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Influence of granulated blast furnace slag on mechanical properties of foam concrete

Hanizam Awang[1]* and Zaid Shaker Aljoumaily[2]

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*Corresponding author: Hanizam Awang, School of Housing, Building, and Planning, Universiti Sains Malaysia, 11800 Gelugor, Penang, Malaysia
E-mail: hanizam@usm.my

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Raja Rizwan Hussain, King Saud University, Saudi Arabia

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Abstract: This paper experimentally comparing the mechanical properties between ground granulated blast furnace slag (GGBS) and unground blast furnace slag (GBS) as a partial replacement for cement for the production of foam concrete. A total of 14 foam concrete mixes were prepared under a design density of 1,300 kg/m^3, two different filler-to-binder ratios, and cement replacement levels of 30–70% of the weight of the binder. A soluble salt of polymeric sulfonates of organic compounds (PS-1) was added to the mixes, with GGBS and GBS replacements at a dosage varying from 0.2–2% of the total cementitious material. Compressive, flexural, and tensile strengths were investigated for up to 90 days. Results show that foam concrete with superior quality as compared with that of the control mix can be produced by using GBS. Results show that 30% GBS foam concrete mix exhibited higher compressive, flexural, and splitting tensile strengths than the control mix of GBS at all ages for both filler-to-binder ratios.

Subjects: Composites; Concrete & Cement; Waste & Recycling

Keywords: foam concrete; slag; replacement; properties

1. Introduction

Foam concrete has been proven to be more environmentally friendly than conventional concrete as it uses fewer natural resources, is superior in fire and thermal insulation, reduces the weight of superstructures or substructures, minimizes the overall cost of construction, and can be handled and constructed relatively faster and easier (Kearsley, 1999). Foam concrete is a mortar- or slurry-based material with mechanically entrained air bubbles having a minimum volume of 20%. Air bubbles are introduced to the base mix (mortar or cement slurry) by mixing a stable pre-formed foam, which in

ABOUT THE AUTHORS

The current paper is part of ongoing research carried out by the authors. The research focuses on the used of waste material such as palm oil ash, fly ash, rice husk ash, ground granulated blast furnace slag, silica fume, etc. in foam concrete as cement replacement under different replacement levels. The utilization of these materials reduces carbon dioxide (CO_2) footprint attributed to cement production and enhances the properties of concrete. The utilization of cementitious waste material as a partial replacement for cement for the production of concrete will increase the possibility of developing a more environmentally friendly concrete and minimizing the amount of cement used for its production.

PUBLIC INTEREST STATEMENT

Foam concrete is a lightweight concrete and has been proven to be more environmentally friendly as it uses fewer natural resources, provides good thermal insulation, reduces the weight of structure. The construction industry has been extensively using foam concrete because of its energy-saving and environmentally friendly features. This paper experimentally compares the properties of foam concrete utilizing byproduct waste which is produced from the iron and steel industries. The use of waste material for the production of foam concrete will increase the possibility of developing a more environmentally friendly foam concrete and minimize the amount of cement used for its production.

itself is a mixture of compressed air and a suitable foaming agent (Ramamurthy, Kunhanandan Nambiar, & Indu Siva Ranjani, 2009). The construction industry has been extensively using foam concrete because of its energy-saving and environmentally friendly features (Bing, Zhen, & Ning, 2012). Foam concrete is becoming an innovation product that offers a wide range of densities lower than that of conventional concrete (i.e. 1,000 kg/m^3–1,600 kg/m^3), better capability for fire protection, and superior heat and sound insulation (Lim, Tan, Lim, & Lee, 2013). However, foam concrete tends to consume more cement to achieve the desired mechanical properties (Neville, 1996). Previous research have utilized cementation material in foam concrete as cement replacement under different replacement levels, such as classified (graded) and unclassified (ungraded) fly ash, rice husk ash, ground granulated blast furnace slag (GGBS), silica fume, and oil palm ash (Awang, Al-Mulali, Abdul Khalil, & Aljoumaily, 2014; Jitchaiyaphum, Sinsiri, & Chindaprasirt, 2011; Jones & McCarthy, 2005a; Zulkarnain & Ramli, 2011). The utilization of these materials reduces carbon dioxide (CO_2) footprint attributed to cement production and enhances the properties of concrete (Chandra, 1996).

GGBS has been used for the production of cement or cementitious materials in two ways: as a raw material in the production and in the combination of Portland cement. According to Neville (1996), GGBS could be used with Portland cement as bended cement (25% GGBS), Portland cement blast furnace slag (25–70% GGBS), and cement slag (70% GGBS or more). Numerous studies have incorporated GGBS in the production of concrete (Chi, Chang, & Huang, 2012; Memon, Sumadi, & Ramli, 2007; Parniani, Hussin, & Mansour, 2011; Yüksel, Siddique, Özkan, & Khatib, 2008). Previous studies suggest that this supplementary cementitious material enhances the performance characteristics of concrete, such as strength, workability, permeability, durability, and corrosion resistance. Study done by Islam, Alengaram, Jumaat, and Bashar (2014) found that this cementitious material could be used for development of sustainable construction material. The compressive strength of geopolymer mortar increases as the GGBS content is increased up to 70%. The utilization of GGBS is limited mostly to conventional concrete, and only few researchers have explored the possibility of incorporating GGBS in foam concrete (Samson, Cyr, & Gao, 2017; Zhao et al., 2015).

Although GGBS has been extensively used for the production of concretes as a pozzolanic material, the incorporation was done after further processing the unground granulated blast furnace slag (GBS) by either grinding or heat treatment. However, these treatments do apply considerable cost (Chao-Lung, Anh-Tuan, & Chun-Tsun, 2011; Zerbino, Giaccio, & Isaia, 2011). Study on the GBS as alternative sources of fine aggregate in normal concrete has been explored by Patra and Mukharjee (2017). They found that the quality of concrete increases with the incorporation of GBS and a sustainable construction material can be developed by utilizing GBS in place of the natural fine aggregates.

However, the investigations dealing with GBS in producing foam concrete are not often found in existing literature. Therefore, the current study aims to investigate the influence of GBS on fresh and hardened properties of foam concrete with a density of 1,300 kg/m^3 under cement replacement levels of 30, 50, and 70%. The utilization of GBS as a partial replacement for cement for the production of foam concrete will increase the possibility of developing a more environmentally friendly foam concrete and minimizing the amount of cement used for its production.

2. Experimental program

2.1. Materials

The binding materials used in the current study were Portland cement (OPC), GBS, and GGBS. The fine aggregate used was locally available river sand, which is classified as fine sand according to Bs EN 12620 (2013). Fine sand was used as the filling material without undergoing any washing or drying processes. The recommended fine aggregate utilized in foam concrete should have a maximum particle size of 4 mm with 60–90% of the fine aggregate passing through a 600-micron sieve. Normal tap water was used in this research to satisfy the requirement mentioned in BS EN 1008 (1997),

Table 1. General properties of the foaming agent and aqueous foam

Appearance of the foaming agent	Dark brown-colored agent
Specific density of the foaming agent	1.1
Dilution ratio (premix)	1:29
Expansion rate	12–15 times
Appearance of the aqueous foam	Cream-colored foam
Density of the aqueous foam	65–70 kg/m^3
Shelf life	12–18 months

which prescribed a pH level ranging from 6–8. The pre-formed foam method was adopted in this research utilizing a protein-based foaming agent with the trade name of Noraite PA-1. The premix was diluted by maintaining a foaming agent-to-water ratio of 1:29, as recommended by the manufacturer. Table 1 illustrates the general properties of the foaming agent and the aqueous foam.

The water-reduction agent (PS-1) was based on a soluble salt of polymeric sulfonates of organic compounds and incorporated at a percentage varying from 0.2–2% of the total cementitious material. Table 2 shows the typical properties of the water-reduction agent (PS-1).

2.2. Basic properties of binding materials

A few basic tests on the physical properties of the binding material, such as fineness (Blaine surface area), specific gravity, and particle size distribution were conducted. The specific gravity was determined in accordance to ASTM C 188-95 (ASTM, 2001). Table 3 shows the fineness and the specific density of the binding material.

Analysis on the particle size distribution was performed on the three binding materials to determine the average particle size distribution (x_{50}) and to clearly present the comparison between the three binders in the form of a distribution curve. Figure 1 shows the particle size distributions of the binding materials.

Figure 1 shows that GBS had the largest average particle size distribution (X_{50}) of 527.86 µm, whereas GGBS had a smaller and narrower average particle size distribution (X_{50}) of 11.54 µm, followed by OPC with 7.96 µm. The chemical composition of the binding materials was determined through an X-ray fluorescence test. Table 4 shows the chemical composition of the binding materials. Both GBS and GGBS complied with the BS EN 15167-1 (2006), and Bs EN 197-1 (2011).

Table 2. Typical properties of the super plasticizer (PS-1)

Chemical content	A mixture of sodium acids and glycol compounds
Appearance	Brown- to light brown-colored liquid
Total solid %	40
PH solution	7.5–8
Salt content	Maximum of 5%
Insoluble	Negligible
Chloride as NaCl	Nil

Table 3. Fineness and the specific density of the binding materials

Fineness (cm^2/g)			Specific density		
Cement	GGBS	GBS	Cement	GGBS	GBS
3923	3,149	138	3.13	2.92	2.63

Figure 1. Particle size distributions of the binding materials.

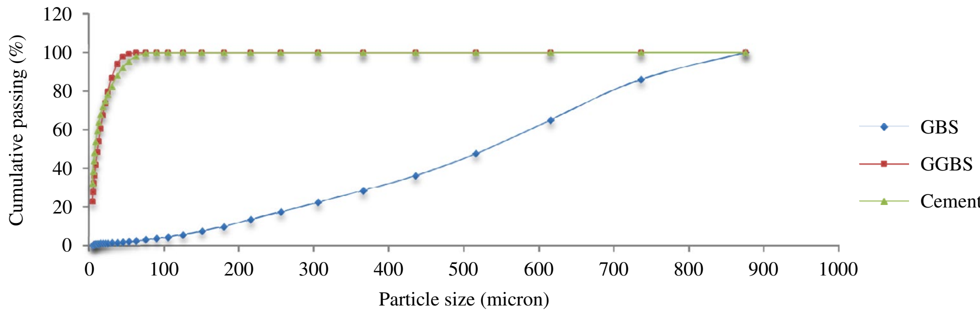


Table 4. Chemical composition of the binding materials (wt. %)			
Constituents	**OPC**	**GGBS**	**GBS**
Lime (CaO)	64.61	42.3	38.3
Silica (SiO_2)	21.26	33.9	39.1
Alumina (Al_2O_3)	5.6	14.8	12.1
Iron oxide (Fe_2O_3)	3.31	0.91	1.03
Magnesia (MgO)	2.04	5.6	8.5
Sulfur trioxide (SO_3)	2.13	0.1	0.65
Loss of ignition	0.64	1.0	0.8
MnO	–	0.21	0.27
Titanium oxide (TiO_2)	–	0.54	0.6
Potassium oxide (K_2O)	–	0.25	0.31
Sodium oxide (Na_2O)	–	0.22	0.23
Alkalis	0.9	0.38	–

Activity indexing of GBS and GGBS was performed, which followed the procedure mentioned in ASTM C989 (2014). As expected, the activity index was lower than the standardized ratio due to the fineness of the GBS, which has the same size as that of sand particles. However, the strength of GBS developed with age, specifically by generating an additional calcium silicate hydrate (CSH), which could explain the pozzolanic activity of GBS. Table 5 shows the strengths and the indexes of GBS and GGBS mortar at 7 and 28 days.

2.3. Mix constituents

The target density was 1,300 kg/m^3 for all of the mixes under two different mix ratios, namely, 1:1:0.45 and 1:2:0.45 (cement:sand:water), and the design density was specified to be 1,450 kg/m^3. A difference of 150 kg/m^3 was added to the target density based on the equation presented by Kearsley and Mostert (2005). The amount of water was added based on the mortar consistency. Spread tests were performed to determine the consistency of the fresh mixed mortar as described in ASTM C1437. A fresh mortar was poured into a standard one-liter cup without any compaction and vibration. The spread (inverted slump) diameter values were measured to evaluate the flowability of the mortar and kept from 18–20 cm for all of the mixes. The PS-1 added was 1% of the total

Table 5. GBS and GGBS indexing				
	Compressive strength (MPa)		**Indexing (%)**	
	7 days	**28 days**	**7 days**	**28 days**
Mortar (0%)	32.5	53.1	-	-
GBS mortar (50%)	9.7	22.7	29.8	42.7
GGBS mortar (50%)	19.2	54.7	59	103

Table 6. Mix constituents of foam concrete mixes

Mixes	Cement (kg/m³)	GBS (kg/m³)	GGBS (kg/m³)	Sand (kg/m³)	Designed water (kg/m³)	PS-1 (kg/m³)
I-0	583.2	–	–	583.2	262.4	–
IG30	408.3	174.9	–	583.2	262.4	5.83
IG50	291.6	291.6	–	583.2	262.4	5.83
IG70	174.9	408.3	–	583.2	262.4	5.83
IGG30	408.3	–	174.9	583.2	262.4	5.83
IGG50	291.6	–	291.6	583.2	262.4	5.83
IGG70	174.9	–	408.3	583.2	262.4	5.83
II-0	414.2	–	–	828.4	186.4	–
IIG30	289.9	124.3	–	828.4	186.4	4.14
IIG50	207.1	207.1	–	828.4	186.4	4.14
IIG70	124.3	289.9	–	828.4	186.4	4.14
IIGG30	289.9	–	124.3	828.4	186.4	4.14
IIGG50	207.1	–	207.1	828.4	186.4	4.14
IIGG70	124.3	–	289.9	828.4	186.4	4.14

weight of the binder with mixes consisting of GBS and GGBS. Table 6 illustrates the mix constitutes calculated in cubic meters. For simplicity, the mixes with cement-to-sand ratio of 1:1 are referred to as Series I, whereas the mixes with cement-to-sand ratio of 1:2 are referred to as Series II. The letter G stands for GBS and is followed by the percentage of the replacement level, and GG stands for GGBS.

2.4. Mixing procedure

After all of the materials have been prepared, the foam density and foam machine flow rate were checked. The fine aggregate was fed into the mixer with 10% of the calculated amount of water, followed by the cementitious material. To obtain a more homogeneous batch, the constituents were left for 3–4 min in the mixer. The water-reduction agent PS-1 was diluted with a calculated amount of water and was added to the batch all at once. The rest of the water was added gradually until the desired mortar consistency was achieved; this step was done following the technique adopted from ASTM (2004). The desired mortar density was achieved by weighing a standard one-liter cup of the base mortar mix. The required amount of foam was then injected into the batch, and the density of the foam concrete was checked once all of the aqueous foam had been blended. Afterward, the density of the freshly mixed foam concrete was determined.

For the evaluation of the fresh properties of the foam concrete mixes, both stability and consistency will be determined. On the one hand, stability is determined based on the foam quantity. Foam stability is the ratio of the actual foam quantity required by the mix and the theoretical quantity of the foam (Jones & Mccarthy, 2005b). The consistency of the fresh mixed foamed concrete represented by a measured fresh density to designated density ratio was kept to nearly unity, without segregation and bleeding (Lim et al., 2013). A sealed curing regime was adopted in the current study by wrapping the specimens in a plastic sheet until the day of testing (Kearsley, 2006).

2.5. Testing program

The mechanical properties of the foam concrete, consisting of compressive, splitting tensile, and flexural strength, were determined according to BS EN 12390-3 (2009a), BS EN 12390-6 (2009b), and BS EN 12390-5 (2009c), respectively. The testing period for the mechanical properties was conducted at 7, 28, and 90 days. On average, three samples were used for each of the tests. The size of the cube samples used for the compression test was 100 × 100 × 100 mm, and a cylinder with a height of

Table 7. Fresh properties of the foam concrete mixes

Mix	Required amount of foam (m^3)	Actual amount of foam (m^3)	Fresh density (kg/m^3)	Stability (%)	Consistency (%)
I-0	0.326	0.326	1,460	1.00	1.01
IG30	0.304	0.304	1,445	1.00	1.00
IG50	0.263	0.261	1,460	0.99	1.01
IG70	0.208	0.205	1,445	0.99	1.00
IGG30	0.308	0.308	1,475	1.00	1.02
IGG50	0.297	0.298	1,470	1.00	1.01
IGG70	0.285	0.283	1,465	0.99	1.01
II-0	0.342	0.344	1,442	1.01	0.99
IIG30	0.332	0.332	1,425	1.00	0.98
IIG50	0.300	0.297	1,460	0.99	1.01
IIG70	0.261	0.261	1,460	1.00	1.01
IIGG30	0.336	0.336	1,450	1.00	1.00
IIGG50	0.310	0.311	1,470	1.00	1.01
IIGG70	0.297	0.297	1,480	1.00	1.02

200 mm and a diameter of 100 mm was used for the tensile strength test. Prisms, with dimensions of 500 × 100 × 100 mm, were tested for their flexural strength. The mechanical properties were tested using an ELE international testing machine with a maximum capacity of 3,000 kN.

3. Results and discussions

3.1. Fresh properties

The calculated and the actual amount of foam required along with the freshly obtained density are listed in Table 7. Mixes in Series I generally exhibit a lower amount of foam required than those in Series II, which is due to heavy mortar density in Series II. Results revealed that the inclusion of either GBS or GGBS in the matrix of foam concrete-based mixture reduced the amount of foam required as compared with control mixes in both series. The amount of foam required was found to decrease with the increasing level of replacements. This phenomenon is due to the lower specific density of both by-product materials as compared with OPC. GBS foam concrete mixes exhibit low foam demand due to low mortar density.

The foam stability values range from 0.99–1.01, indicating that the difference between the calculated and the actual amount of foam is insignificant. The consistency of the foam concrete mixes ranged from 0.98–1.02, which indicates that the freshly obtained densities are close to the required design density. The pre-formed foam concrete mixes were stable when they hardened after 24 h. The values presented in Table 7 are all consistent with those of the studies of Jones and Mccarthy (2005b), Ramamurthy et al. (2009), and Lim et al. (2013).

3.2. Compressive strength

Table 8 presented the compressive strength of Series I and II mixes with GGBS and GBS, respectively. Regardless of the type of binding material, replacement level, and filler-to-binder ratio, all of the mixes exhibit strength development with age. As the amount of filling material increased, the compressive strength declined. Thus, all of the mixes in Series I exhibit higher strength than those in Series II, which is consistent with those in the research of Hamidah, Azmi, Ruslan, Kartini, and Fadhil (2005) and Kearsley and Wainwright (2001). Mixes with GGBS replacement of cement showed higher compressive strengths than those exhibited by their correspondent control mixes at all ages.

Table 8. The compressive strength of GGBS and GBS

Compressive strength (MPa)			
Mix	7-days	28-days	90-days
I-0	8.12	10.00	10.33
IG30	8.25	10.10	10.62
IG50	6.30	7.65	8.63
IG70	3.96	4.76	5.43
IGG30	9.98	12.48	13.71
IGG50	9.57	11.90	12.78
IGG70	9.30	11.16	12.18
II-0	4.98	6.10	6.82
IIG30	5.28	6.45	7.43
IIG50	3.85	4.58	5.84
IIG70	1.94	2.82	3.23
IIGG30	7.87	9.20	10.70
IIGG50	6.98	7.85	10.06
IIGG70	5.86	6.74	8.11

For any given series, up to 30% of GBS in the foam concrete mixture reduce the compressive strength as compared with those of control mixes; this condition is attributed to the decreasing amount of cement content, thereby decreasing the amount of alkali hydroxide generated through primary cement hydration, which allows the reaction with pozzolanic oxides (Aïtcin, 2008; American Concrete Institute (ACI), 2003). However, mixes with 30% GBS in both series (i.e. IG30 and IIG30) exhibit higher compressive strength as compared with control mixes in both series; this condition can be attributed to the lesser amount of artificial pores (required amount of foam) and sufficient cement content. Furthermore, the addition of PS-1 also caused the reduction in micropores, hence, creating a stronger paste (Siddique & Khan, 2011).

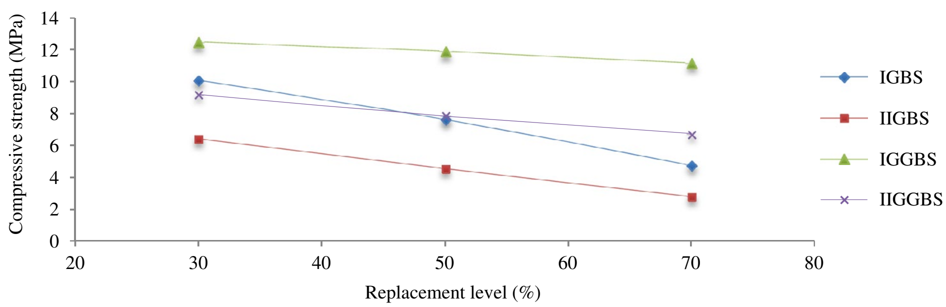
Strength activity indices for all mortars are shown in Table 9. The strength activity index is the ratio of the strength of the GGBS or GBS foamed concrete to the strength of the reference (foamed concrete) at each specific curing time. The strength activity indices at 7, 28, and 90 days for GGBS were recorded higher than 100% and gradually increases with the increasing of curing age. Meanwhile for the GBS mixes (IG 30, IG 50, IIG 30) the strength activity indices at 7, 28, and 90 days were higher than the minimum requirement of 75% as specified in ASTM C 618-05. IIGS 50 presents a strength activity index of 48.2, 75.1 and 85.6% of the reference strength at 7, 28, and 90 days, respectively. At the early ages of 7 days, replacing OPC with 50% GBS in series II was found reduce the compressive strength in comparison to the control mix. This could be attributed to dilution effect and delayed onset of pozzolanic reaction of GBS. At 28 days, the strength activity index increases to more than 75%, which could have contributed by the pozzolanic reaction of GBS with Ca(OH).

As GGBS can be incorporated into foam concrete mixtures, the results generally showed that all of the mixes at different replacement levels gained higher compressive strength at all ages than the control mixes in both series. The strength increased because GGBS creates a denser and more compact paste (Ruiwen, 2004). In addition, the low specific weight of GGBS led to a decrease in the amount of foam required to achieve the desired design density, hence, reducing the amount of artificial pores in the paste. Increasing the replacement level beyond 30% GGBS results to a decrease in the compressive strength. The decreases of strength occurred because of the lower cement content (reduction in C_3S content) resulting in a reduction in the quantity of hydration compounds. Figure 2 shows the effect of the replacement for both by-product materials on compressive strength at the age of 28 days.

Table 9. The strength activity index (%)

Mix	7-days	28-days	90-days
I-0	100	100	100
IG30	101.6	101	102.8
IG50	77.6	76.5	83.5
IG70	48.8	47.6	52.6
IGG30	122.9	124.8	132.7
IGG50	117.9	119	123.7
IGG70	114.5	111.6	117.9
II-0	100	100	100
IIG30	106	105.7	108.9
IIG50	48.2	75.1	85.6
IIG70	39	46.2	47.4
IIGG30	158	150.8	156.9
IIGG50	140.2	128.7	147.5
IIGG70	117.7	110.5	118.9

Figure 2. Effect of the replacement levels of the by-product materials on the strength of foam concrete at the age of 28 days.



For the comparison between the performance of both GBS and GGBS in foam concrete, Table 10 lists the ratio of strength at the age of 28 days for mixes containing GBS and their corresponding GGBS mixes. In both series, GGBS foam concrete mixes exhibit higher compressive strengths than GBS mixes at the same replacement levels. This condition can be attributed to the higher level of fineness of GGBS as compared with that of GBS. As the fineness level increases the reactivity of the material, the area reacting with calcium hydroxide and the output of CSH both increase as well (Siddique & Bennacer, 2012; Tan, De Schutter, Ye, Gao, & Machiels, 2014). The strength ratio of the mixes containing 30% GBS replacement levels were 81 and 70% for Series I and II, respectively. However, increasing the replacement level of GBS decreased the strength ratio, because increasing its replacement level negatively affected the strength in contrast to that of GGBS.

Table 10. Ratio of strength at the age of 28 days for mixes containing GBS and their corresponding GGBS mixes

Replacement level (%)	Series I	Series II
30	0.81	0.70
50	0.64	0.58
70	0.43	0.42

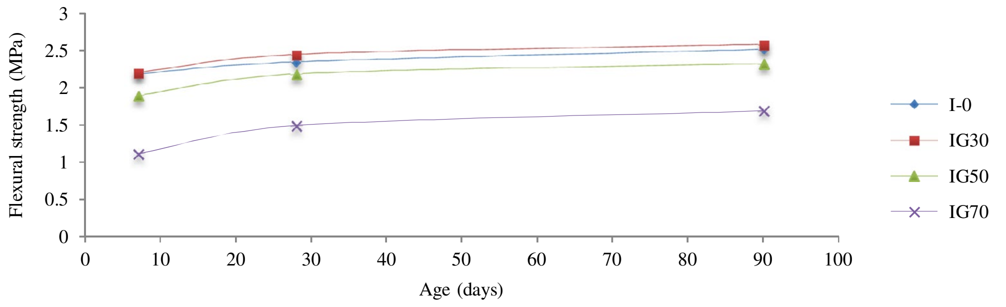


Figure 3. Flexural strength as a function of age for GBS foam concrete mixes in Series I.

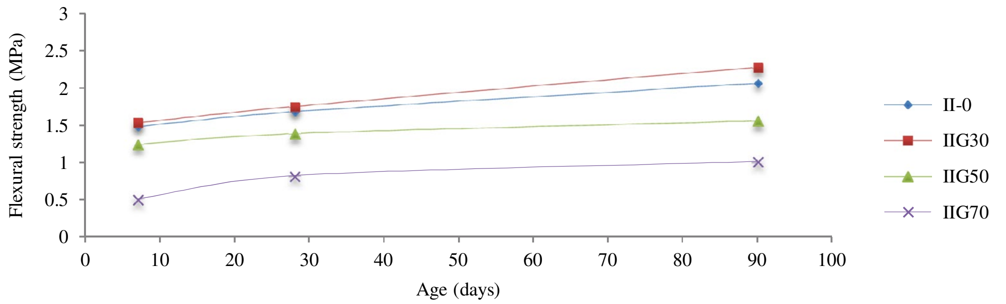


Figure 4. Flexural strength as a function of age for GBS foam concrete mixes in Series II.

3.3. Flexural strength

The results on flexural strength shown in Figures 3 and 4 have the same trend as those on compressive strength. All of the mixes in both series showed strength developments with age. The increase in filler-to-binder ratio affected the flexural strengths regardless of replacement level or the type of the by-products materials. The increase in sand content reduced the flexural strengths of the foam concrete mixes. Therefore, mixes in Series I exhibit the highest flexural strengths in comparison with the other series, which exhibited higher sand content counterparts. This condition can be attributed to the increased binder quantity, which creates a stronger paste. In addition, the reduction in sand content increases the amount of paste surrounding the sand particle; hence, increasing the flexural required the breaking of the prism (Hamidah et al., 2005; Wimpenny, 2006).

Mixes with 30% replacement levels of the weight of the binder showed higher flexural strengths than those of the control mix at all ages. This condition can be attributed to the higher paste content due to the decrease of foam quantity, thereby reducing the amount of water due to the morphology of the GBS particles and increasing the PS-1 dose, resulting in the reduction of the micropores in the paste and to the sufficient amount of cement with the aid of the GBS replacement level that acts as a pozzolanic material. However, the increase in GBS content beyond the 30% replacement level decreased the flexural strength. Increasing the GBS content will reduce the amount of fine particles in the paste, thereby resulting in an increase of course materials and a decrease in the actual amount of paste. This condition results in a reduction of the samples' flexural capacity.

Foam concrete mixes with GGBS in both series showed that the 30% GGBS replacement level exhibited the highest flexural strength as compared with the other mixes. The increase in paste volume, the addition of PS-1, the sufficient amount of cement, and the high reactivity of the GGBS particles are all reasons that could explain the increase in flexural strength. Increasing the GGBS content beyond 30% reduced the flexural strength as compared with that of the mix with 30% GGBS.

As mentioned earlier, the flexural strength followed the same trend as that of the compressive strength. This condition indicates the existence of a relationship between flexural strength and its corresponding compressive strength. Figure 5 plots the flexural strength at the age of 28 days as a function of their corresponding compressive strength for mixes with GBS and GGBS replacements.

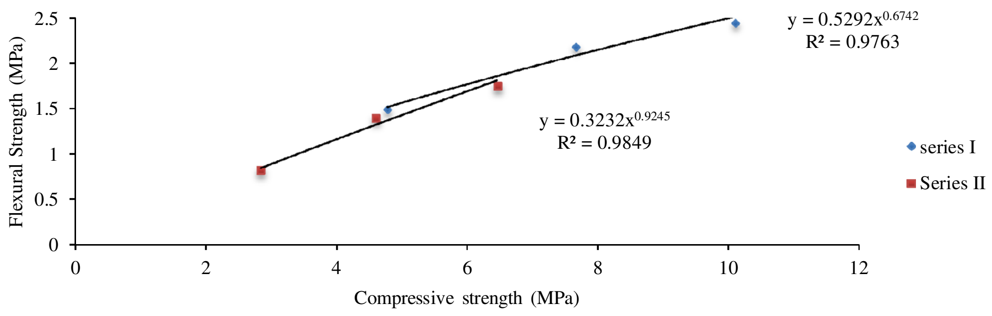


Figure 5. Flexural strength at the age of 28 days as a function of its corresponding compressive strength for GBS mixes in the two series.

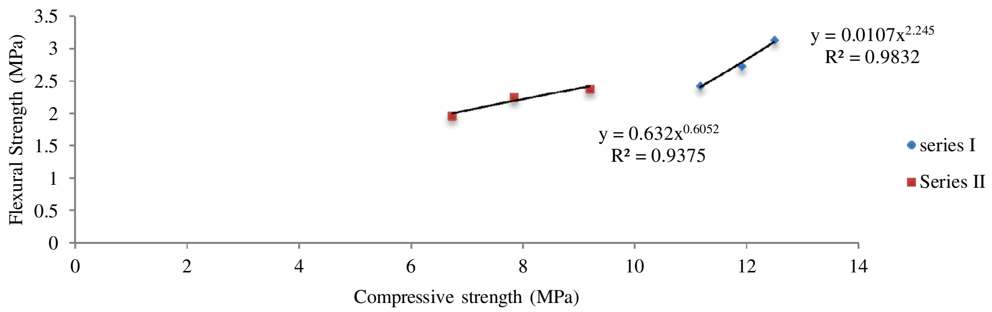


Figure 6. Flexural strength at the age of 28 days as a function of its corresponding compressive strength for GGBS mixes in the two series.

For the two series with GBS content, the best-fit relationships were found to be power correlations with R^2 values ranging from 0.976–0.985. Figure 6 also shows that the best-fit correlation between the flexural and compressive strengths for the mixes with GGBS were found to be power relationships with R^2 values ranging from 0.937–0.983.

3.4. Splitting tensile strength

As shown in Figures 7 and 8, increasing the filler-to-binder ratio, regardless of the replacement level or the type of replacement, decreased the splitting tensile strength. Therefore, the splitting tensile strength follows the same trend as the compressive strength and flexural strength with respect to

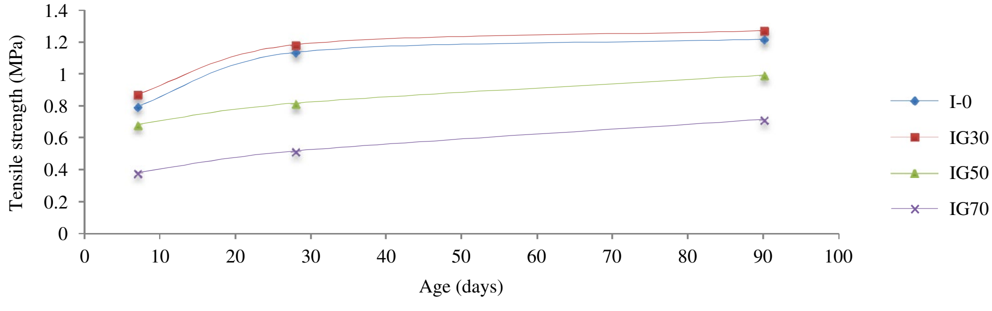


Figure 7. Splitting tensile strength of GBS foam concrete for Series I as a function of age.

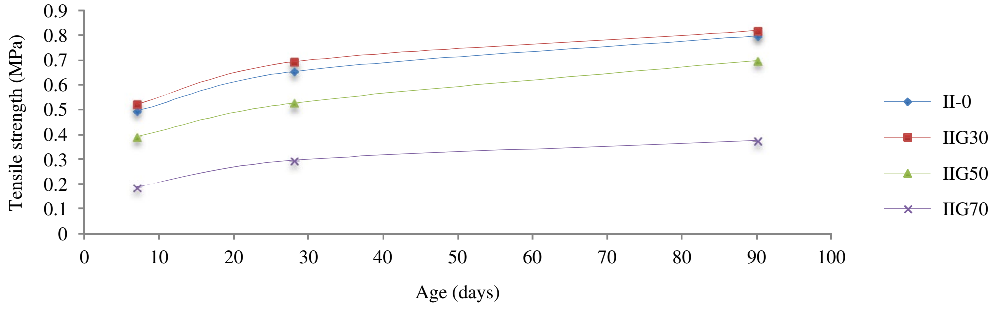


Figure 8. Splitting tensile strength of GBS foam concrete for Series II as a function of age.

the effect of filler-to-binder ratio. GBS foam concrete mixes for any given series showed a decrease in splitting tensile strength with increasing GBS content beyond 30% of the weight of the binder. Similar to the compressive strength, mixes with 30% GBS replacement levels showed higher splitting tensile strengths than the control mix at all ages. This condition can be explained by the reason attributed to the compressive strength. The lower foam content increased the paste volume, the lower water content decreased the micropores within the paste, and the sufficient amount of cement enabled the mix to ensure a complete hydration process and pozzolanic reaction to produce a stronger and denser paste that requires more force to be split in half.

The figures illustrate that all of the mixes exhibited increased splitting tensile strengths with age. For the control mixes, the increase of strength with age is due to the hydration process that results in the creation of calcium hydroxide ($Ca(OH)_2$) and CSH, thereby creating a denser paste with age. For any given series, GBS and GGBS mixes showed higher splitting tensile strengths than the control mix regardless of age and replacement level. Mixes with 30% GGBS replacement levels showed splitting tensile strengths higher than other mixes. Increasing the replacement level to 50 and 70% lowered the splitting tensile strengths as compared with the mixes with 30% GGBS replacement levels. The results show that all of the mixes with GGBS replacements increased with age. This increase in tensile strength can be attributed to the pozzolanic reaction, which takes place in the paste of the foam concrete mix. GGBS is highly reactive; therefore, when the hydration process has completed its reaction, the pozzolanic reaction occurs between the calcium silicates (C_2S) and the $Ca(OH)_2$, thus increasing the amount of CSH produced in the paste. The additional CSH produced by the pozzolanic reaction increases the density of the paste and reduces the micropores within it, thus creating a stronger paste. The samples' relationships between their splitting tensile strength and compressive strength at the age of 28 days are shown in Figures 9 and 10 for GBS and GGBS mixes in Series I and II, respectively.

The formulae showing that the relationships for the GBS and GGBS samples express a power-type correlation, which achieved R^2 values of 0.964 and 0.992. These high values show that a strong correlation exists between the tested parameters. The power-type correlation is consistent with that in the study of Jones and McCarthy (2005c) that similarly showed a power-type correlation.

Figure 9. Splitting tensile strength at the age of 28 days as a function of corresponding compressive strength for GBS mixes in the two series.

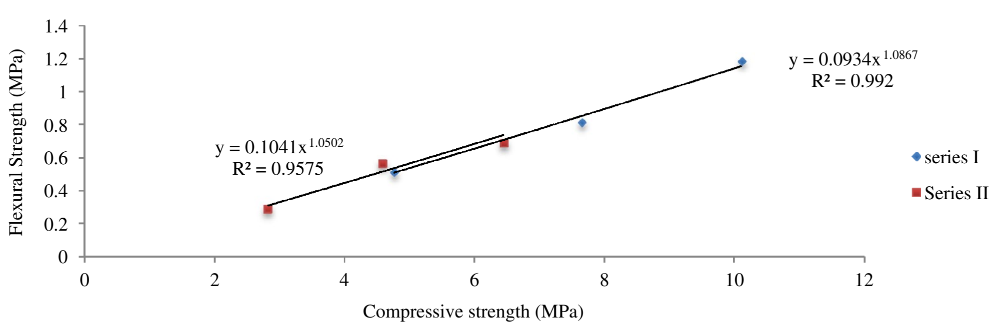
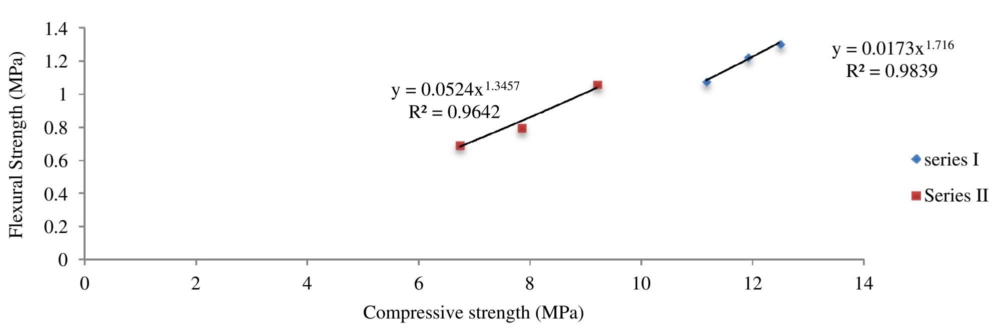


Figure 10. Splitting tensile strength at the age of 28 days as a function of corresponding compressive strength for GGBS mixes in the two series.



4. Conclusion

The feasibility of utilization of GBS as replacement of cement for making a foamed concrete mixes has been investigated in the present study. GBS as a replacement for cement for the production of foam concrete without undergoing grounding process exhibited a good potential in terms of saving energy and cost. Moreover, the utilization of GBS for the production of foam concrete was shown to be more environmental friendly than conventional concrete. The fresh properties of GBS foam concrete mixes showed superior values in terms of consistency and stability, which demonstrated consistency. For each given series, GBS mixes required a lower amount of foam as compared with control and GGBS mixes at the same replacement level. In addition, the amount of foam decreased as the replacement level increased. All of the mixes gained strength with age, and the strength decreased with the increase in filler ratio. GBS foam concrete mix with 30% replacement level showed higher strength than the control mix in both series at all ages. However, beyond that level, the strength declined as the GBS level increased. In both series, GGBS foam concrete mixes recorded higher strength than the control and GBS foam concrete mixes due to GGBS fineness. Mixes IG30 and IIG30 had compressive strength ratios of 81 and 70%, respectively, with respect to their corresponding mixes with GGBS (IGG30 and IIGG30) at the age of 28 days. This research provides evidence that GBS can be a good replacement for cement in the production of foam concrete. The utilization of GBS without a grinding process is made possible with the help of a superplasticiser dose to reduce the water demand of the mix. Such incorporation will not only reduce the cost of foamed concrete but will also enhance the possibility of utilising unground GBS in the production of concrete.

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Author details
Hanizam Awang[1]
E-mail: hanizam@usm.my
ORCID ID: http://orcid.org/0000-0003-1070-9534
Zaid Shaker Aljoumaily[2]
E-mail: zaid.aljoumaily@gmail.com
ORCID ID: http://orcid.org/0000-0001-7618-3841
[1] School of Housing, Building, and Planning, Universiti Sains Malaysia, 11800 Gelugor, Penang, Malaysia.
[2] Union Company for Precasting Concrete Technology, No. 15, Street 18, District 635, Alkhadraa, Baghdad, Iraq.

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