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Effect of waste glass as powder and aggregate on strength and shrinkage of fiber reinforced foam concrete

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Abstract. Foam concrete can be considered as environmental friendly material due to its low weight, its minimal cost and a possibility to add waste materials in its production. This paper investigates the possibility of producing foam concrete with waste glass as powder and aggregate. Then, the effect of using waste glass on strength and drying shrinkage of foam concrete was examined. Also, the effect of incorporating polypropylene fibers (12 mm length and proportion of 0.5% of a mix volume) on distribution of waste glass as coarse particles within 1200 kg/m^3 foam concrete mixes was evaluated. Waste glass was used as powder (20% of cement weight), as coarse particles (25%, 50% and 100% instead of sand volume) and as fine particles (25% instead of sand volume). From the results, the problem of non-uniform distribution of coarse glass particles was successfully solved by adding polypropylene fibers. It was found that using of waste glass as coarse aggregate led to reduce the strength of foam concrete mixes. However, using it with polypropylene fibers in combination helped in increasing the strength by about 29- 50% for compressive and 55- 71% for splitting tensile and reducing the drying shrinkage by about (31- 40%). In general, not only the fibers role but also the uniformly distributed coarse glass particles helped in improving and enhancing the strength and shrinkage of the investigated foam concrete mixes.

Keywords: fibers; foam concrete; particles distribution; recycled waste glass; shrinkage; strength

1. Introduction

Lightweight concrete (LWC) becomes more popular construction material due to its characteristics such as durability, good strength, self-weight, good compressive strength, thermal and sound insulation (ACI 523.3R 1993). Using of lightweight concrete in construction building not only reduces the cost and weight but also achieves sustainability (Lo *et al.* 2007). LWC can be produced by replacing finer sizes of aggregate with hollow, cellular and porous aggregates or by incorporating air into the mortar (Hilal 2021).

ACI 523.3R (1993) reported that to produce lightweight concrete, the solid materials should be replaced with air voids to achieve a lower density material which can be used for structural load-bearing and thermal insulation. In general, lightweight concrete can be produced by using lightweight aggregate (lightweight aggregate concrete), omitting fine aggregate from the mix (no-

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fines concrete) and adding foam or generating gas bubbles (aerated concrete). Foam concrete is a lightweight concrete which can be produced (with densities ranging from 400 to 900 kg/m^3) by entraining large volumes of air bubbles (with voids size ranging from 0.1 to 1 mm) into the cement paste by using a chemical foaming agent (Kearsley and Wainwright 2001, Hilal *et al.* 2014).

Foam concrete uses in several applications such as void filling, roof insulation, floor construction and highway works due to its free flowing, self-compaction, low strength and good insulation.

In addition, foam concrete is considered as environmental friendly material due to minimal cost and a potential to add waste materials in its production (Ramamurthy *et al.* 2009, Mhedi *et al.* 2018). However, natural or waste materials as coarse particles have not yet used in production of foam concrete due to their heavy weight which making them settle down (segregation) during a mixing process.

Glass is gradually increased over the recent years due to the increase in consumption and the rapid improvement in the standard of living (Corinaldesi *et al.* 2005, Gorospe *et al.* 2019). It is as material occupied large parts of landfills spaces and causing series environmental problems (air, water and soil pollution). Waste glass is a non-biodegradable material making it environmentally less friendly. To overcome over this problems, reusing of waste glass represents the best solution. Use of recycled waste glass in the production of concrete provides significant environmental benefits due to conserving the natural resources, saving energy and money, reducing in landfills spaces and reducing the emission of CO_2 and other greenhouse gases (Sharifi *et al.* 2016, Harrison *et al.* 2020).

Khan *et al.* (2019) studied the potential of using waste glass powder as partial replacement of cement in foam concrete. The effect of waste glass powder, water to cement ratio, cement content and foam volume on dry density, plastic density and compressive strength of foam concrete were investigated. It was found that the compressive strength increased with increasing the plastic density and dry density of foam concrete. It was noticed that the trail mix with 20% recycled glass powder as 10% filler and 10% Pozzolanic materials achieved the highest compressive strength and the lowest plastic and dry density compared with the other investigated mixes of foam concrete. Therefore, this percentage will be adopted as a replacement for cement in this research. Later, Khan *et al.* (2022) investigated the potential of using waste glass as powder (RWGP) in producing foam concrete non-load bearing wall panels for acoustic barriers application. Then, the axial and flexural behavior of constructed lightweight wall panels made of foam concrete with RWGP was investigated. It was found that the wall panels tested under axial compression or under four-point bending load exhibited no surface cracking up to 85% or 50% of the peak axial or flexural load, respectively.

Foam concrete is characterized as a lightweight material since there is no coarse aggregate in its constituents. According to the best knowledge of the researchers, until now there is no study investigated adding recycled waste glass as coarse aggregate in foam concrete. Therefore, the challenge of this study is how to add the waste glass particles as coarse aggregate to the foam concrete mixture with achieving a uniform distribution of them within the mixture i.e., without a segregation problem. The aim of this study is to investigate the potential of using recycled glass as coarse or fine aggregate in production of foam concrete by examining its particles distribution within the mix. Also, to investigate the effect of waste glass addition as powder (instead of cement weight) or aggregate (instead of sand volume) on some properties of foam concrete.

Fig. 1 Foam generator used in this study

2. Experimental details

2.1 Materials used

Ordinary Portland cement (Type I) was used in this study which conforms to ASTM C150/C150M (2015). Natural sand with a maximum size of 2.36 mm was used which conforms to ASTM C144 (2002).

For mixing process, tap water was used. A protein foaming agent was used in this study. It is diluted with water (1 g of foaming agent per 40 g of water) and compressed in foam generator to produce 1 liter of foam with density of 30 kg/m^3 (ASTM C796/C796M, 2012), see Fig. 1. Natural coarse aggregate with a maximum size of 10 mm was used in this study as substituting of sand with percentage of 25% to compare the effect of it with coarse glass particles in foam concrete mixes.

In terms of waste glass powder, it was used as a partial replacement of cement with percentage of 20% by weight. The chemical composition of waste glass powder was determined using the X-ray fluorescence technique as SiO_2 (78.70), CaO (11.18%), Al_2O_3 (4.65%), Fe_2O_3 (3.23%), SO_3 (0.07%), K_2O (1.99%), TiO_2 (0.09%), ZrO_2 (0.01%), and MnO (0.02%). In terms of its grain sizes, about 50% of them were smaller than the 45 μm. Khan *et al.* (2019) noted that RWGP grain sizes smaller than 45 μm would serve as pozzolanic material and grain sizes larger than 45 μm would serve as filler material in concrete mixes. Then, fine glass with a maximum size of 2.36 mm was used as a replacement of sand volume with percentage of 25%. In addition, coarse waste glass was used as a replacement of sand volume. The percentages of 25, 50, and 100% of sand volume were used with particles size ranging between 4.75 mm and 9.5 mm. The specific gravity of waste glass is 2.4. As trial to solve the segregation problem of coarse glass particles, polypropylene fibers, PPF (mono-filament type) from Sika Company with 12 mm length were used at proportion of 0.5% of the mix volume and density of 910 kg/m^3.

2.2 Mix design

In this paper, all investigated foam concrete mixes were designed at density of 1200 kg/m^3. Cement content was 400 kg/m^3 and water to cement ratio (w/c) was found by trials as 0.49. Foam

Table 1 Constituent proportions of investigated foam concrete mixes with RWG

Materials	FC	FCGP	FCGF	FCGC	GC50%	GC100%	FCGCF
Cement (kg/m^3)	400	320	400	400	400	400	400
Sand (kg/m^3)	604	604	453	453	302	0	302
W/C	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Foam (liter/m^3)	450	450	450	450	450	450	450
Glass powder (kg/m^3)	-	80	-	-	-	-	-
Fine glass (kg/m^3)	-	-	137	-	-	-	137
Coarse glass (kg/m^3)	-	-	-	137	274	547	137

volume was determined from the mix design (absolute volumes method) to produce a stable foam concrete mix (fresh density to target density ratio close to unity) (Hilal *et al.* 2015). To investigate the effect of using recycled waste glass (RWG) on the properties of foam concrete, it was used with different percentages as partial replacements of cement and sand. 20% of cement was replaced (by weight) with glass powder to produce (FCGP) mix. 25% as volume of fine aggregate was replaced with waste glass particles with sizes less than 2.36 mm to produce (FCGF) mix. Also, coarse glass was added instead of 25%, 50% and 100% of fine aggregate volume to produce FCGC, GC50% and GC100% mixes, respectively. Lastly, fine aggregate was replaced by 25% of fine glass and 25% of coarse glass in combination to produce (FCGCF) mix. In addition, another set of experiments was designed with the same constituent proportions of the mixes shown in Table 1, but with adding polypropylene fibers (PPF) with 12 mm length and an addition of 0.5% of the total mix volume to produce mixes as FC-P, FCGP-P, FCGF-P, FCGC-P, GC50%-P, GC100%-P and FCGCF-P.

2.3 Production

In this paper, dry constituents were added and mixed in a rotary mixer with a volume of 0.1 m^3 for a few minutes. Then, mixing water was added to the dry materials in stages until achieving a homogenous mix. After thorough mixing, pre-formed foam was prepared by using a foam generator and added into the mix. After that, a produced mixture was placed into molds with two approximately equal layers, and a rubber-headed hammer was used to tap the sides of molds. After finishing filling process, a trowel was used to level the surfaces of the specimens. All specimens were removed from the molds after 24 hours and wrapped in cling film to prevent evaporation and left in room temperature to cure until the tests age (Hilal *et al.* 2015). Fig. 2 shows a flowchart of foam concrete production process.

3. Tests

3.1 Consistency

Consistency of foam concrete was determined by measuring a spreadability of its mixture. After filling a cylinder with open-ended (75 mm diameter and 150 mm length), it was raised vertically. The average of two diameters was taken for unfoamed concrete (before adding foam) and foam concrete (after adding foam) (Mhedi *et al.* 2018).

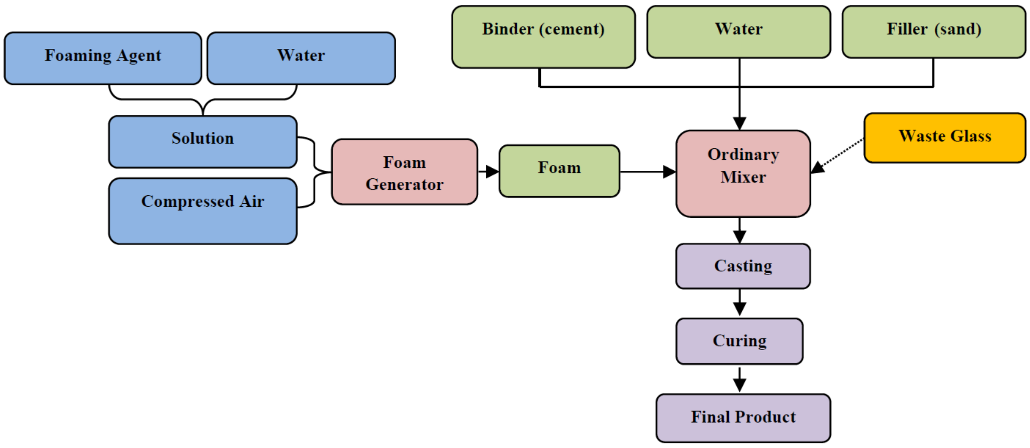


Fig. 2 Flowchart of foam concrete production process

(a) Slices after cutting (b) Slice after polishing

Fig. 3 Sample preparation for WG particles distribution

3.2 Waste glass particles distribution

To investigate the distribution of waste glass (WG) particles within mixes of foam concrete, 100×100×100 mm cube was cut to six slices parallel to the cast face by using a diamond cutter. Then, a rotating grinder was used to polish the surface of slices which were cleaned after completion this polishing process using a soft brush. The surface of each slice was treated with fine white powder to fill the pores so the glass particles in the surface of slice will be well recognized (Hilal *et al.* 2015). In each slice, all glass particles were colored by using a black paint. Image J software was applied to analyzes the captured images of treated slices and then find the proportion of WG particles in each slice (Mhedi *et al.* 2018). This investigation was adopted to check the potential of a uniform distribution of coarse WG particles within the specimen, see Fig. 3.

3.3 Compressive strength

This test was carried out on 100 mm^3 cubes at ages of 7 and 28 days in accordance with ASTM

Fig. 4 Drying shrinkage specimens in a humidity chamber

C513/C513M (2011). A digital compression testing machine with a capacity of 2000 kN and loading rate of 0.3 MPa/s was used. Three specimens were tested at each age and the average of them was taken.

3.4 Splitting tensile strength

Cylindrical foam concrete specimens with size of (100×200 mm) and density of 1200 kg/m^3 were tested at ages of 7 and 28 days according to ASTM C496/C496M (2011). The average of three readings was taken at each age.

3.5 Drying shrinkage

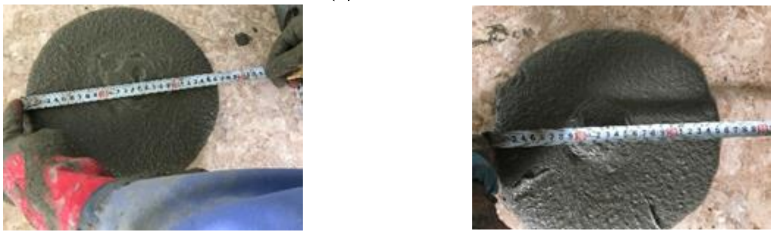
As stated by Nambiar and Ramamurthy (2002), shrinkage behavior of foam concrete can be assessed according to the recommended practice of RILEM-ACC 5.2 (1992). The test was carried out on prisms with size of (40×40×160 mm). After 48 hours from casting, the specimens attached in a holder frame were placed in humidity chamber at temperature of 23±1.7℃ and relative humidity of 50±4%. Top end of each specimen was attached to spherical dial gauge with accuracy of 0.002 mm to take length change measurements, see Fig. 4. For each mix, two specimens were tested for drying shrinkage and the average of their readings was taken. Length change of specimen was measured every two days during a period of 35 days (Obaid and Hilal 2021).

4. Results

4.1 Consistency

Consistency of all investigated foam concrete mixes was evaluated by measuring a spread diameter. It was found that at lower densities, high foam volume, the spread diameter reduced. Nambiar and Ramamurthy (2008) stated that, for a given density, the spread diameter reduced with increasing added foam volume to the base mixture (unfoamed mixture). This may be due to the adhesion between the bubbles and the solid particles in the base mix. For a given density 1200 kg/m^3, it was noticed that the spread diameter before adding foam (unfoamed mixture) was about

(a) FC mix



(b) FCGF mix

(C) FCGC mix

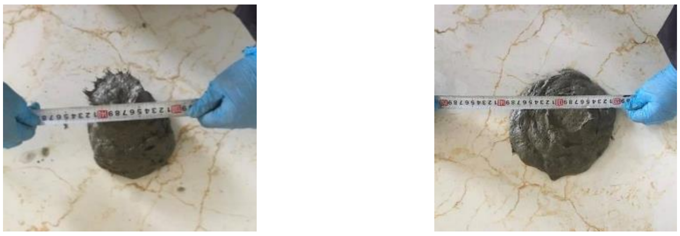
(a) before adding foam (b) after adding foam

Fig. 5 Spread diameter of some investigated mixes

Table 2 Spread diameter values of foam concrete mixes with RWG and FFP

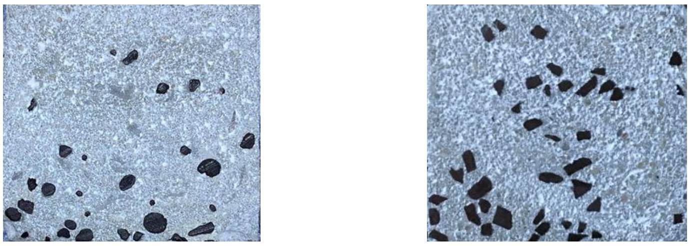
Mix type	With waste glass					With waste glass and polypropylene fibers				
	FC	FCGP	FCGF	FCGC	FCGCF	FCP	FCGPP	FCGFP	FCGCP	FCGCFP
Spread diameter (before adding foam), mm	220	270	260	270	255	200	180	190	190	190
Spread diameter (after adding foam), mm	200	260	250	255	240	180	170	180	175	170

220 mm, while it reduced to 200 mm after adding foam (FC mix). Also, it was found that adding of waste glass as powder in foam concrete mix resulted in increasing the spread diameter compared with conventional foam concrete (FC) mix i.e., enhancing the consistency of foam concrete. This is due to the less water absorption of waste glass particles compared to that of raw materials (cement and sand) noted that the water content was constant. Spread diameter for FCGP mix (with waste glass as powder) increased by about 50 mm compared with conventional foam concrete mix (FC). This increasing may be due to reducing the amount of cement content which led to reduce the demanded of water required for mixing. In addition, FCGC mix (with coarse glass particles) achieved a higher spread diameter value (270 mm) compared to that of the other



(a) before adding foam (b) after adding foam

Fig. 6 Spread diameter for FCGC-P mix with coarse glass particles and polypropylene fibers



(a) with 25% natural coarse (b) with 25% coarse waste glass

Fig. 7 Distribution of aggregate particles in foam concrete

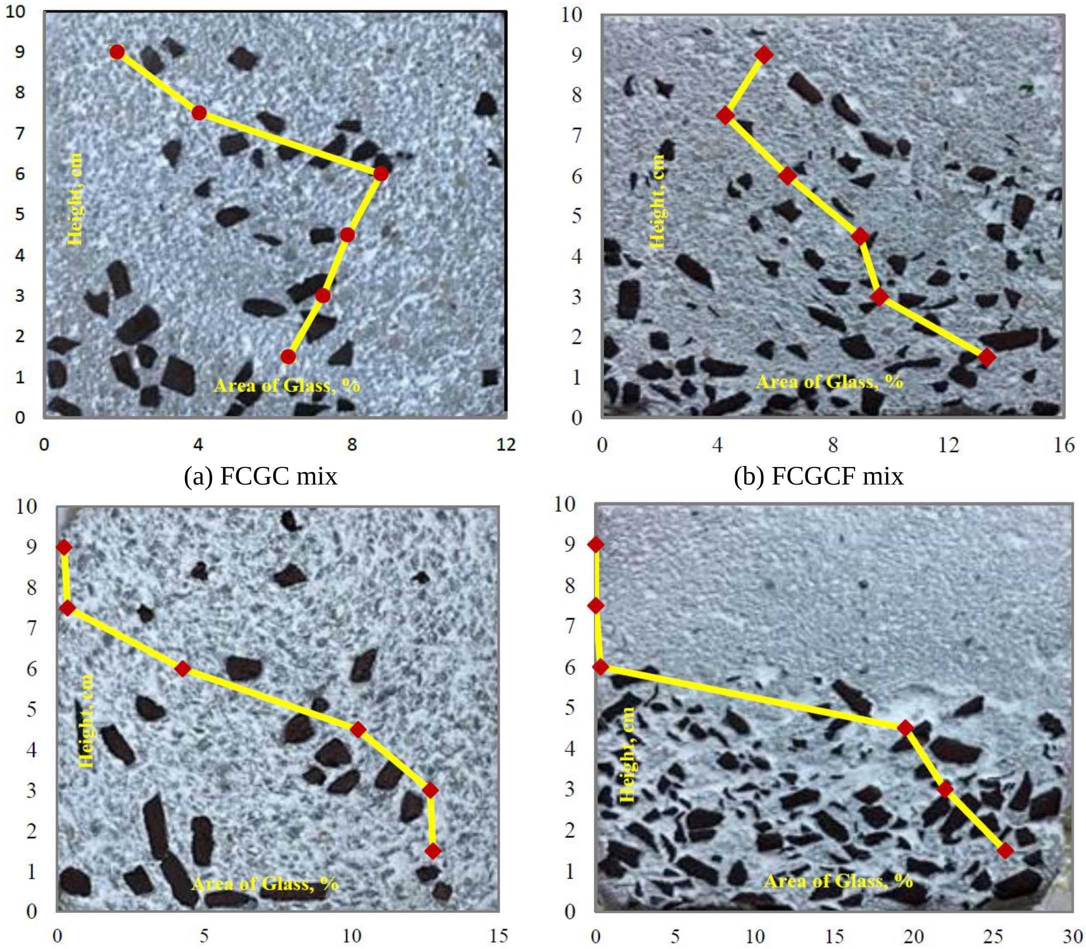
mixes. This may be due to the smooth surface of coarse glass, which leads to reduce the inter-particles friction, see Fig. 5. The spread diameter values of investigated foam concrete mixes with recycled waste glass were listed in Table 2.

In terms of adding polypropylene fibers (PPF), it was observed that the spread diameter values reduced by about 20 mm to 70 mm compared to mixes without fibers as shown in Table 2. This may be due to the cohesion and bond that were provided in the concrete mixture by fibers, see Fig. 6.

4.2 Investigation of waste glass particles distribution

To determine and compare the distribution of normal coarse aggregate and coarse glass particles in foam concrete mixes, particles distribution was investigated by analyzing images of treated slices captured by a high resolution camera. An ImageJ software was used to analyze the proportion of glass particles in slices cut from different levels of the sample height. It was found that the 25% normal coarse aggregate particles were settled completely in the bottom of specimens compared to 25% coarse waste glass particles which were separated down to the low layers of the specimen with a few ones in the top, see Fig. 7. Moreover, it was observed that the foam concrete mix made with normal aggregate was very weak and brittle.

In this paper, waste glass as coarse aggregate with different ratios (25%, 50% and 100%) was added. From the findings, even with reducing the quantity of added glass particles, the distribution of waste glass particles of FCGC mix (with a percentage of 25%) was not uniform. The glass particles were located in the bottom layers of the specimen while a few quantities appeared in the top as shown in Fig. 8(a). In addition, it was observed that with using of waste glass in foam concrete mixes with the percentages of 50% and 100%, large quantities of their particles located in the bottom layers of the specimens while no particles appeared in the top layers as shown in Fig.



(a) FCGC mix (b) FCGCF mix

(c) GC50% mix (d) GC100% mix

Fig. 8 Image of slice perpendicular to the casting face of mix and proportions of glass particles at different levels of the cubic sample height

8(b) and 8(d). This is due to the heavy weight of coarse glass particles compared to that of fine sand. A similar distribution behavior of coarse glass particles was observed for foam concrete mix made with fine and coarse waste glass in combination (FCGCF mix), see Fig. 8(c).

From the earlier discussion, it is obvious that there is an issue in producing foam concrete with coarse waste glass as aggregate. Therefore, trials were carried out to enhance the distribution of waste glass particles within foam concrete products. A trial was carried out by adding polypropylene fibers (PPF) to make the mixture stiffer leading to a uniform distribution of the WG particles. polypropylene fibers (PPF) were added with a ratio of 0.5% by mix volume in foam concrete mixes made with waste glass to enhance the particles distribution. It was observed that addition of polypropylene fibers enhanced particles distribution of RWG within foam concrete mixes for all investigated percentages (25%, 50% and 100% of fine sand). However, FCGC-P with 25% percentage showed the best WG distribution among the other two mixes, see Fig. 9(a), (b) and (d). In addition, particles distribution of WG in FCGCF-P mix was enhanced as well, see Fig.

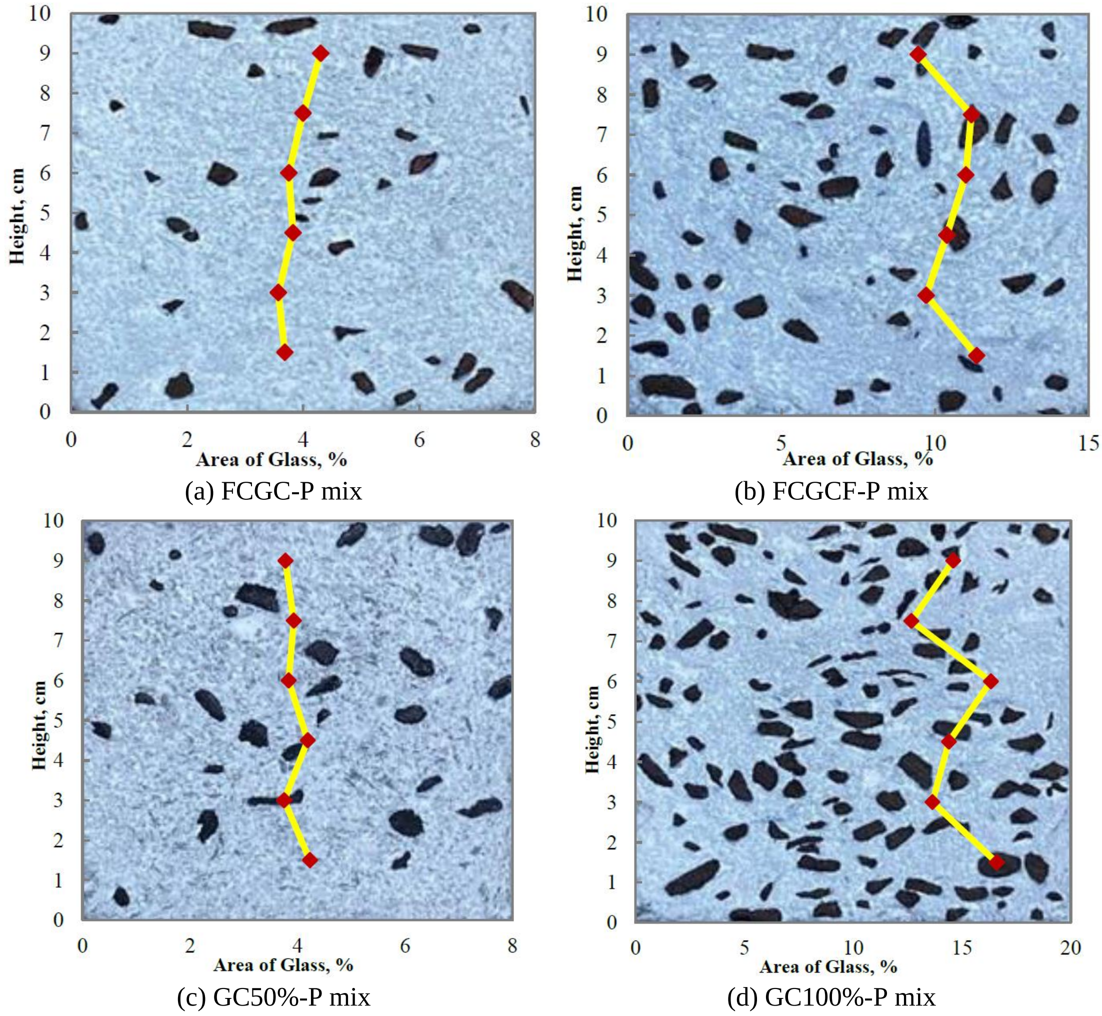
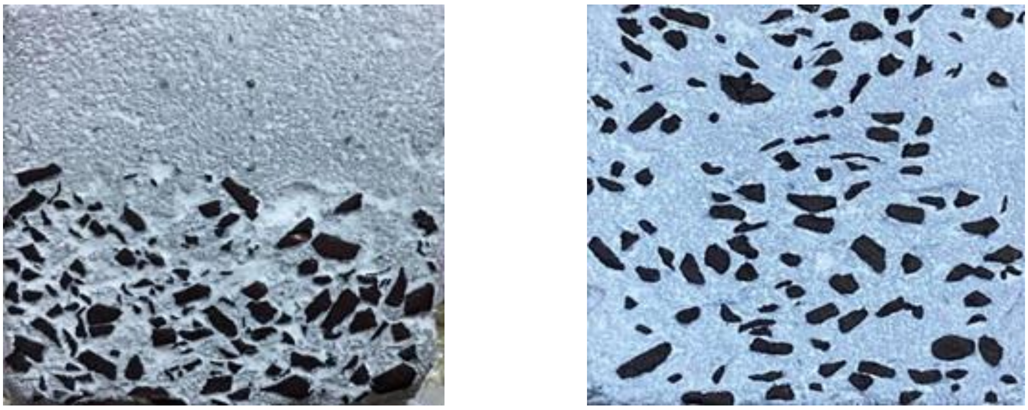


Fig. 9 Image of slice perpendicular to the casting face of mix and proportions of glass particles at different levels of the cubic sample height

9(c). The reason for this is due to a randomly distributed of fibers in foam concrete mixture made with coarse glass restrained these particles making them uniformly distributed. Fig. 10 shows the enhancement of 100% WG particles mix with and without adding PPF.

4.3 Compressive strength

Fig. 11 shows the 7 and 28 days compressive strengths of investigated foam concrete mixes made with different percentages of recycled waste glass. It can be seen that using recycled waste glass as fine aggregate helped in improving the compressive strength of foam concrete at both selected ages. However, it was observed that adding glass powder (FCGP mix) slightly decreased the compressive strength. Foam concrete mix with fine glass (FCGF) showed an increase in compressive strength by about 7% compared to conventional foam concrete mix (FC). This may



without any additives with PPF

Fig. 10 Enhancement of 100% WG particles distribution

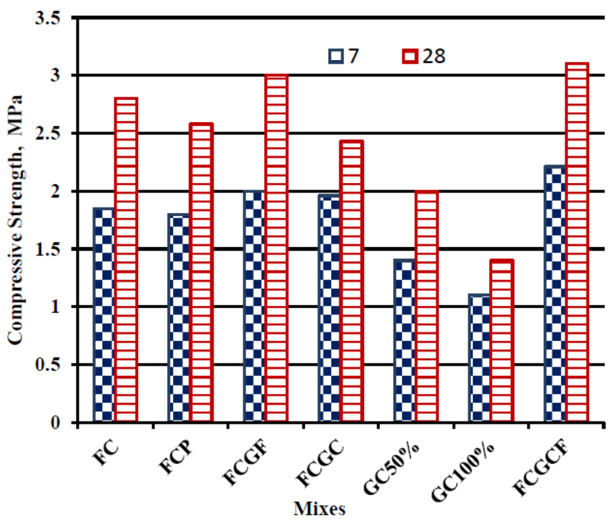


Fig. 11 Compressive strength of foam concrete mixes made with different grading and percentages of waste glass

be due to the angular nature of fine glass, which increased the bonding with the cement paste and then enhancing the mix strength. It was concluded that replacing coarse aggregate by crashed glass particles resulted in lower strength of normal concrete (de Castro and de Brito 2013, Tan and Du 2013, Afshinnia and Rangaraju 2016). Also, it was observed from this study that replacing sand with coarse glass by 25%, 50% and 100% (FCGC, GC50% and GC100% mixes) decreased compressive strength of foam concrete by about 13%, 29% and 50%, respectively, compared to conventional FC mix. This can be attributed to the non-uniformly distribution of coarse glass particles within the mix which resulted in locating the added foam bubbles in the top layers of specimen and then reducing the strength. Noting that the mechanism of failure, cracks initiation and propagation, of normal concrete is different from that of foam concrete. Moreover, adding fine and coarse glass particles in combination (FCGCF mix) resulted in the highest compressive strength (11% higher than that of FC mix).

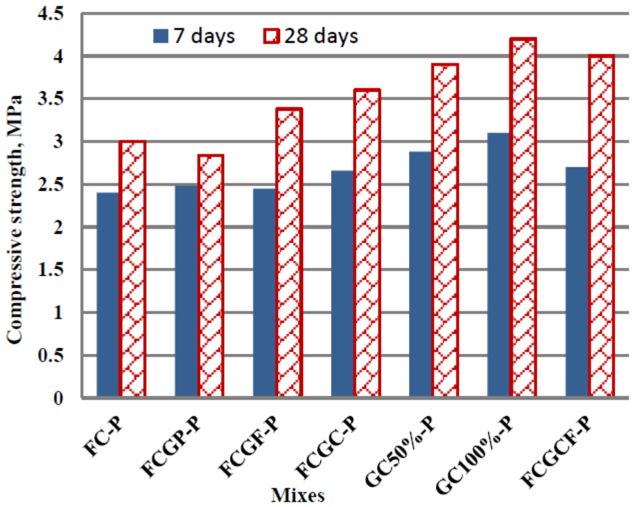


Fig. 12 Compressive strength of foam concrete mixes made with different percentages of waste glass and polypropylene fibers

In terms of polypropylene fibers, adding them to foam concrete mixes reduced the microcracks and prevented the easy initiation and propagation of cracks within the matrix (Hadipramana *et al.* 2013). In the mixes made with polypropylene fibers, the network structure formed easily, and a lower stress of foam concrete concentrated at the crack tip and thus increased compressive strength (Tawfiq and Ruiz 1999). A little effect on compressive strength of foam concrete was observed with the addition of polypropylene fibers. Adding polypropylene fibers in conventional foam concrete mix (FC-P) slightly increased the compressive strength by about 7% compared to FC mix. Using of polypropylene fibers in glass powder mix enhanced its compressive strength. Also, FCGF-P mix made with fine glass and polypropylene fibers showed an increase in compressive strength by about 12% than that of FCGF mix and 21% than FC mix. It was found that the compressive strength of foam concrete mixes made with coarse glass and polypropylene fibers (FCGC-P, GC50%-P and GC100%-P) increased by about 20%, 30% and 40%, respectively, compared to the corresponding mixes made with fiber (FC-P mix) However, the strength increments were higher in comparison with the conventional foam concrete mix without fibers (FC mix) as 29%, 39% and 50% for FCGC-P, GC50%-P and GC100%-P mixes, respectively. In addition, using of 25% fine glass, 25% coarse glass and polypropylene fibers in combination (FCGCF-P mix) helped in improving the compressive strength by about 29% than that of FCGCF mix and 43% compared to FC mix.

Fig. 12 shows compressive strength of foam concrete mixes made with recycled waste glass and polypropylene fibers. In comparison with the mixes without fibers, it can be seen that not only adding the fibers but also achieving uniformly distribution of the coarse glass particles helped in enhancing the compressive strength of the mixes made with coarse waste glass particles.

4.4 Splitting tensile strength

Fig. 13 shows the splitting tensile strength of investigated foam concrete mixes made with waste glass. It was found that adding of glass powder slightly decreased the splitting tensile

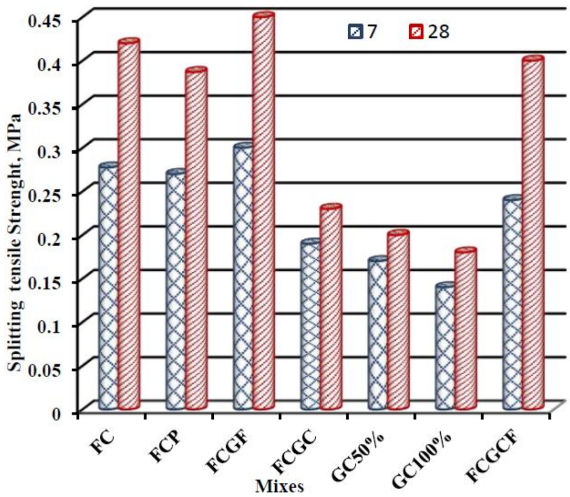


Fig. 13 Splitting tensile strength of foam concrete mixes made with waste glass

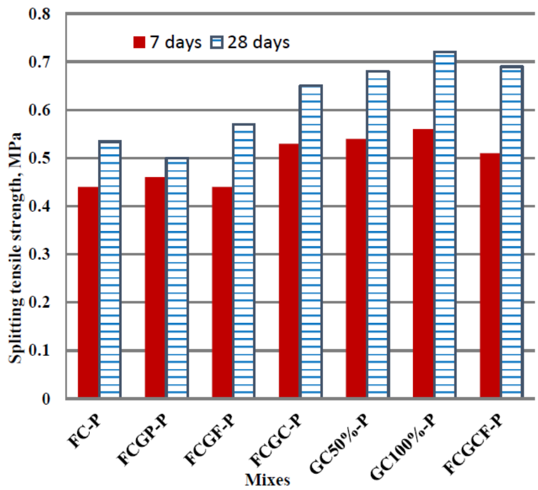


Fig. 14 Splitting tensile strength of foam concrete mixes made with waste glass and polypropylene fibers

strength. However, using it as fine aggregate helped in improving the splitting tensile strength by about 7%. This may be attributed to the angular shape of fine glass particles compared to sand which may result in enhancing the interlocking and producing higher friction forces inside the mix. From the other hand, using waste glass as coarse aggregate in producing of foam concrete mixes at different percentages led to decrease the splitting tensile strength by about 45%, 52% and 57% for the addition of 25%, 50% and 100%, respectively. This reduction in splitting tensile strength value may be due to the non-uniformly distribution of coarse glass particles which resulted from settling them down and uplifting the foam bubbles to the top layers of specimen. Owing to having coarse glass particles, FCGCF mix also showed a decrease in splitting tensile strength by about 5% compared to FC mix.

In terms of polypropylene fibers, Fig. 14 shows that using of them in foam concrete mixes containing recycled waste glass helped in achieving an improvement in splitting tensile strength for all investigated mixes. Noting that the non-uniformly distribution of coarse glass particles was solved with adding fibers. Adding polypropylene fibers in conventional foam concrete showed an increasing in splitting tensile strength by about 13% of that of FC mix. Using polypropylene fibers prevented the formation of microcracks due to the interfacial bonding between these fibers and the matrix and resulted in bridging the cracks and finally improving the splitting tensile strength. Also, using of polypropylene fibers in glass powder mix enhanced the splitting tensile strength by about 11% compared to FCGP mix. FCGF-P mix made with recycled fine waste glass and polypropylene fibers showed an increase in splitting tensile strength by about 14% than that of FCGF mix and 36% of that of FC mix. Moreover, incorporating of polypropylene fibers in mixes made with different percentages of coarse waste glass (FCGC-P, GC50%-P and GC100%-P) helped in improving the splitting tensile strength by about 23%, 28% and 36%, respectively, compared to FC-P mix. This indicates that not only using fibers but also enhancing the coarse waste glass particles distribution is necessary to improve the strength. The splitting tensile increments were 55%, 62% and 71%, respectively, compared to FC mix. This implies that using the fibers and coarse waste glass together in foam concrete mixes has more effect in improving the splitting tensile strength. The results also showed that the using of polypropylene fibers with 25% fine and 25% coarse glass together (FCGCF-P mix) increased the splitting tensile strength of foam concrete by about 64% than that of mix without PPF (FCGCF mix).

4.5 Drying shrinkage

Jones and McCarthy (2003) stated that due to the absence of normal coarse aggregate, foam concrete possesses high drying shrinkage up to 10 times greater than that observed in normal concrete. Roslan et al (2012) reported that foam concrete mixes at lower densities shrink more than that at higher densities due to the large foam volume entrained inside them i.e., large number of air pores. It was reported that the presence of coarse aggregate in concrete restrained the shrinkage of concrete and affected the long-term drying shrinkage of it (Zhang *et al.* 2013). Therefore, using waste glass as coarse aggregate in producing of foam concrete mixes may help in improving their drying shrinkage.

From the results, it was noticed that the drying shrinkage of foam concrete decreased with increasing particles size of glass compared to conventional foam concrete (FC mix). Using of glass powder as cement replacement reduced the drying shrinkage by about 6% compared to FC mix. This may be because of the Pozzolanic and filling actions of glass powder which enhanced the microstructure of cement paste by reducing its capillary and gel pores. Also, the use of fine waste glass as a partially substitution of sand reduced the drying shrinkage by about 10%. The reason for this is the providing of more restraint for cement paste with using fine waste glass particles resulting in and then reducing the drying shrinkage (Obaid and Hilal 2021). FCGC mix (with 25% coarse glass particles) also showed a reduction in drying shrinkage by about 15% compared to FC mix, see Fig. 15. Compared to conventional foam concrete mix FC, the higher reduction in drying shrinkage (19%) was for FCGCF mix which made with 25% fine and 25% coarse glass particles.

From Fig. 16, it can be seen that the drying shrinkage gradually decreased with increasing percentages of added coarse glass. The reduction in drying shrinkage of FCGC, GC50% and GC100% mixes compared to that of FC mix was about 15%, 18% and 24%, respectively. This indicates that the presence of coarse glass as coarse aggregate provided better restraint and the angularity shape of its particles helped in restraining the shrinkage of foam concrete. In addition, the volume and stiffness of added coarse glass particles can be considered as important factors

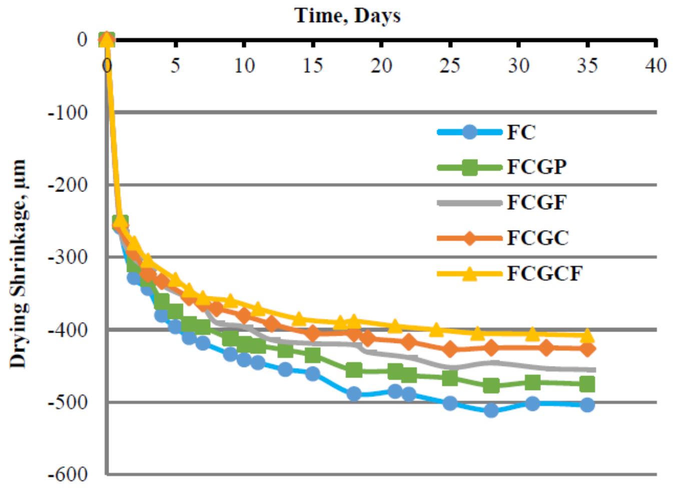


Fig. 15 Drying shrinkage of foam concrete mixes made with different grading of waste glass

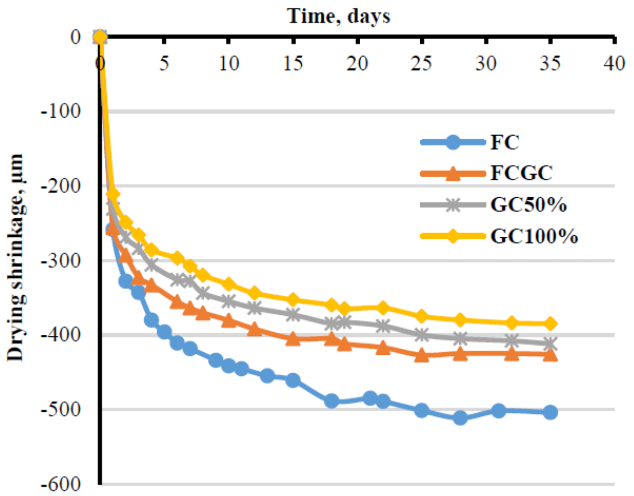


Fig. 16 Drying shrinkage of foam concrete mixes made with different percentages of waste glass

preventing drying shrinkage.

It can be seen from Fig. 17 that adding polypropylene fibers in foam concrete mixes helped in reducing the shrinkage compared to mixes without them. It was observed that adding fibers in FC-P mix reduced the shrinkage by about 16% compared to FC mix. This because that fibers as an anti-micro-crack agent helped in preventing cracks from widening. Saje *et al.* (2011) reported that adding polypropylene fibers helped in delay the rate of water evaporation and then reduce the drying shrinkage of foam concrete. Adding polypropylene fibers in foam concrete mixes with glass powder (FCGP-P mix) led to decrease the drying shrinkage by about 8% compared to FC-P mix. An enhancement in drying shrinkage by about 12% than that of FC-P mix, was observed with the addition of polypropylene fibers to mixes made with fine glass particles. In addition, using of polypropylene fibers with fine and coarse glass in combination (FCGCF-P mix) reduced drying shrinkage by about 25% than that of FC-P mix.

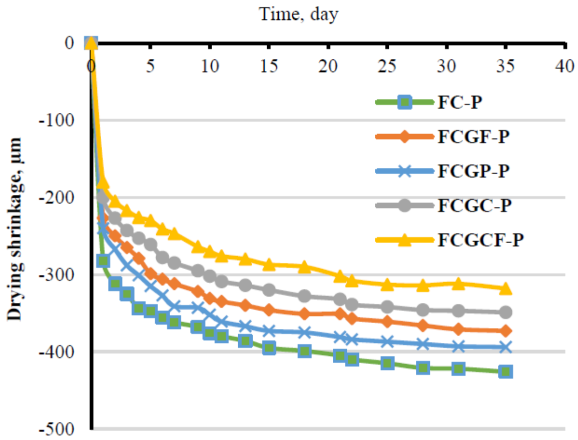


Fig. 17 Drying shrinkage of foam concrete mixes made with different grading of waste glass and polypropylene fibers

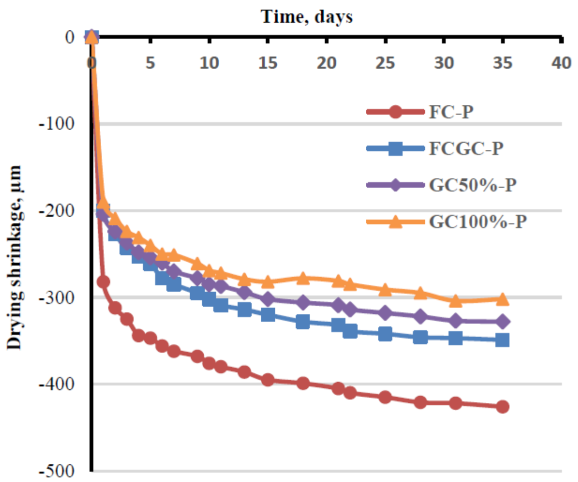


Fig. 18 Drying shrinkage of foam concrete mixes made with different percentages of coarse waste glass and polypropylene fibers

Also, Fig. 18 shows that using of polypropylene fibers with different percentages of coarse glass (25%, 50% and 100%) reduced the drying shrinkage by about 18- 29% compared to FC-P mix due to the same reasons that were mentioned earlier. However, using the fibers and coarse glass particles in combination helped in reducing the drying shrinkage by about 31- 40% compared to FC mix. As concluded earlier, this indicates that not only the fibers role but also the uniformly distributed coarse glass particles helped in reducing the drying shrinkage of the investigated foam concrete mixes.

5. Conclusions

From the experimental work, it was noticed that the problem of non- uniform distribution of coarse waste glass particles was successfully solved by adding the polypropylene fibers and this represents the most important finding of this study. Also, it was found that the density of all investigated foam concrete mixes was reduced with adding waste glass as aggregate instead of sand due to its lower specific gravity. However, no effect on density was noticed with adding polypropylene fibers due to its small used quantity and low specific gravity.

In terms of a fresh state, an enhancement in flowability of foam concrete mixes made with waste glass was noticed by increasing their spreadability compared to the conventional mix. However, as expected, a reduction in flowability was noticed with using polypropylene fibers.

A reduction in compressive strength of foam concrete (about 13-50%) was recorded with incorporation of waste glass as coarse aggregates due to their non- uniformly distribution within the mix. However, using the fibers and coarse waste glass in combination in producing foam concrete mixes helped in improving their strength by about 29- 50% for compressive and 55- 71% for splitting tensile. The coarser the glass particles the stronger the fiber reinforced foam concrete. In addition, a remarkable reduction in drying shrinkage (about 31- 40%) was achieved by adding polypropylene fibers to mixes made with coarse glass particles.

In general, not only the fibers role but also the uniformly distributed coarse glass particles helped in improving and enhancing the strength and shrinkage of the investigated foam concrete mixes.

It should be noted here that a future work will be carried out to examine the Alkali Silica Reaction in foam concrete made with waste glass as powder, fine and coarse glass as well as the effect of glass type on this reaction.

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