Construction and Building Materials 239 (2020) 117804

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Performance of recycled waste glass sand as partial replacement of sand in concrete

Nafisa Tamanna *, Rabin Tuladhar, Nagaratnam Sivakugan

College of Science and Engineering, James Cook University, QLD 4811, Australia

HIGHLIGHTS

- Recycled glass sand (RGS) improved resistance to chloride ion penetration.
- RGS showed a significant improvement in the strength of concrete.
- Addition of RGS significantly reduced expansion caused by alkali-silica reaction.

ARTICLE INFO

Article history:
Received 17 April 2019
Received in revised form 1 November 2019
Accepted 4 December 2019
Available online 23 December 2019

Keywords:
Recycling
Recycled glass sand
Sand replacement
Green concrete

ABSTRACT

The aim of this research is to utilize recycled waste glass effectively as a partial replacement for the sand in concrete. A series of tests were conducted to determine the properties of the constituents, fresh concrete, and hardened concrete including its durability characteristics to investigate the suitability of using recycled waste glass sand (RGS) in concrete. Concrete was produced by replacing natural river sand with 20%, 40% and 60% of recycled glass sand. In this study, mixed-colour soda lime glass, collected by Cairns Regional Council, Australia was used. The test results showed a significant improvement in the strength of concrete. RGS concrete also showed improved resistance to chloride ion penetration. Besides, RGS addition significantly reduced expansion caused by alkali-silica reaction. The experimental results ascertain that the addition of RGS can be a good substitute for natural sand, and therefore, can be effectively used in industrial applications.

© 2019 Elsevier Ltd. All rights reserved.

1. Introduction

The construction sector experiences a growing demand for concrete due to rapid infrastructure development. This development accelerates concrete production upwards of 25 million cubic meters each year in Australia [1] as well as leads to massive extraction of natural resources such as natural aggregate. Sand and gravel are the most extracted natural resources in the world corresponding to 79% or 28.6 giga tonnes per year in 2010 [2]. The natural river sand has been used as a fine aggregate in concrete construction for several decades. In spite of the abundance of sand on the earth's surface, it is a finite natural resource that can soon be depleted. Excessive extraction of sand not only results in sand scarcity, but also harms marine ecosystems, water supply and turbidity, marine food source and climate. Besides, excessive dredging for sand can aggravate damage due to flood, tsunami and storm surge because of erosion of shoreline and river banks. It also affects ground water supply as a result of lowering of the water table and saltwater intrusion, and cause damage to river embankment, bridge piers, and civil infrastructures [2]. Furthermore, greenhouse gas emission is associated with the extraction of sand and its transportation from the extraction site to the construction site. Construction industry is therefore very keen to use alternative materials such as recycled waste glass as a replacement of natural sand in concrete [3]. A million tonnes of waste glass are collected annually in Australia for future sorting and recycling process [4]. However, the addition of contaminants such as a plastic cap, metals, paper with waste glass stream, inconsistency in the chemical composition of different type of glasses, as well as difficulty in sorting different coloured glasses, make the recycling process difficult. Using crushed glass in concrete as sand replacement gives an attractive platform to use waste glass. It not only reduces the extraction of natural sand but also helps in reducing the amount of waste glass going into landfills.

Several studies have been conducted to investigate the use of recycled crushed glass in concrete in the past few years [5–8]. Crushed glass is considered as a good alternative for sand because

* Corresponding author.
E-mail address: nafisa.tamanna@my.jcu.edu.au (N. Tamanna).

https://doi.org/10.1016/j.conbuildmat.2019.117804
0950-0618/© 2019 Elsevier Ltd. All rights reserved.

of its chemical composition and physical characteristics [7]. In addition, due to the smooth surface and relatively low water absorption, glass sand can improve the fresh concrete properties [9]. Although, glass sand enhances the resistance to chloride ion penetration, contradictory outcomes are found on mechanical and durability properties of hardened concrete [6–8,10–14]. Furthermore, the main concern of using glass sand in concrete is Alkali-Silica Reaction (ASR) that occurs between amorphous silica in glass and alkali in cement. Excessive expansion occurs in the presence of moisture, and the resulting pressure cracks concrete causing strength and durability issues. ASR expansion is prominent when larger glass particles (>4.5 mm size) are used as coarse aggregates replacement in concrete. Minor cracks can form at the edge of glass aggregates during crushing operations [15]. Alkalis produced during hydration of cement can penetrate into these cracks, and in presence of moistures produces expansive ASR gels. However, when finer glass particles is used as sand replacement in concrete results in non-expansive pozzolanic reaction forming calcium silicate hydrate (C-S-H) with a low calcium-silicate ratio [16]. Past research have shown contradictory results on ASR expansion regarding the glass particle colour and glass proportion in the mixture [17].

Several studies have been conducted to the use of waste glass in concrete in Australia [18–20]. However, very limited field trials have been undertaken to observe the suitability of waste glass sand as partial sand replacement in concrete. Besides, the properties and performance of recycled glass sand depends upon the source and types of waste glass. This research was conducted to provide lab results to the Cairns Regional Council with the municipal glass waste collected by the council so that the council can implement the recycled glass on their concrete works. This research studied the use of mixed coloured soda-lime glass supplied by Cairns Regional Council, Australia as sand replacement in concrete. In this research, concrete with a target characteristic strength of 32 MPa was produced by replacing natural river sand with 20%, 40%, and 60% of crushed recycled glass sand (RGS) to investigate the effect of replacement levels on fresh and hardened properties of concrete. The impact on workability, compressive strength, tensile strength, and flexural strength were evaluated. The durability of concrete with RGS was also analysed by rapid chloride penetration test (RCPT) and alkali-silica reaction (ASR) test. The study aims to develop and promote the use of sustainable concrete mix with recycled glass as sand replacement at an industrial scale.

2. Experimental Procedures

2.1. Materials

General purpose cement with specific surface area of 562 m^2/kg was used throughout the research. The equivalent alkali content (Na_2O_{eq} = Na_2O + 0.658 K_2O) of this cement was calculated to be 0.39% (expressed as low alkali cement, i.e. less than 0.6%). The coarse aggregate used was obtained from Edmonton Quarry, following the grain size requirement specified by AS 2758.1 [21]. For fine aggregate, natural coarse sand and fine sand were used with a nominal size of 5 mm and 2 mm, respectively. Coarse and fine sand were obtained from Barron River and Tableland regions, respectively. The properties of aggregate are tabulated in Table 1. SIKA RE Retarder was used as an admixture.

Mixed coloured soda-lime glass supplied by the Cairns Regional Council was utilised as a partial coarse sand replacement. Council collects all commingled recyclables from the yellow recycling bins and transports to Materials Recovery Facility (MRF) unit. All collected recyclable materials, which includes paper, cardboard, plastic bottles, aluminium cans, and glass bottles are sorted and large items removed as it passes through the conveyor belt. 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 where larger contaminants are removed manually. Glass items are then sent to glass crushing facility.

Table 1
Properties of natural aggregate supplied by Pioneer North Queensland.

Aggregates	20 mm Coarse aggregate	Coarse sand	Fine sand
Nominal size of sample (mm)	20	5	2
Particle density dry (t/m^3)	2.68	2.55	2.60
Particle density saturated surface dry (t/m^3)	2.69	2.58	2.62
Water absorption (%)	0.4	0.9	0.7

Glass crushing is done at three stages through- imploder, shearing unit, and sanding unit. The imploder has rotating blades to crush glass (Fig. 1a). After imploder, glass particles are moved to the shearing unit for further crushing process by shearing (Fig. 1b). Some large glass particles and other impurities are removed before reaching the sanding unit. Rotating grinding shaft (Fig. 1c) of the sanding unit crushes into sand fineness. Glass sand particles are dropped into two separate drums through 5 mm (coarse glass) and 3 mm (fine glass) holes. The coarse glass particles of 5 mm in size are then sent to landfill while the fine glass particles are sent to be utilised in construction. In this study, fine glass of 3 mm (Fig. 2) was used as received, without any modification (i.e., cleaning or sorting), and tested to meet the requirements of Cement concrete Aggregate Australia (CCAA).

2.2. Concrete mix design

Concrete mix design used in this study for control specimen closely followed the mix design used by Pioneer North Queensland (PNQ) for their commercial concrete plant (as shown in Table 2). The mix design was designed for a characteristic strength of 32 MPa at 28 days. Based on the mix design, the target slump value was in the range of 80–100 mm. By trial and error, it was found that 0.53 w/c ratio achieved the targeted slump value. A total of four concrete batches were prepared, including the control concrete without any recycled glass sand for comparison purpose. The other three concrete batches corresponded to the replacement of coarse sand with 20%, 40%, and 60% recycled glass sand, noted as 20 RGS, 40 RGS, and 60 RGS, respectively.

Four batches of concrete were mixed separately in a pan mixer according to AS 1012.2 [22]. Mixtures were poured into moulds to cast cylinders and beams for compressive, flexural, tensile strength and rapid chloride penetration test. Vibration was applied by a mechanical vibrating table. After casting, all samples in the mould were allowed to set initially for 24 h. Then, specimens were demoulded and cured for a specific period, for instance, 7, 28, 56 days in water at 23 ± 2 °C, according to AS 1012.8.1 [23].

2.3. Experimental methods

The experimental study included (a) material properties tests – particle size distribution test and sugar content test and (b) fresh concrete properties – slump test and fresh concrete density test (c) hardened concrete properties – compressive, tensile and flexural strength tests. Rapid Chloride Penetration Test (RCPT) and Alkali-Silica Reaction (ASR) test were also carried out on concrete and mortar specimen, respectively to determine durability properties of concrete.

Fig. 1. Glass crushing machine (a) Imploder (b) Shearing unit and (c) Grinding shaft.

Fig. 2. Fine glass sand (3 mm) used as a partial coarse sand replacement.

The detection of sugar in aggregate is a qualitative method to determine the presence or absence of sugar. The presence of sugar interferes with the chemical reaction that delays setting of concrete. This test can directly detect sugar from honey, wine, fruit juices and other sources of glucose. The mixed coloured glass used in this study was mainly obtained from the glass containers such as beverage bottles and food containers, and are prone to sugar contaminations. The detection of sugar in RGS was conducted following AS 1141.35 [24]. Fehling's reagent was used to detect sugar in aggregate. Fehling's solution was prepared by mixing equal volumes of the blue aqueous solution of copper (II) sulphate pentahydrate crystals (Fig. 4a i) and colourless solution of aqueous potassium sodium tartrate (also known as Rochelle salt) (Fig. 4a ii) with a strong alkali (commonly sodium hydroxide). The aggregate to be tested was added to Fehling's solution, and the resultant mixture was heated. A reddish-brown precipitate indicates the presence of sugar in aggregate.

In this research, fresh and hardened concrete properties were also evaluated to investigate the effect of using RGS in concrete as a partial fine aggregate replacement. The properties of fresh concrete were investigated by conducting a slump test and fresh density test. The slump test was carried out according to AS 1012.3.1 [25]. Concrete cylinders were weighted forthwith after casting the moulds (fresh density) and prior testing (hardened density) as per AS 1012.12.1 to assess the density [26]. Compressive strength, flexural strength, and indirect tensile strength tests were conducted to investigate the basic hardened properties according to AS 1012.9 [27], AS 1012.11 [28] and AS 1012.10 [29], respectively. Cylinders with 100 mm diameter and 200 mm height were cast for compressive strength following AS 1012.8.1 [23]. Seven cylinders were cast and cured for each batch; one cylinder was used for the 7 days testing and three of each cylinders were used for the 28 and 56-days testing. All cylinders were cured in water until testing commenced. A total of seven beams, 100 mm × 100 mm × 360 mm were cast to test flexural strength for 28 days of curing. Cylinders of 150 mm diameter and 300 mm height were cast for tensile strength and cured until 28 days.

RCPT was conducted to assess concrete durability, according to ASTM C 1202 [30]. A concrete specimen of 100 mm in diameter and 50 mm thickness which was cut from 200 mm cylinder using a water-cooled diamond saw. The circumference surface of the specimen was coated with epoxy for vacuum saturation conditioning. A 60 V direct current was applied between two liquid cells for 6 h duration. One of the cells was filled with a 0.3 N sodium hydroxide solution, and the other cell was filled with 3% sodium chloride solution. The total current passing through the specimen was recorded in every 30 min and calculated by integrating the current with time equation as per standard. The specimen was categorised based on the amount of total charge passed using ASTM C 1202 [30]. The higher the penetrability shown by RCPT test shows lower resistance to chloride penetration into concrete and hence the lower durability. Reversely, very low permeability shows higher resistance to chloride ion penetration.

Accelerated mortar bar test was conducted on mortar with and without RGS to determine the potential deleterious alkali silica reaction as per Australian Standard AS 1141.60.1 [31]. Two gang prism moulds of size 25 mm × 25 mm × 285 mm with a gauge length of 250 mm were used in this experiment. A gauge stud

Table 2
Materials content for 1 m^3 of concrete mixture.

Material	Cement (kg)	Fine Aggregate (kg)		Recycled Glass Sand (kg)	Coarse Aggregate (kg)	Water (L)	Plasticizer(mL)
		Fine Sand	Coarse Sand		20 mm		
Control	336	270	632	–	981	180	60
20 RGS	336	270	505.6	126.4	981	180	60
40 RGS	336	270	379.2	252.8	981	180	60
60 RGS	336	270	252.8	379.2	981	180	60

Table 3
Mix design of mortar mixes for three ASR prism bars [31].

Material	Cement (g)	Sand (g)	Recycled Glass Sand (g)	Water (mL)
Control	440	990	–	206.8
20 RGS	440	792	198	206.8
40 RGS	440	594	396	206.8
60 RGS	440	396	594	206.8

Table 4
Grading requirements of glass sand as manufactured fine aggregate.

Sieve Size, mm		% by mass	20 RGS (g)	40 RGS (g)	60 RGS (g)
Passing	Retained on				
4.75	2.36	10	19.8	39.6	59.4
2.36	1.18	25	49.5	99	148.5
1.18	0.600	25	49.5	99	148.5
0.600	0.300	25	49.5	99	148.5
0.300	0.150	15	29.7	59.4	89.1

Table 5
Test program with relevant standards.

Tests	Standard	Curing (days)
Particle size distribution	AS 1141.11.1	–
Detection of Sugar	AS 1141.35	–
Slump test	AS 1012.3.1	–
Density of concrete	AS 1012.12.1	7, 28, 56
Compressive strength	AS 1012.8.1	7, 28, 56
Flexural strength	AS 1012.11	28
Tensile strength	AS 1012.10	28
Rapid chloride penetration test (RCPT)	ASTM C1202	28, 56
Alkali-Silica Reaction (ASR)	AS 1141.60.1	1, 3, 7, 10, 14, 21

was attached to each end of the mould to obtain precise comparator readings. Three mortar bars were prepared for each mix according to the proportion specified in AS 1141.60.1 (Table 3). In this test, the grading requirements of manufactured fine aggregate was followed for RGS as tabulated in Table 4.

Comparator readings were recorded at 1, 3, 7, 10, 14 and 21 days and the expansion was calculated according to the standard. The reactivity of aggregate was classified based on ASR expansion value. All the test program with relevant standard are tabulate in Table 5.

3. Results and discussion

3.1. Characterization of crushed glass sand as aggregate

3.1.1. Particle size distribution

Fig. 3 shows the particle size distribution of natural coarse sand and RGS; determined by sieve analysis according to AS 1141.11.1 [32] with grading limits. Coarse sand and RGS were well graded; however, RGS showed slightly coarser distribution compared to natural coarse sand as well as grading limits. Coarse sand presented homogeneous distribution whereas, RGS had particles with a specific size of range predominating. The portion of finer particles in RGS was lower than coarse sand, with the maximum percentage of 44% retained on 1.18 mm sieve following 30% retained on 0.600 mm. RGS showed the coarser distribution in the middle of sieves (0.300–1.18 mm) compared to the lower limit which is negligible to be taken into account as fine aggregate in concrete. Angular nature of RGS can provide better bonding with the cement paste in the concrete [33].

3.1.2. Detection of sugar

100 g RGS was placed in a 250 mL beaker and covered with water. Then, 50 mL of 1 N hydrochloric acid was added to the mixture. The mixture was boiled for 5 min and filtered immediately while still hot (Fig. 4b). As the filtrate was found to be acidic to litmus paper, 5 mL of filtrate was cooled and neutralized with 1 N sodium hydroxide solution. The precipitate was removed by filtration. Finally, 3 mL of Fehling's solution (described in experimental methods) was added into the mixture and heated in a boiling water bath for 5 min. Glass sand did not show reddish brown precipitate after the addition of Fehling's solution which indicated the absence of sugar (Fig. 4c). It was inferred from the test that RGS used in this research was free from contamination and therefore, suitable to replace sand in concrete. Glass bottles used in this study were mainly for food and beverages, however, the sugar detection test showed no sign of sugar in the mixed coloured glass. The possible reason for the absence of sugar can be that the crushed glass was stored outside at the MRF site in Cairns and the rain over time may have washed sugar content away from the stockpile. This shows that simple washing of crushed glass can effectively remove any sugar content from the glass.

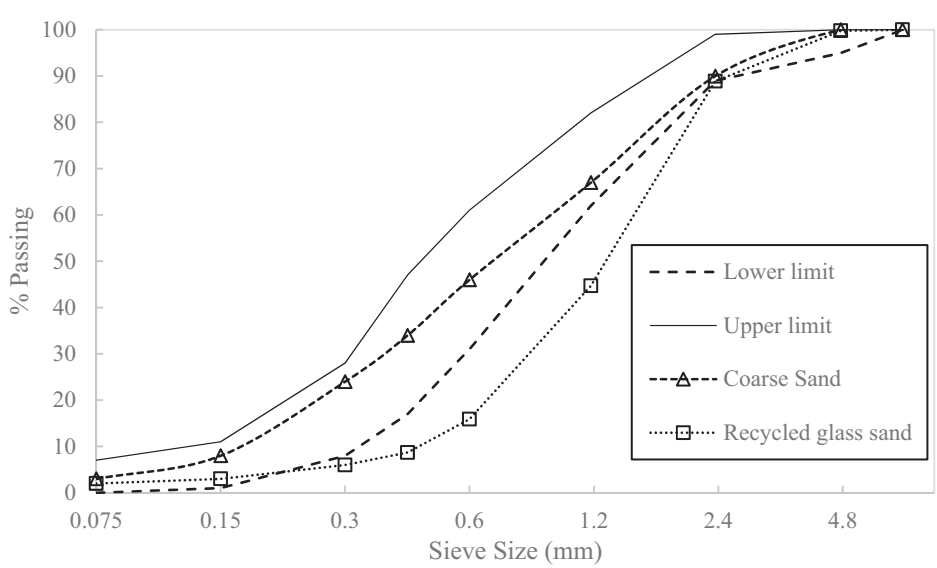

Fig. 3. Particle size distribution curves of natural coarse sand and crushed glass sand.

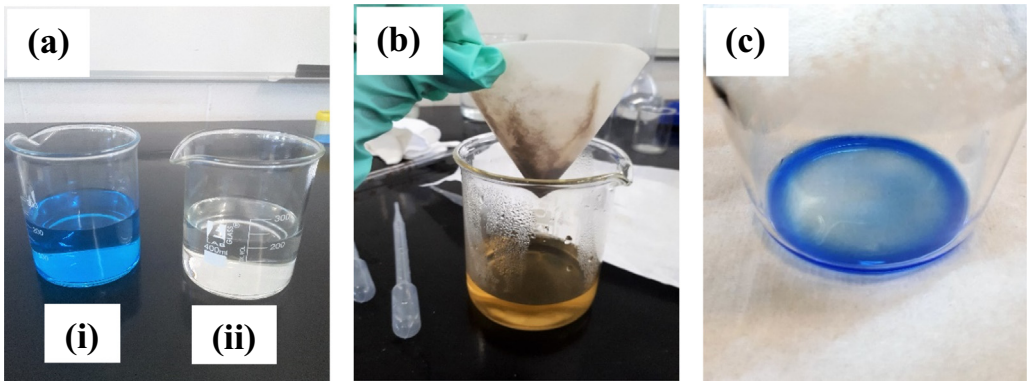

Fig. 4. Procedures to determine the presence or absence of sugar in aggregate.

Table 6
Slump and density of control concrete, concrete with RGS.

Sample Name	Slump (mm)	Fresh Density (kg/m^3)	Hardened density (kg/m^3)		
			7 days	28 Days	56 Days
Control	90	2394	2406	2399	2396
20 RGS	60	2377	2387	2372	2378
40 RGS	65	2365	2361	2369	2382
60 RGS	40	2350	2358	2356	2361

3.2. Fresh properties of concrete

3.2.1. Slump test

The slump test was carried out to assess the workability of concrete with RGS and without RGS (Table 6). Control concrete showed 90 mm slump, which was in the range of targeted slump of 80–100 mm. However, the workability decreased significantly with an increase in the quantity of RGS. This decreasing trend was in agreement with the study by Adaway and Wang [18]. The 20 RGS and 40 RGS exhibited similar slump values, nearly 69% and 71% of control concrete, respectively. The 60 RGS showed even lesser slump compared to any other mixtures, only 46% slump value of control concrete. Shape of the glass sand particles, for instance, sharp edges, and rough texture resulted in lower fluidity of mixture and hence the decrease in slump was observed. Similar decrease pattern was observed by Tan and Du [34] on the flowability of mortar.

3.2.2. Density of concrete

Table 6 shows the fresh and hardened density of concrete containing RGS as a fine aggregate replacement. Control concrete exhibited a fresh density of 2394 kg/m^3 whereas 20 RGS and 40 RGS concrete had a fresh density of 2377 kg/m^3 and 2365 kg/m^3. Density of RGS concrete was very similar to that of control concrete. The slightly reduced value of density in RGS concrete can be due to the lower specific gravity of RGS compared to sand used in the study. RGS had a specific gravity of 2.42 while sand exhibited 2.62. The dry density of concrete was measured at 7, 28 and 56 days. Control concrete showed a hardened density of 2406 kg/m^3, 2399 kg/m^3 and 2396 kg/m^3 at 7, 28 and 56 days respectively. As can be seen in Table 6, hardened density of RGS concrete was found very similar to that of control concrete.

3.3. Mechanical properties of concrete

3.3.1. Compressive strength of concrete

The compressive strength tests of RGS concrete with various ratios were carried out and made a comparison with concrete without glass sand (control concrete) as shown in Fig. 5. Control concrete and concrete with 20 RGS achieved design strength as early as in 7 days, which was mainly characterised for 28 days. The 20 RGS concrete gained a compressive strength of 34.2 MPa at 7 days, which was 5.8% higher than that of control. As the replacement level increased, the strength slightly decreased.

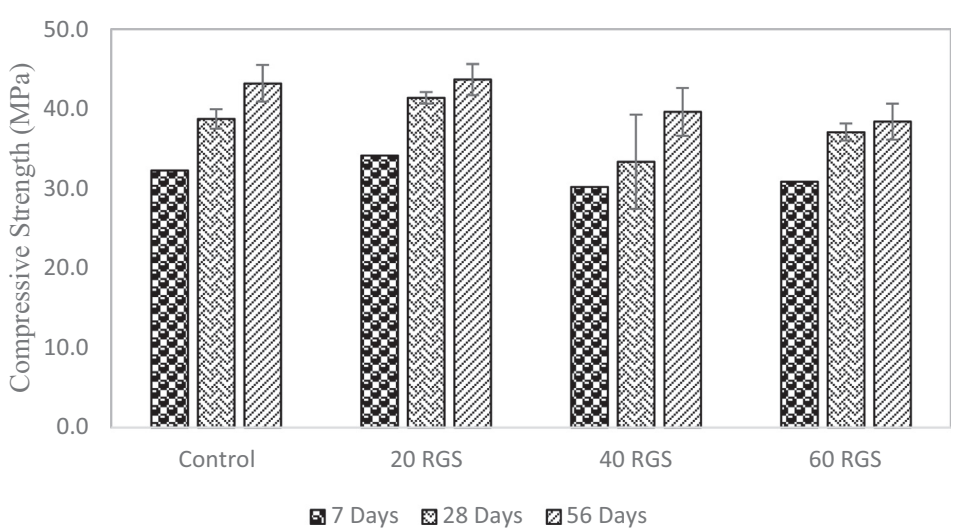

Fig. 5. Compressive strength development of concrete with RGS.

However, 60 RGS concrete achieved a slightly higher compressive strength (2.3%) than 40 RGS concrete at 7 days.

All concrete mixtures achieved the characteristic strength of 32 MPa at 28 days. The control concrete gained strength of about 38.75 MPa at 28 days. The concrete with 20 RGS obtained the highest strength (i.e., 41.40 MPa) which was 7% higher than the control concrete at 28 days. The other two fine aggregate replacement (i.e., 40 RGS and 60 RGS) performed favourably with the strength of 86% and 96% of the control concrete, respectively. The increase in strength for the fine aggregate replacement is attributed to the angular nature of the RGS than the naturally rounded sand particles, which has also been proved by other research [18]. Besides, strength development of concrete depends on the interlocking bond between cement matrix and glass sand, which is governed by the development of interfacial transition zone (ITZ).

The control concrete reached 43.22 MPa of strength, 34% improvement at 56 days. The 20 RGS concrete achieved the highest compressive strength at 56 days, albeit 1% compared to control concrete. It was evident that RGS quantity had a slightly negative impact on its strength as glass sand quantity increased. Increased glass sand quantity weakens the mechanical bond inside concrete microstructure, leading to a decrease in the strength of ITZ. The 40 RGS and 60 RGS concrete achieved strengths of 92% and 89%, respectively, compared to control concrete. However, strength development showed a slow increase in strength at 56 days compared to 28 days of strength. The 40 RGS mix increased the most with 31%, followed by 20 RGS with 28% and 60 RGS with 24%.

3.3.2. Flexural and tensile strength of concrete

Flexural strength and indirect tensile strength were conducted on control and RGS concrete at 28 days. There was no significant difference in both flexural and tensile strength for glass sand addition compared to the control concrete as shown in Fig. 6. Strength results tended to increase with an increase in glass sand quantity. The angular size of glass sand can attribute to a better interlocking between cement and glass sand. However, a decrease in strength was found for 40 RGS and 60 RGS for flexural and tensile strength, respectively. Reduction in tensile strength of concrete with higher percentage RGS replacement (60%) is in line with the reduction in compressive strength at 60% replacement level. Percentage of indirect tensile strength to compressive strength was in the range between 8 and 11%, as tabulated in Table 7.

Table 7
Percentage of indirect tensile strength to compressive strength at 28 days.

Sample Name	28 days (%)
Control concrete	8.85
20 RGS	8.36
40 RGS	10.54
60 RGS	8.33

3.4. Durability of concrete

3.4.1. Rapid chloride penetration test

Concrete durability depends on its resistance to the ingress of moisture and chloride ions into the concrete. In this research, RCPT was conducted on the concrete cylinder at 28 and 56 days to evaluate the resistance of concrete to chloride ion penetration. Fig. 7 depicts the average charge passing through the concrete containing river sand (control concrete) and RGS. Results show that control concrete appeared as the most vulnerable to ingress of chloride ion at both curing periods. Charge passed through the control concrete was 5234 C at 28 days, which is classified as high permeable concrete according to ASTM C 1202 [30]. As the curing period increases, the RCPT value was noticed to reduce. At 56 days, reduction in chloride ion penetration was seen to be 19% less compared to control concrete at 28 days, but it was still in the high permeable range.

Concrete with RGS showed improved resistance to chloride ion penetration. Similar improved resistance was also found in the study by Du and Tan [35]. RCPT value for 20 RGS was found 4285 Coulombs at 28 days, classified as high permeable concrete. The RCPT value was noticed to decrease at 56 days, and it exhibited moderately permeable concrete. 40 RGS exhibited the highest resistance among other replacements and presented 29% and 32% improvement in chloride resistance compared to control concrete at 28 and 56 days, respectively. This agrees with the increase in compressive strength of concrete with increase in RGS replacement levels up to 40%. During the concrete mixing, it was observed that uniform mixing of materials could be achieved for 20 RGS and 40 RGS. However, for the high replacement level of natural sand with glass sand (60 RGS), mixing and finishing of the concrete specimen was relatively difficult. It is observed that up to 40% replacement, the cohesion between the cement and glass sand

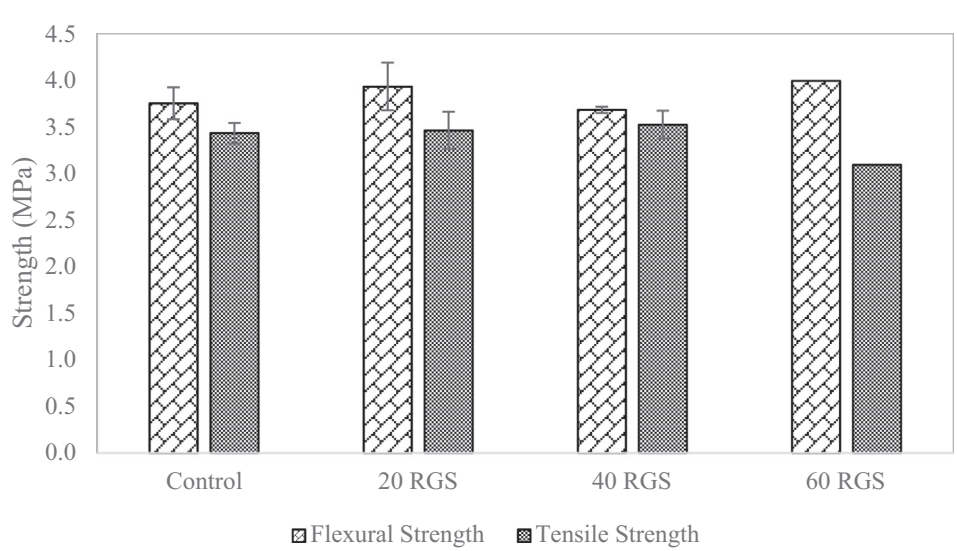

Fig. 6. Flexural and tensile strength of concrete with RGS.

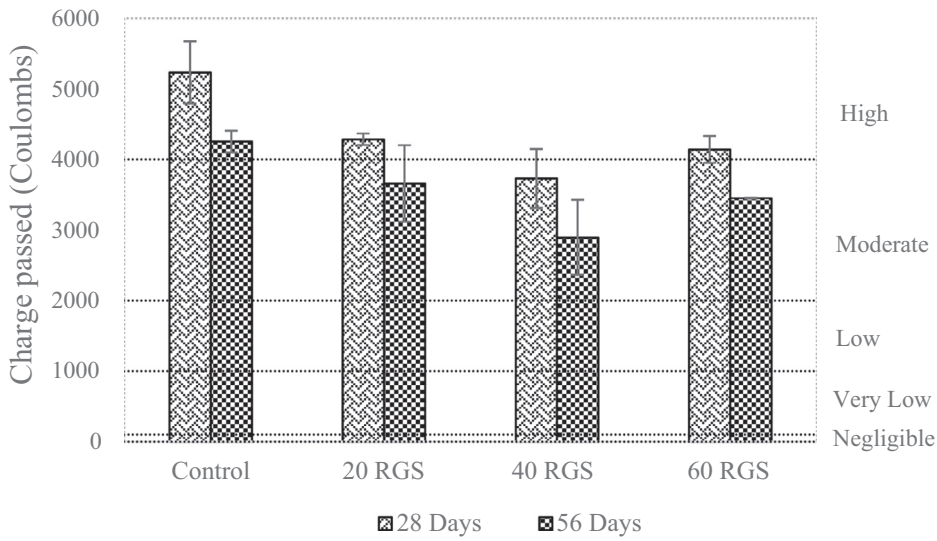

Fig. 7. RCPT results of concrete with river sand and RGS at 28 days and 56 days.

improve the microstructure of the ITZ, as also noted by Du and Tan [35]. However, at higher glass sand replacement (60 RGS) the concrete was observed to be more porous due to difficulty in mixing with high glass sand percentage. This has resulted in the increase in charge passing through the 60 RGS specimen in the RCPT test at 28 days, as well as 56 days, as shown in Fig. 7. However, 60 RGS showed 20% and 19% more resistant than that of control concrete at 28 and 56 days, respectively.

3.4.2. Alkali silica reaction test

The main concern of using RGS as a fine aggregate replacement in concrete is Alkali-Silica Reaction (ASR). The expansions of the mortar bar showed an increasing trend over time as can be seen in Fig. 8. However, all mortar bar specimens exhibited expansion less than 0.10% at 21 days which is classified as non-reactive, based on AS 1141.60.1. The highest expansion value of about 0.086% was observed for control mortar bars (with no RGS) at 21 days. It is noticeable that the ASR expansion of RGS mortar was less than that of control mortar bar. The expansion was found to be reduced with an increase in glass sand content from 20% to 60%. The least ASR expansion was noticed for 40 RGS, followed by 60 RGS at 21 days. Aggregates (both river sand and RGS) was within the non-reactive classification at 21 days, as specified in AS 1141.60.1. However, addition of RGS in mortar further reduced ASR expansion.

Experiments conducted by Rajabipour et al. [15] and Du and Tan [36] showed that alkali-silica reaction expansion that leads to ASR cracking is induced within the internal cracks of the large soda lime glass particles rather than at the glass cement paste interface. Alkali ions can penetrate through the internal cracks in large aggregates that are produced during the crushing process and form ASR gel. However, no cracks were detected on crushed glass sand surface used in this research because of smaller glass particles as shown in Fig. 9. Smaller glass particle (less than 4.5 mm) with no surface cracks does not have alkali ions from penetrating into the glass particles forming ASR gel. This resulted in no ASR expansion when smaller size glass particles were used to replace natural sand in concrete. Besides, finer size RGS reacts with portlandite ($Ca(OH)_2$) and forms secondary calcium silicate

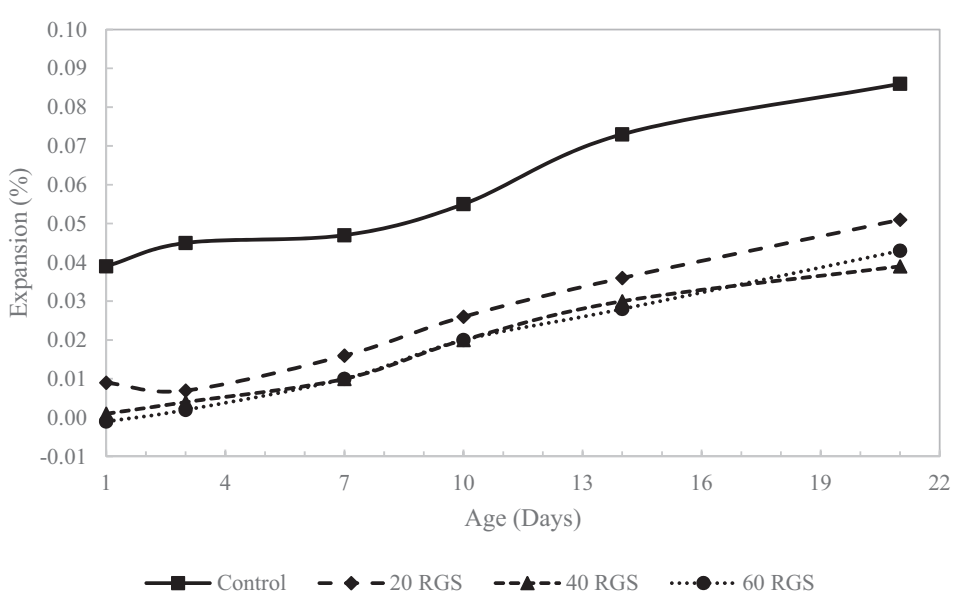

Fig. 8. ASR expansion of mortar with crushed glass.

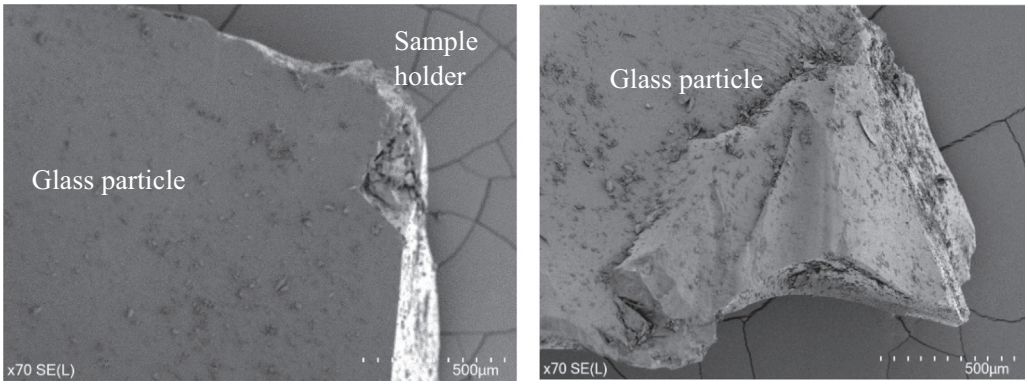

Fig. 9. SEM of crushed glass sand particle.

hydrate (C-S-H) with a low Ca/Si ratio. Hou et al. [37] explained that pozzolanic C-S-H is formed in the microstructure as long as $Ca(OH)_2$ is present to react with dissolved silica and hinder the formation of expansive ASR gels.

4. Conclusion

A series of experiments were conducted to investigate the influence of RGS concerning strength characteristics and durability properties. Addition of RGS had a significant impact on workability due to angular edges and rough texture of the glass sand. Although the fresh density was reduced successively with the increase in glass content, the improvement was noticed in the hardened density with curing time. Target compressive strength was being achieved by all concrete mixtures in 28 days and most significantly, in 7 days by control concrete and 20 RGS concrete. No adverse reduction in strength was noticed up to 60% replacement of natural sand with RGS. The RGS concrete showed satisfactory tensile and flexural strength result; the latter exhibited a similar propensity to compressive strength. RGS concrete showed enhanced resistance to chloride ion penetration up to 60% replacement and made concrete less permeable. The addition of recycled glass as coarse sand replacement was also proven not detrimental against alkali-silica reaction. Furthermore, use of RGS to replace natural sand reduces the alkali-silica reaction due to the pozzolanic reaction between finer glass particles and alkali from cement hydration. The results show that recycled crushed glass can be used to replace up to 60% sand in concrete. However, with an increase in replacement rate, workability of concrete can reduce, and measures need to be taken to improve the workability of concrete by the addition of suitable admixture. The successful application of using RGS in concrete can reduce sand dredging, along with the reduction of glass waste going into landfill sites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to acknowledge Cairns Regional Council and Pioneer North Queensland Pty Ltd for providing recycled glass sand and other materials for the research. We would like to thank Joshua Flanders, Dustin Peacocke, Joshua Lancini and Brendan Hall for their supports during experiments.

References

[1] N. Tamanna, R. Tuladhar, N. Avosa, S. Sivakugan, The effect of using waste glass powder as cement replacement in concrete, 28th Biennial Conference of the Concrete Institute of Australia, Adelaide, SA, Australia (2017).
[2] A. Torres, J. Brandt, K. Lear, J. Liu, A looming tragedy of the sand commons, Science 357 (6355) (2017) 970–971, https://doi.org/10.1126/science.aao0503.
[3] J.W. Isler, Assessment of Concrete Masonry Units Containing Aggregate Replacements of Waste Glass and Rubber Tire Particles, Master of Science in Civil Engineering Thesis, University of Colorado Denver, 2012.
[4] A. Arulrajah, T.A. Kua, S. Horpibulsuk, M. Mirzababaei, A. Chinkulkijniwat, Recycled glass as a supplementary filler material in spent coffee grounds geopolymers, Constr. Build. Mater. 151 (2017) 18–27, https://doi.org/10.1016/j.conbuildmat.2017.06.050.
[5] Y. Sharifi, M. Houshiar, B. Aghebati, Recycled glass replacement as fine aggregate in self-compacting concrete, Front. Struct. Civil Eng. 7 (4) (2013) 419–428, https://doi.org/10.1007/s11709-013-0224-8.
[6] Z.Z. Ismail, E.A. Al-Hashmi, Recycling of waste glass as a partial replacement for fine aggregate in concrete, Waste Manage. 29 (2) (2009) 655–659, https://doi.org/10.1016/j.wasman.2008.08.012.
[7] H. Du, K.H. Tan, Use of waste glass as sand in mortar: Part II – Alkali-silica reaction and mitigation methods, Cem. Concr. Compos. 35 (1) (2013) 109–117, https://doi.org/10.1016/j.cemconcomp.2012.08.029.
[8] S. de Castro, J. de Brito, Evaluation of the durability of concrete made with crushed glass aggregates, J. Clean. Product. 41 (2013) 7–14, https://doi.org/10.1016/j.jclepro.2012.09.021.
[9] H. Zhao, C.S. Poon, T.C. Ling, Utilizing recycled cathode ray tube funnel glass sand as river sand replacement in the high-density concrete, J. Clean. Product. 51 (2013) 184–190, https://doi.org/10.1016/j.jclepro.2013.01.025.
[10] L.A. Pereira-de-Oliveira, J.P. Castro-Gomes, P. Santos, Mechanical and durability properties of concrete with ground waste glass sand, 11 DBMC International Conference on Durability of Building Materials and Components, Istanbul, Turkey (2008).
[11] M.C. Limbachiya, Bulk engineering and durability properties of washed glass sand concrete, Constr. Build. Mater. 23 (2) (2009) 1078–1083, https://doi.org/10.1016/j.conbuildmat.2008.05.022.
[12] M.J. Terro, Properties of concrete made with recycled crushed glass at elevated temperatures, Build. Environ. 41 (5) (2006) 633–639, https://doi.org/10.1016/j.buildenv.2005.02.018.
[13] E.E. Ali, S.H. Al-Tersawy, Recycled glass as a partial replacement for fine aggregate in self compacting concrete, Constr. Build. Mater. 35 (2012) 785–791, https://doi.org/10.1016/j.conbuildmat.2012.04.117.
[14] M.I. Malik, M. Bashir, S. Ahmad, T. Tariq, U. Chowdhary, Study of concrete involving use of waste glass as partial replacement of fine aggregates, IOSR J. Eng. (IOSRJEN) 3 (7) (2013) 08–13.
[15] F. Rajabipour, H. Maraghechi, G. Fischer, Investigating the alkali-silica reaction of recycled glass aggregates in concrete materials, J. Mater. Civ. Eng. 22 (12) (2010) 1201–1208, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000126.
[16] A. Rahma, N.E. Naber, S.I. Ismail, Effect of glass powder on the compression strength and the workability of concrete, Cogent Eng. 4 (1) (2017).
[17] A. Mohajerani, J. Vajna, T.H.H. Cheung, H. Kurmus, A. Arulrajah, S. Horpibulsuk, Practical recycling applications of crushed waste glass in construction materials: a review, Constr. Build. Mater. 156 (2017) 443–467, https://doi.org/10.1016/j.conbuildmat.2017.09.005.
[18] M. Adaway, Y. Wang, Recycled glass as a partial replacement for fine aggregate in structural concrete -Effects on compressive strength, Electron. J. Struct. Eng. 14 (1) (2015) 116–122.
[19] X. Yu, T.Y. Song, Z. Pan, Performance of concrete made with steel slag and waste glass, Constr. Build. Mater. 114 (2016) 737–746, https://doi.org/10.1016/j.conbuildmat.2016.03.217.
[20] A. Mohammadina, Y.C. Wong, A. Arulrajah, S. Horpibulsuk, Strength evaluation of utilizing recycled plastic waste and recycled crushed glass in concrete footpaths, Constr. Build. Mater. 197 (2019) 489–496, https://doi.org/10.1016/j.conbuildmat.2018.11.192.

[21] AS2758.1, Aggregates and Rock for Engineering Purposes, in Australian Standards AS 2758.1. (2014)
[22] AS1012.2, Methods of Testing Concrete, Methods 2: Preparing Concrete Mixes in the Laboratory, in Australian Standards AS 1012.2. (2014).
[23] 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).
[24] AS1141.35, Methods for Sampling and Testing Aggregates, Methods 35: Sugar, in Australian Standards AS 1141.35. (2007).
[25] AS1012.3.1, Methods of Testing Concrete, Methods 3.2: Determination of Properties Related to the Consistency of Concrete- Slump Test, in Australian Standards AS 1012.3.1. (2014).
[26] 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)
[27] 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).
[28] AS1012.11, Methods of Testing Concrete, Method 11: Determination of The Modulus of Rupture, in Australian Standards AS 1012.11. (2014).
[29] AS1012.10, Methods of Testing Concrete, Method 10 Determination of Indirect Tensile Strength of Concrete Cylinders ('Brazil' or Splitting Test), in Australian Standards AS 1012.10. (2000).
[30] ASTMC1202, 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).
[31] AS1141.60.1, Methods for Sampling and Testing Aggregates, Method 60.1: Potential Alkali-Silica Reactivity- Accelerated Mortar Bar Method, in Australian Standards AS 1141.60.1. (2014).
[32] AS1141.11.1, Methods for Sampling and Testing Aggregates, Method 11.1: Particle Size Distribution- Sieving Method, in Australian Standards AS 1141.11.1. (2009).
[33] J. An, S.S. Kim, B.H. Nam, S.A. Durham, Effect of aggregate mineralogy and concrete microstructure on thermal expansion and strength properties of concrete, Appl. Sci. (Switzerland) 7 (12) (2017) 1307, https://doi.org/10.3390/app7121307.
[34] K.H. Tan, H. Du, Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties, Cem. Concr. Compos. 35 (1) (2013) 109–117, https://doi.org/10.1016/j.cemconcomp.2012.08.028.
[35] H. Du, K.H. Tan, Concrete with recycled glass as fine aggregates, ACI Mater. J. 111 (1) (2014) 47–57.
[36] H. Du, K.H. Tan, Effect of particle size on alkali–silica reaction in recycled glass mortars, Constr. Build. Mater. 66 (2014) 275–285, https://doi.org/10.1016/j.conbuildmat.2014.05.092.
[37] X. Hou, L.J. Struble, R.J. Kirkpatrick, Formation of ASR gel and the roles of C-S-H and portlandite, Cem. Concr. Res. 34 (9) (2004) 1683–1696, https://doi.org/10.1016/j.cemconres.2004.03.026.