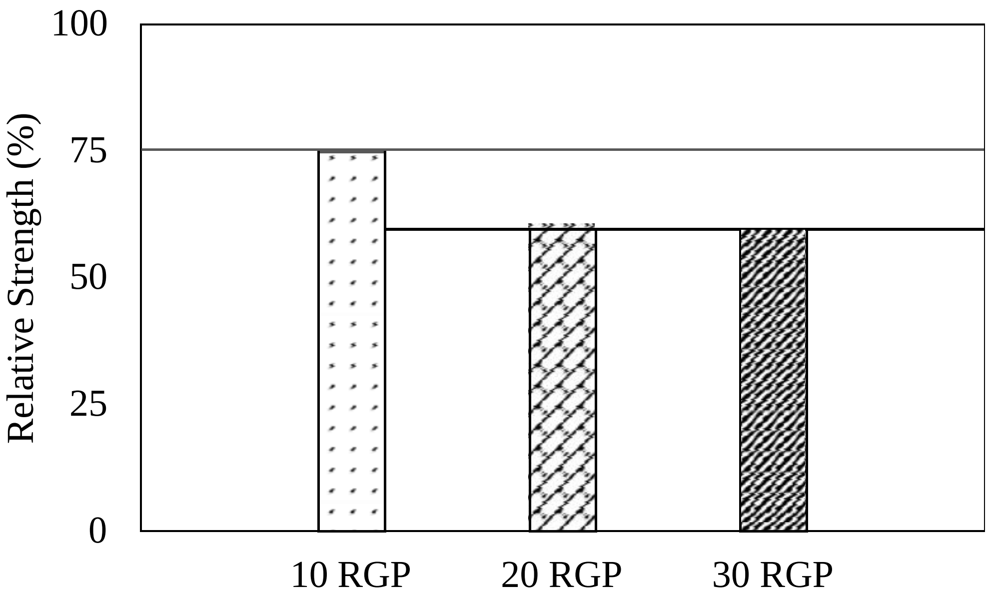

Fig. (12). Strength of RGP mortar relative to control mortar at 28 days.

CONCLUSION

This research studied the use of crushed recycled glass powder as a partial cement replacement in concrete. The recycled glass considered in this study was mixed colored soda-lime glass, collected from domestic waste by Cairns Regional Council, Australia. Having less water affinity and a smooth surface, RGP improved the workability of concrete. A reduction in fresh density was observed with the addition of RGP due to the lower specific gravity of glass powder. The addition of RGP improved hardened density with curing time even though a decrease was noticed with the increase in RGP replacement level. RGP did not show significant strength gain at an early age due to the delay in pozzolanic reaction; however, 10 RGP concrete achieved the target characteristic strength of 32 MPa at 28 days. Besides, RGP showed a substantial strength development at 56 days. The addition of RGP exhibited adequate flexural and tensile strength but, a similar downtrend was observed in flexural and tensile strength as compressive strength with the increase in RGP content. RGP concrete exhibited a reduction in permeability due to large specific surface area and production of more C-S-H gel. 10 RGP was found to satisfy the requirement of 75% relative strength requirement as per AS 3582.1 to be considered as supplementary cementitious material. Pozzolanic behavior was also confirmed by TGA and SEM analysis from 10 RGP. This research showed that the use of RGP as cement replacement is feasible for replacement level up to 10%. However, long term curing and lower particle size distribution are mandatory for the successful use of RGP with higher replacement levels without compromising the strength. The outcome of this research aims to contribute towards sustainable development by reducing the consumption of cement, as well as the reduction of glass waste going into landfills.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The authors confirm that the data supporting the findings of this research are available within the article.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Authors would like to thank Joshua Flanders, Dustin Peacocke, Joshua Lancini and Brendan Hall for their supports during experiments. Authors are also grateful to Cairns Regional Council and Pioneer North Queensland Pty Ltd for their material support throughout the study.

REFERENCES

[1] N. Sivakugan, Gnanendran , T. Carthigesu, Tuladhar , Rabin , Kannan , and Bobby M., *Civil Engineering Materials.,* Cengage Learning, 2017.

[2] R.M. Andrew, "Global CO2 emissions from cement production", *Earth Syst. Sci. Data,* vol. 10, no. 1, pp. 195-217, 2018. [http://dx.doi.org/10.5194/essd-10-195-2018]

[3] A. Sprince, A. Korjakins, and L. Pakrastinsh, "*Creep Behaviour of Concrete with Glass*. in ", *Proce of the 8th International Scientific and Practical Conference, Environment.Technology. Resources,* 2011

[4] C.I. Federation, *Industry Report,* vol. 2013. Australia, 2013.

[5] K. Afshinnia, and P.R. Rangaraju, "Impact of combined use of ground glass powder and crushed glass aggregate on selected properties of Portland cement concrete", *Constr. Build. Mater.,* vol. 117, pp. 263-272, 2016. [http://dx.doi.org/10.1016/j.conbuildmat.2016.04.072]

[6] G.M.S. Islam, M.H. Rahman, and N. Kazi, "Waste glass powder as partial replacement of cement for sustainable concrete practice", *Int J of Sustainable Built Environ,* vol. 6, no. 1, pp. 37-44, 2017. [http://dx.doi.org/10.1016/j.ijsbe.2016.10.005]

[7] M. Kamali, and A. Ghahremaninezhad, "Effect of glass powders on the mechanical and durability properties of cementitious materials", *Constr. Build. Mater.,* vol. 98, pp. 407-416, 2015. [http://dx.doi.org/10.1016/j.conbuildmat.2015.06.010]

[8] N.A. Soliman, and A. Tagnit-Hamou, "Development of ultra-high-performance concrete using glass powder - Towards ecofriendly concrete", *Constr. Build. Mater.,* vol. 125, pp. 600-612, 2016. [http://dx.doi.org/10.1016/j.conbuildmat.2016.08.073]

[9] A. Rahma, N. El Naber, and S. I. Ismail, "Effect of glass powder on the compression strength and the workability of concrete", *Cogent Eng,* vol. 4, no. 1, 2017. [http://dx.doi.org/10.1080/23311916.2017.1373415]

[10] A. Arulrajah, "Kua, Teck-Ang, Horpibulsuk, Suksun, Mirzababaei, Mehdi, and Chinkulkijniwat, Avirut, Recycled glass as a supplementary filler material in spent coffee grounds geopolymers", *Constr. Build. Mater.,* vol. 151, pp. 18-27, 2017. [http://dx.doi.org/10.1016/j.conbuildmat.2017.06.050]

[11] A. Scmidt, and W.H.F. Saia, "Alkali-aggregate reaction tests on glass used for exposed aggregate wall apnel work", *J. Am. Concr. Inst.,* vol. 60, pp. 1235-1236, 1963.

[12] C.D. Johnston, "Waste glass of coarse aggregate for concrete", *J. Test. Eval.,* vol. 2, no. 5, pp. 344-350, 1974. [http://dx.doi.org/10.1520/JTE10117J]

[13] İ.B. Topçu, and M. Canbaz, "Properties of concrete containing waste glass", *Cement Concr. Res.,* vol. 34, no. 2, pp. 267-274, 2004. [http://dx.doi.org/10.1016/j.cemconres.2003.07.003]

[14] M.J. Terro, "Properties of concrete made with recycled crushed glass at elevated temperatures", *Build. Environ.,* vol. 41, no. 5, pp. 633-639, 2006. [http://dx.doi.org/10.1016/j.buildenv.2005.02.018]

[15] X. Yu, "Tao, Zhong, Song, Tian-Yi, and Pan, Zhu, Performance of concrete made with steel slag and waste glass", *Constr. Build. Mater.,* vol. 114, pp. 737-746, 2016. [http://dx.doi.org/10.1016/j.conbuildmat.2016.03.217]

[16] N.N.M. Pauzi, M. Jamil, R. Hamid, A.Z. Abdin, and M.F.M. Zain, "Influence of spherical and crushed waste Cathode-Ray Tube (CRT) glass on lead (Pb) leaching and mechanical properties of concrete", *J. Build. Eng.,* vol. 21, pp. 421-428, 2019. [http://dx.doi.org/10.1016/j.jobe.2018.10.024]

[17] H. Du, and K.H. Tan, "Effect of particle size on alkali-silica reaction in recycled glass mortars", *Constr. Build. Mater.,* vol. 66, pp. 275-285, 2014. [http://dx.doi.org/10.1016/j.conbuildmat.2014.05.092]

[18] G.H.A.T. Ting, Yi. Wei Daniel, Qian. Ye, and Tan. Ming Jen, "Utilization of recycled glass for 3D concrete printing: rheological and mechanical properties", *J. Mater. Cycles Waste Manag.,* vol. 21, no. 4, pp. 994-1003, 2019. [http://dx.doi.org/10.1007/s10163-019-00857-x]

[19] R.G. Pike, and D. Hubbard, "Physicochemical studies of the destructive alkali-aggregate reaction in concrete", *J. Res. Natl. Bur. Stand.,* vol. 59, no. 2, pp. 127-132, 1957. [http://dx.doi.org/10.6028/jres.059.013]

[20] A. Shayan, and A. Xu, "Value-added utilisation of waste glass in concrete", *Cement Concr. Res.,* vol. 34, no. 1, pp. 81-89, 2004. [http://dx.doi.org/10.1016/S0008-8846(03)00251-5]

[21] D.K. Ashish, "Feasibility of waste marble powder in concrete as partial substitution of cement and sand amalgam for sustainable growth", *J. Build. Eng.,* vol. 15, pp. 236-242, 2018. [http://dx.doi.org/10.1016/j.jobe.2017.11.024]

[22] Y. Sharifi, M. Houshiar, and B. Aghebati, "Recycled glass replacement as fine aggregate in self-compacting concrete", *Front. Struct. Civ. Eng.,* vol. 7, no. 4, pp. 419-428, 2013. [http://dx.doi.org/10.1007/s11709-013-0224-8]

[23] H. Du, and K.H. Tan, "Use of waste glass as sand in mortar: Part II - Alkali-silica reaction and mitigation methods", *Cement Concr. Compos.,* vol. 35, no. 1, pp. 109-117, 2013. [http://dx.doi.org/10.1016/j.cemconcomp.2012.08.029]

[24] S. De Castro, and J. De Brito, "Evaluation of the durability of concrete made with crushed glass aggregates", *J. Clean. Prod.,* vol. 41, pp. 7-14, 2013. [http://dx.doi.org/10.1016/j.jclepro.2012.09.021]

[25] H. Zhao, C.S. Poon, and T.C. Ling, "Utilizing recycled cathode ray tube funnel glass sand as river sand replacement in the high-density

concrete", *J. Clean. Prod.,* vol. 51, pp. 184-190, 2013. [http://dx.doi.org/10.1016/j.jclepro.2013.01.025]

[26] M.I. Malik, Muzafar Bashir, Sajad Ahmad, Tabish Tariq, and Umar Chowdhary, "Study of concrete involving use of waste glass as partial replacement of fine aggregates", *IOSR J Eng (IOSRJEN),* vol. 3, no. 7, pp. 08-13, 2013.

[27] E.E. Ali, and S.H. Al-Tersawy, "Recycled glass as a partial replacement for fine aggregate in self compacting concrete", *Constr. Build. Mater.,* vol. 35, pp. 785-791, 2012. [http://dx.doi.org/10.1016/j.conbuildmat.2012.04.117]

[28] T-C. Ling, and C-S. Poon, "Properties of architectural mortar prepared with recycled glass with different particle sizes", *Mater. Des.,* vol. 32, no. 5, pp. 2675-2684, 2011. [http://dx.doi.org/10.1016/j.matdes.2011.01.011]

[29] B. Taha, and G. Nounu, "Utilizing waste recycled glass as sand/cement replacement in concrete", *J. Mater. Civ. Eng.,* vol. 21, no. 12, pp. 709-721, 2009. [http://dx.doi.org/10.1061/(ASCE)0899-1561(2009)21:12(709)]

[30] M.C. Limbachiya, "Bulk engineering and durability properties of washed glass sand concrete", *Constr. Build. Mater.,* vol. 23, no. 2, pp. 1078-1083, 2009. [http://dx.doi.org/10.1016/j.conbuildmat.2008.05.022]

[31] C. Yuksel, Reza Saleh. Ahari, Babak Abbaspoursani,. Ahari, and Kambiz. Ramyar, "Evaluation of three test methods for determining the alkali-silica reactivity of glass aggregate", *Cement Concr. Compos.,* vol. 38, pp. 57-64, 2013. [http://dx.doi.org/10.1016/j.cemconcomp.2013.03.002]

[32] N. Degirmenci, A. Yilmaz, and O.A. Cakir, "Utilization of waste glass as sand replacement in cement mortar", *Indian J. Eng. Mater. Sci.,* vol. 18, no. 4, pp. 303-308, 2011.

[33] C.S. Lam, C.S. Poon, and D. Chan, "Enhancing the performance of pre-cast concrete blocks by incorporating waste glass – ASR consideration", *Cement Concr. Compos.,* vol. 29, no. 8, pp. 616-625, 2007. [http://dx.doi.org/10.1016/j.cemconcomp.2007.03.008]

[34] T-C. Ling, and C-S. Poon, "A comparative study on the feasible use of recycled beverage and CRT funnel glass as fine aggregate in cement mortar", *J. Clean. Prod.,* vol. 29-30, pp. 46-52, 2012. [http://dx.doi.org/10.1016/j.jclepro.2012.02.018]

[35] G. Lee, Tung-Chai. Ling, Yuk-Lung. Wong, and Chi-Sun. Poon, "Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR of concrete blocks", *Constr. Build. Mater.,* vol. 25, no. 5, pp. 2611-2618, 2011. [http://dx.doi.org/10.1016/j.conbuildmat.2010.12.008]

[36] N. Tamanna, Norsuzailina Mohamed. Sutan, Rabin. Tuladhar, Delsey Ching Lee. Teo, and Ibrahim. Yakub, "Pozzolanic properties of glass powder in cement paste. J of Civil Eng", *Sci & Technol,* vol. 7, no. 2, pp. 75-81, 2016.

[37] N. Tamanna, "Tuladhar, Rabin, Avosa, Nathan, and Sivakugan, Siva", *The effect of using waste glass powder as cement replacement in concrete, in the 28th Biennial Conference of the Concrete Institute of Australia,* , 2017

[38] N. Tamanna, N.M. Sutan, and R. Tuladhar, "The effect of waste glass powder on microstructural behaviour when used a partial cement replacement", *5th International fib Congress,* 2018 Melbourne, VIC, Australia

[39] Y. Shao, Thibaut. Lefort, Shylesh. Moras, and Damian. Rodriguez, "Studies on concrete containing ground waste glass", *Cement Concr. Res.,* vol. 30, no. 1, pp. 91-100, 2000. [http://dx.doi.org/10.1016/S0008-8846(99)00213-6]

[40] D.G. Vijaykumar, M.H. Vishaliny, and D.D. Govindarajulu, "Studies on glass powder as partial replacement of cement in concrete production", *Int. J. Emerg. Technol. Adv. Eng.,* vol. 3, no. 2, pp. 153-156, 2013.

[41] C. Shi, Yanzhong. Wu, Chris. Riefler, and Hugh. Wang, "Characteristics and pozzolanic reactivity of glass powders", *Cement Concr. Res.,* vol. 35, no. 5, pp. 987-993, 2005. [http://dx.doi.org/10.1016/j.cemconres.2004.05.015]

[42] A. Khmiri, B. Samet, and M. Chaabouni, "Assessment of the waste glass powder pozzolanic activity by different methods", *IJRRAS,* vol. 10, no. 2, pp. 322-328, 2012.

[43] D.M. Patil, and D.K.K. Sangle, "Experimental investigation of waste glass powder as partial replacement of cement in concrete", *Int J. of Adv Technol in Civil Engin.,* vol. 2, no. 1, pp. 112-117, 2013.

[44] R-U-D. Nassar, and P. Soroushian, "Field investigation of concrete incorporating milled waste glass", *J. Solid Waste Technol. Manag.,* vol. 37, no. 4, pp. 307-319, 2011. [http://dx.doi.org/10.5276/JSWTM.2011.307]

[45] V. Gunalaan, and P.S.G. Kanapathy, "Performance of using waste glass powder in concrete as replacement of cement", *Am J. of Eng Res (AJER),* 2013. [cited 2 12]; 175-181].

[46] V. Vaitkevičius, E. Šerelis, and H. Hilbig, "The effect of glass powder on the microstructure of ultra high performance concrete", *Constr. Build. Mater.,* vol. 68, pp. 102-109, 2014. [http://dx.doi.org/10.1016/j.conbuildmat.2014.05.101]

[47] M.C. Bignozzi, "Glass waste as supplementary cementing materials: The effects of glass chemical composition", *Cement Concr. Compos.,* vol. 55, pp. 45-52, 2015. [http://dx.doi.org/10.1016/j.cemconcomp.2014.07.020]

[48] A. Saccani, and M.C. Bignozzi, "ASR expansion behavior of recycled glass fine aggregates in concrete", *Cement Concr. Res.,* vol. 40, no. 4, pp. 531-536, 2010. [http://dx.doi.org/10.1016/j.cemconres.2009.09.003]

[49] W. Management, Ed., *(NEA), N.E.A., Waste Statistics and Overall Recycling.,* Singapore, 2017.

[50] W. Management, Ed., *(NEA), N.E.A., Waste Statistics and Overall Recycling.,* Singapore, 2018.

[51] "(NEA), N.E.A", *Advancing sustainable materials management: 2013 fact sheet,* USA., 2015.

[52] "(NEA), N.E.A", *Municipal Solid Waste (MSW) in the United States: facts and figures for 2010.,* USA., 2010.

[53] "AS3583.6", *Methods of Test for Supplementary Cementitious Materials, Method 6 : Determination of Relative Water Requirement and Strength Index, in Australian Standards AS 3583.6,* 2018.

[54] "AS2701", *Methods of Sampling and Testing Mortar for Masonry Construction, Section 5: Method for Determination of Water Retention, in Australian Standard AS 2701,* 2001.

[55] 55"AS1012.2", *Methods of Testing Concrete, Methos 2: Preparing Concrete Mixes in the Laboratory, in Australian Standards AS 1012.2,* 2014.

[56] "AS1012.8.1", *Methods of Testing Concrete, Method 8.1: Method for Making and Curing Concrete-Compression and Indirect Tensile Test Specimens, in Australian Standards AS 1012.8.1,* 2014.

[57] "AS2350.12", *Methods of Testing Portland, Blended and Masonry Cements, Method 12 : Preparation of a Standard Mortar and Moulding of Specimens, in Australain Standard AS 2350.12,* 2006.

[58] "AS1012.3.1", *Methods of Testing Concrete, Methos 3.2: Determination of Properties Related to the Consistency of Concrete-Slump Test, in Australian Standards AS 1012.3.1,* 2014.

[59] "AS1012.12.1", *Method of Testing Concrete, Method 12.1: Determination of Mass Per Unit Volume of Hardened Concrete- Rapid Measuring Method, in Australian Standards AS 1012.12.1,* 2014.

[60] "AS1012.9.1", *Methods of Testing Concrete, Method 9: Compressive Strength Tests- Concrete, Mortar and Grout Specimens, in Australian Standards AS 1012.9.1,* 2014.

[61] "AS1012.10", *Methods of Testing Concrete, Method 10 Determination of Indirect Tensile Strength of Concrete Cylinders ('Brazil' or Splitting Test), in Australian Standard AS 1012.10.,* 2000.

[62] "AS1012.11", *Methods of Testing Concrete, Method 11: Determination of The Modulus of Rupture, in Australian Standards AS 1012.11,* 2014.

[63] "AS3582.1", *Supplementary Cementitious Materials, Part 1: Fly Ash, in Australian Standards AS 3582.1,* 2016.

[64] "AS/NZS2350.11", *Methods of Testing Portland, Blended and Masonry Cements, Method 11: Compressive Strength, in Australian Standard AS/ NZS 2350.11,* 2006.

[65] "ASTMC1202", In: *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, in ASTM C1202.,* ASTM International: West Conshohocken, PA: USA, 2012.

[66] "ASTMC618", In: *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, in ASTM C 618,* ASTM International: West Conshohocken, PA,: USA, 2014.

[67] A.Z.M. Muhammad Nazrin Akmal, F Mat Yahaya, H Mohd Hanafi, and Z Nur Azzimah, *Utilization of fly ash as partial sand replacement in oil palm shell lightweight aggregate concrete.*

[68] R-U-D. Nassar, and P. Soroushian, "Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement", *Constr. Build. Mater.,* vol. 29, no. 1, pp. 368-377, 2012. [http://dx.doi.org/10.1016/j.conbuildmat.2011.10.061]

[69] M. Adaway, and Y. Wang, "Recycled glass as a partial replacement for fine aggregate in structural concrete -Effects on compressive strength", *Electron J. of Struc Engi,* vol. 14, no. 1, pp. 116-122, 2015.