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IJSCET

http://publisher.uthm.edu.my/ojs/index.php/ijscet

ISSN : 2180-3242 e-ISSN : 2600-7959

International Journal of Sustainable Construction Engineering and Technology

Influence of Ground Granulated Blast Furnace Slag (GGBS) as Cement Replacement on the Properties of Sand Cement Brick

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DOI: https://doi.org/10.30880/ijscet.2022.13.04.029
Received 15 August 2022; Accepted 31 October 2022; Available online 13 November 2022

Abstract: Carbon dioxide (CO_2) emissions from cement manufacturing contribute significantly to greenhouse gases. However, cement manufacture is necessary since a vast number of bricks are required to satisfy residential housing demand. Considering this crucial environmental impact, cement is encouraged to form futuristic civilizations. Cement replacement is ideally a good proposition to produce green and sustainable sand cement brick to reduce CO_2 emissions. This study investigates the influence of Ground Granulated Blast Furnace Slag (GGBS) as a partial cement replacement of sand cement brick. The percentages replacement of GGBS are 0%, 10%, 20%, 30%, 40%, 50% and 60% by mass of the cement with mix design ratio of 1:3 and 0.6 water cement ratio. All the bricks were curing up to 90 days. The water absorption test and compressive strength of bricks were also carried out for its durability and mechanical properties. The experimental results indicate that the 20% of GGBS as replacement of cement in sand cement brick gives better performance than conventional brick in terms of compressive strength and water absorption after curing of 56 days.

Keywords: Cement brick, carbon dioxide, GGBS, density, particle size, water absorption, compressive strength, durability

1. Introduction

Cement is characterized among building materials in emitting a massive amount of greenhouse gases as a result of developing economies, which exceeds 10 billion metric tons each year (Belaid, 2022). There are two major sources of CO_2 emissions in cement manufacture. The first component is the chemical process related with the creation of clinker, which occurs when carbonates ($CaCO_3$) are degraded by heat into oxides (CaO) and CO_2. The second category of CO_2 emissions is the burning of fossil fuels to create the energy necessary to supply the raw materials (Dawood et al., 2021). Consumption of cement is predicted to rise, particularly in emerging nations due to rare metal deposits, such as lanthanum and yttrium, are predicted to deplete (Geng et al., 2019). This situation necessitates a more sensible and efficient use of resources. Bricks are essential components of our contemporary civilization. They are the most often used building materials due to its vast accessibility, excellent workability, long-lasting durability and adaptability (Cao & Masanet, 2021). Extensive usage and manufacturing of cement bricks, mostly due to rising infrastructure and household demands. Simultaneously, conventional brick making methods are not environmentally beneficial due to significant CO_2 emission at stages of production. There are two common bricks used in the construction of houses, buildings, and other structures

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such as clay brick and sand cement brick. The clay brick is manufactured from clay and burnt at a high temperature, whereas sand cement brick is made from cement, sand, and water. The clay bricks are red, meanwhile the sand bricks are white. The clay bricks have a higher compressive strength than sand cement bricks. The sand cement bricks are convenient, lower expensive, provide less maintenance and abundant (Sani & Muftah, 2012). In essence, massive cement and brick plants may lead to substantial air pollution, environmental issues and excessive noise.

According to the Malaysian Iron and Steel Federation (MISF), the country's steel consumption climbed by roughly 24% in 2010 to 8.2 million tones resulted various solid waste generated such as slag, sludge and dust (Ismail et al., 2010). These wastes comprise substantial amounts of heavy metals and radioactive elements, which might emit greenhouse gases (Clemens, 2001). One of the main process approaches for iron and steel manufacturing is through reduction of iron ore mainly via the blast furnace. Pig iron is made from sintered, whereas made from ore, dolomite, coke and recycled dust. The sinters are burned with gas until the combustion zone reaches 1400C, and a multi-step dry cleaning operation is used, with a substantial proportion of the dust particles recycled into the sinter procedure. Only the dust from the last cleaning stage is discarded which is classifies as blast furnace slag (Khater & Bakr, 2011). Blast furnace slag required quenching process which is called granulation and the product is Ground Granulated Blast Furnace Slag (GGBS). GGBS has been used as mineral admixture, mostly as component of blended cement, called slag cements. More than 85% of the slags produced is used as a construction material for roads, raw material for cement, fertilizer and as a soil stabilizer. GGBS is accepted mineral admixture for use in concrete due to its glassy nature and chemical composition which make it pozzolanic and a cementitious material. However, the hydraulic reactivity of GGBS depends upon processing conditions, chemical composition and particle characteristics. Slowly cooled highly crystalline slags are unreactive and are not marketed as cementitious materials (Ramachandran, 1997).

In continuity, GGBS can be utilized as a cement replacement to produce green and sustainable sand cement brick and concrete as an alternative to overcome waste disposal issues and decrease the extraction of natural raw materials. Several researchers (Phul et al,. 2019) have been conducted study towards GGBS as a cement or sand replacement in brick and concrete production. It was found that the combination of GGBS and Ordinary Portland Cement (OPC) as cement replacement has a potential to produce excellent binding characteristics and improved durability. GGBS possesses the same chemical characteristics as cement but less reactive than OPC. GGBS hydrates when water is added, exactly like OPC, and is most used in conjunction with OPC, generally in the range of 40% to 60% replacement of GGBS, depending on the requirements. Concrete workability increases with increasing replacement percentage of GGBS up to an optimal limit. The optimal workability was found at a replacement percentage of 15%, compared to a control rate of 30%. Concrete with a 30% substitution of cement with GGBS and Fly Ash had a higher compressive strength of than the control sample.

The results reveal by Li & Zhou (2003), the combination of GGBS and Fly Ash (FA) has outstanding behavior in both short and long term compressive strengths, as well as resistance to H_2SO_4 attack. Although the FA sample has a high long-term strength, its early-age strength is poor. The control sample which contains zero GGBS and FA has the lowest long-term compressive strength and is vulnerable to H_2SO_4 attack. FA and GGBS both have a larger modulus than FA alone. As a result, the hydration rate of cementitious materials in the combination is higher than in high volume of FA only, resulting in increased early-age strength. The three-day cube strength of concrete with GGBS with a fineness of 1200 m^2/kg is the same as that of the control sample. GGBS has combines with Portland cement's hydrated lime (CH) to generate a secondary calcium silicate compound. Simultaneously, several homogenous hydration products, such as ettringite and CH which have a greater specific surface than Portland cement.

Hydrated cement paste is composed of roughly 70% C-S-H, 20% $Ca(OH)_2$, 7% sulfur-aluminates, and 3% secondary phases. Because it is partially soluble in water and lacks sufficient strength, the $Ca(OH)_2$ formed as a result of chemical reactions degrades the quality of the concrete by generating voids. The utilization of GGBS improves the binding of $Ca(OH)_2$. Hydration products, such as C-S-H gel, are generated at the end of the slag and $Ca(OH)_2$ reaction (Papadakis & Tsimas, 2002). The early age strength values of GGBS concrete mixes are found to be lower than those of the control mixtures. The strength values of GGBS concrete blends develop more than the control mixtures when the curing period is prolonged. Oner & Akyuz (2007) reveal that GGBS concrete blends have greater strength values than the control mixtures with the same binder amount after 1 year. Since the pozzolanic process is sluggish and reliant on the presence of calcium hydroxide, the strength development for GGBS concrete takes longer. The chemical reaction of Portland cement is classified as follows:

$$\text{Cement } (C_3S, C_2S) + H_2O\ (H) = \text{CSH–gel} + Ca\ (OH)_2\ (CH) \quad (1)$$

While the pozzolanic reaction is:

$$Ca\ (OH)_2\ (CH) + SiO_2\ (S) + H_2O\ (H) = \text{CSH–gel} \quad (2)$$

Hence, this research will be analyzed the influence of the properties of GGBS as a cement replacement in sand cement brick.

2. Experimental Program

2.1 Material

The materials required to produce sand cement bricks are Ordinary Portland cement, Ground Granulated Blast Furnace Slag (GGBS), sand and water.

2.1.1 Ordinary Portland Cement (OPC)

The OPC used in this experimental work is compliant with the Malaysian Standard Specification MS 522: Part 1:2003. OPC shall be obtained by pulverizing clinker, consisting mostly of calcium silicates. The cement is kept under weather-proof and well-ventilated building to protect the cement from dampness.

2.1.2 Ground Granulated Blast Furnace Slag (GGBS)

The metallurgical industry produces slag as by-products. Blast furnace slag is the major non-metallic product consisting of silicates and aluminosilicates of calcium. They are formed either in glassy texture used as a cementitious material or in crystalline form which is used as an aggregate. GGBS is originally white in color powder as shown in Figure 1. GGBS was supplied by the industrial company of YTL Cement Marketing Sdn. Bhd. at Pasir Gudang, Johor, which is ready to be used as the cement replacement in brick.

Fig. 1 - Ground Granulated Blast Furnace Slag (GGBS)

2.1.3 Material Characterization of OPC and GGBS

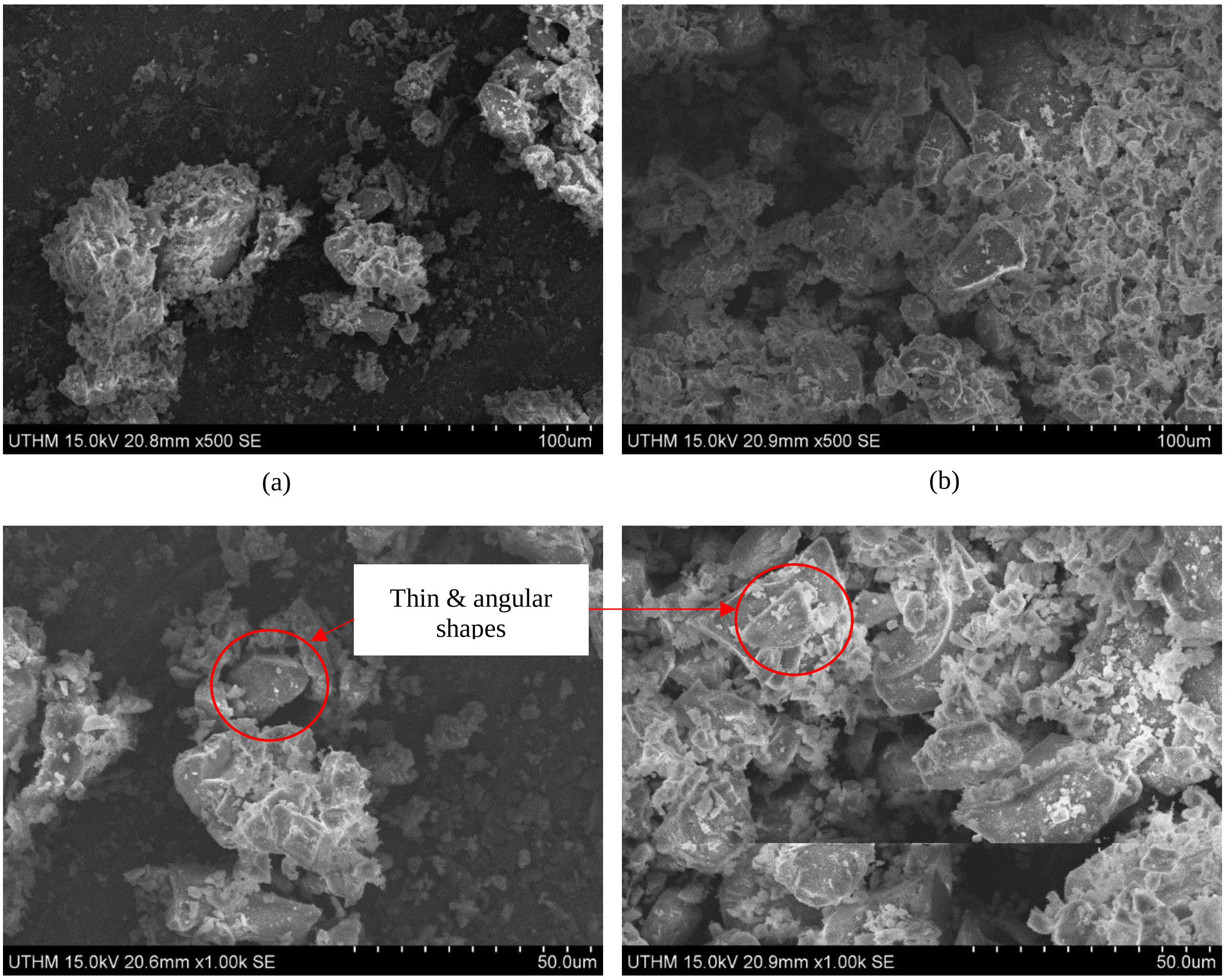
The material characterization of OPC and GGBS were categorized by specific gravity (SG), particle size distribution (PSD) and scanning electron microscopy (SEM). It is important to analyze the properties of GGBS to identify its possibilities to be replaced as cement. The SG and PSD results of OPC and GGBS were tabulated in Table 1. Specific gravity is the ratio of a material's density with the water that test has been carried out according to ASTM C 188. The SG of OPC is lower than GGBS which are 2.87 and 2.54 respectively. Therefore, when the SG is lower, the density of materials also decreases which can minimize the weight of the sample. In addition, the weight of brick plays a vital role because it will increase the stress of the foundation to support the bricks.

The particle size distribution of OPC and GGBS were obtained by using particle size analyzer CILAS 1180 liquid. The particles size of OPC and GGBS range from 2.89 µm to 18.85 µm and 1.32 µm to 9.78 µm respectively. The fineness of GGBS is a major factor affecting the strength of mortars and concrete. Granulated slags can be ground to a desired particle size or surface area, depending on the degree of activation needed and economic considerations. It is reported that GGBS particles less than10 µm contribute to an early strength development up to 28 days while particles in the range of 10-45 µm continue to hydrate beyond 28 days and contribute to later-age strength. Larger particles greater than 45 µm show little or no activity (Ramezanianpour, 2014).

Table 1 - The specific gravity and particle size of OPC and GGBS

Materials	Specific Gravity	Particle size distribution (µm)
OPC	2.87	2.89 to 18.85
GGBS	2.54	1.32 to 9.78

In order to determine the composition between OPC and GGBS, scanning electron microscopy (SEM) was conducted. The SEM provides detailed high-resolution images of the material by restoring a focused electron beam across the surface and detecting secondary or backscattered electron signal. Two different magnifications of the SEM image of 500X and 1000X were analyzed as shown in Figure 2(a), (b), (c) and (d). It is observed that the surface structure of OPC and GGBS are nearly same which have thin particles and angular shapes resulted in porous structure. When the GGBS particles blended with cement, the angular particles appear to interlock with small particles either by hydraulic reactivity, physical or chemical reaction.



(a) (b) (c) (d)

Fig. 2 - Scanning electron micrograph image with different magnifications (a) OPC at 500X; (b) GGBS at 500X; (c) OPC at 1000X and; (d) GGBS at 1000X

2.1.4 Sand

Natural sand used in this study is complying to Standard Specification for Aggregate for Masonry Mortar (ASTM C144-11). The sand should not have more than 50% retained between any two consecutive sieves nor more than 25% between 300µm and the 150µm sieve. Figure 3 shows the sieve analysis result for the sand. The graph shows that the percentage passing of sand is in range between lower and upper limit. The percentage of sand retained between 300µm and the 150µm sieve is 8.5% which is <25%. Therefore, the sand is suitable for sand cement brick production.

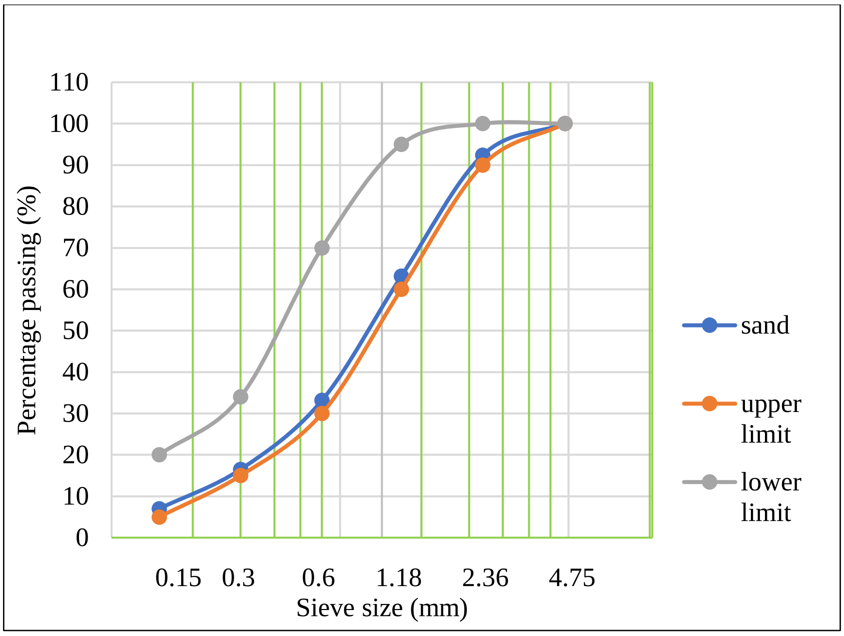


Fig. 3 - Sieve analysis result of sand

2.2 Sand Cement Brick Mix Design

The size of sand cement brick is 215 mm x 103 mm x 65 mm. The mix design was calculated according to the target density of brick about 1800 kg/m^3 and the design mix ratio of cement and sand is 1:3 as shown in Table 2.

Table 2 - Design mix for the sand cement brick production

Design mix ratio	Water cement ratio (w/c)	Volume of brick (m^3)	Target density of brick (kg/m^3)
1:3	0.6	1.439 x 10^{-3}	1800

2.3 Sample Preparation

There are two groups of brick samples which are control and GGBS+OPC as shown in Table 3. The control bricks were consisted of 100% OPC. The percentages replacement of cement with GGBS are 10% up to 60% which are identified with GGBS-10 to GGBS-60. The bricks were tested on 7 days since the cementitious reach around 70% of its total strength. The bricks harden over time and continuously tested at the end of 28, 56 and 90 days due to long term hydration effects. The GGBS can hydrate more CSH gel in a long period which is able to gain more strength. CSH is the adhesive that provides strength and binds particles together.

Table 3 - Percentage of cement replacement

Group	Sample ID	Cement (%)	GGBS (%)
Control	Control	100	0
GGBS+OPC	GGBS-10	90	10
	GGBS-20	80	20
	GGBS-30	70	30
	GGBS-40	60	40
	GGBS-50	50	50
	GGBS-60	40	60

Figure 4 shows the process of sand cement brick production. First, sand was sieved with the aperture sizes of 4.75 mm, 2.36 mm, 1.18 mm, 600 µm, 150 µm and 75 µm according to BS 812 103-1. The s-curve for the sieve analysis test mixer. The additional of 10% extra for each weight materials are required because some of the materials can be attached to the inner parts of the concrete mixer. The mixture was placed in the greased brick mold within a total elapsed time of not more than 2 min and 3 s after completion of the early mixing of the mortar. Each of the bricks were compacted through a tamping bar of total 32 times according to ASTM C109/C109M – 16a. The compaction process is important to remove the air voids which occur in the freshly mixed mortar thus, enhances the mortar bonding between the materials. The bricks were covered with wet sacks to maintain moist surface, immediately upon completion of molding. The bricks were demolded in the range of 24 to 72 hours and labelled according to brick IDs. All the bricks were left for curing process in curing tank for 7 days, 28 days, 56 days and 90 days.

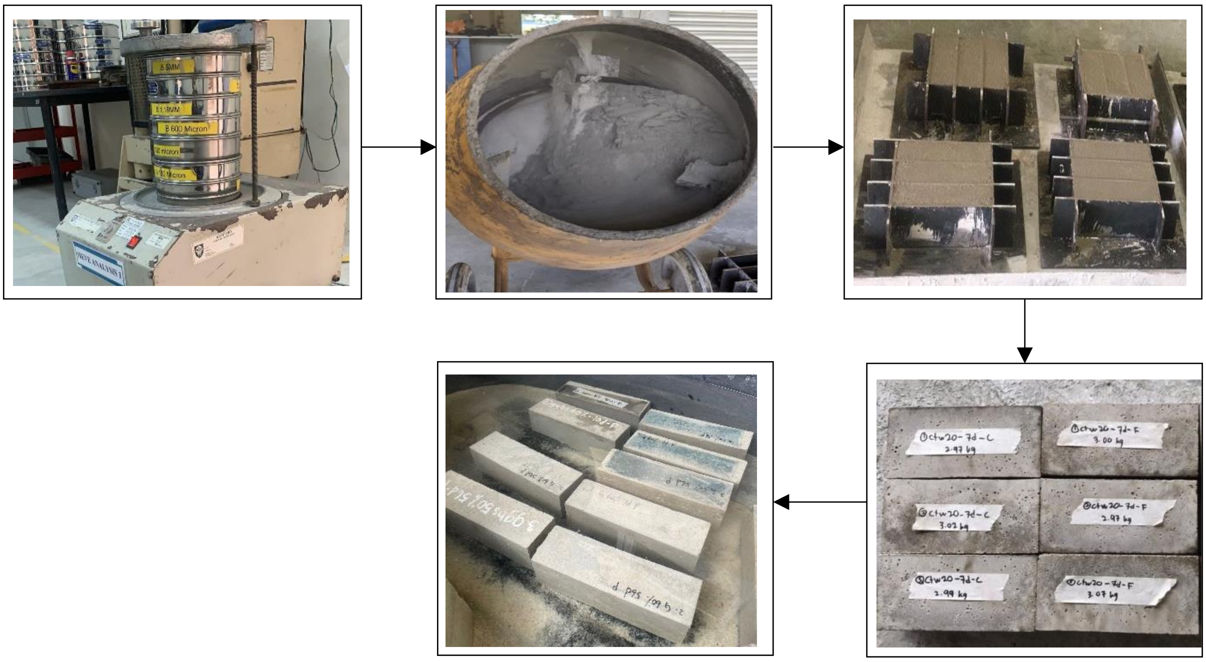


Fig. 4 - The process of sand cement brick production

2.4 Testing Methods

The bricks were measured on density, compressive strength and water absorption.

2.4.1 Density

The density of bricks was measured by dividing the weight of brick by the volume of brick which is 1.439 x 10^{-3} m^3. As mentioned in ASTM C55, the density of brick was divided into three categories which are lightweight, medium weight and normal weight. The brick with less than 1680 kg/m^3 is lightweight, 1680 to 2000 kg/m^3 is medium weight and 2000 kg/m^3 or more is normal weight.

2.4.2 Compressive Strength

The testing machine for the compression test has been attached with spherical upper platen at the center of the upper head of the machine while the below of the samples has been placed above the hardened metal plate to ensure the gap from the plane surfaces by not more than 0.025 mm. Table 3 shows the minimum compressive strength of brick according to ASTM C55. Figure 5 shows the compressive strength test of brick.

Table 4 - Minimum compressive strength of brick according to ASTM C55

Compressive strength, min, (MPa)		
Type	**Average of 3 units**	**Individual unit**
For general use with moderate strength	17.3	13.8

Fig. 5 - Compressive strength testing of brick

2.4.3 Water Absorption

The maximum water absorption requirement for sand cement brick is shown in Table 4. The bricks were immersed in water for 24 to 28 hours such that the top surfaces of the bricks are at least 150 mm below the surface of the water while 3 mm separated from the bottom of the curing tank by using wire mesh. After that, the bricks have been placed in oven for 26 hours as shown in Figure 6 according to ASTM C140/C140M-17a. The percentage of water absorption has been calculated as an equation below:

$$\text{Absorption, } \% = [(w_s - w_d)/w_d] \times 100 \quad (3)$$

w_s = saturated weight of specimen (kg)
w_d = oven-dry weight of specimen (kg)

Table 5 - Maximum of water absorption for individual brick according to ASTM C55

Water Absorption, max, (%)		
Lightweight less than 1680 kg/m^3	**Medium Weight less than 2000 to 1680 kg/m^3**	**Normal weight less than 2000 kg/m^3 or more**
18	15	13

Fig. 6 - The bricks were placed in oven to measure the oven-dry weight

3. Results and Discussion

The performance of sand cement brick containing different percentages of GGBS was analyzed and discussed

3.1 Density

The density of control bricks ranges from 1900 to 2010 kg/m^3 while the density of GGBS+OPC bricks ranges from 1890 to 2010 kg/m^3. The bricks are categorized as medium weight and normal weight brick according to ASTM C55.

3.2 Compressive Strength

Figures 7, 8, 9 and 10 show the compressive strength of the sand cement bricks with 0% to 60% replacement of GGBS at 7, 28, 56 and 90 days of curing respectively. The compressive strength of control bricks increased nearly up to 90 days except on 56 days which is the compressive strength decrease 7.55% from 28 days of curing. Therefore, the compressive strength of control bricks can reach up to 51.1 MPa.

The different percentage replacement of GGBS resulted in different strength of bricks. The compressive strength of GGBS-10 is continually increased in the last 7 days up t0 90 days and recorded higher strength compared to control bricks. The compressive strength of GGBS-20 shows to be decreasing on 7 and 28 days while started to gain back the strength on 56 and 90 days. The compressive strength of GGBS-30, GGBS-40 and GGBS-50 shows lower than control bricks at early stages, while the strength increased starting on 28 to 90 days. The compressive strength of GGBS-60 also lower than control bricks at early age, but the strength gained on 28 and 56 days while the compressive strength on 90 days became worst which is 24.1 MPa. The results shown that GGBS-20 recorded the highest strength at the end of 56 days among the other bricks which is 60.9 MPa. The early strength of brick containing GGBS up to 50% is attributed to the fineness of clinker particles while the later strengths are mainly due to the fineness of GGBS particles. Investigation has been reported on supplementary cementitious materials found that particle size distributions influence the matrix's interlocking behavior and friction resistance, which has a significant impact on the compressive strength and durability resistance of the cured specimens (Chengula & Middendorf, 2018).

However, the compressive strength of GGBS+OPC bricks show that the strength increased at the later age of curing. This is because the hydration of OPC is caused by the massive formation of portlandite crystal [$Ca(OH)_2$] and amorphous calcium silicate hydrate gel [$C_3S_2H_3$] (C-S-H). Since $Ca(OH)_2$ is partially soluble in water and lacks sufficient strength, it degrades the quality of the concrete by producing voids. The use of GGBS improves $Ca(OH)_2$ compound binding. Hydration products such as C-S-H gel are generated at the end of the slag and $Ca(OH)_2$ reaction. CSH is the adhesive that provides strength and binds the structure together (Oner & Akyuz, 2007).

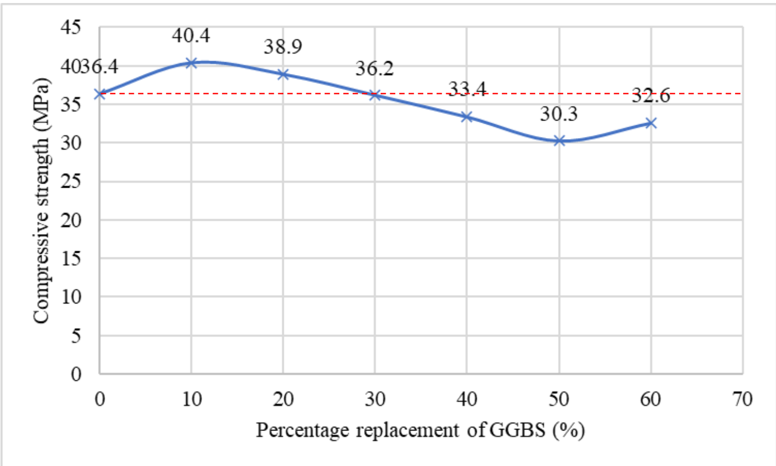


Fig. 7 - The compressive strength of brick on 7 days

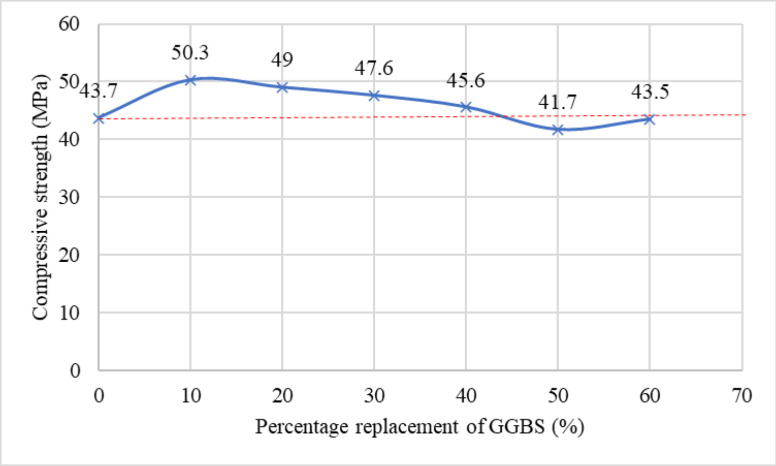


Fig. 8 - The compressive strength of brick on 28 days

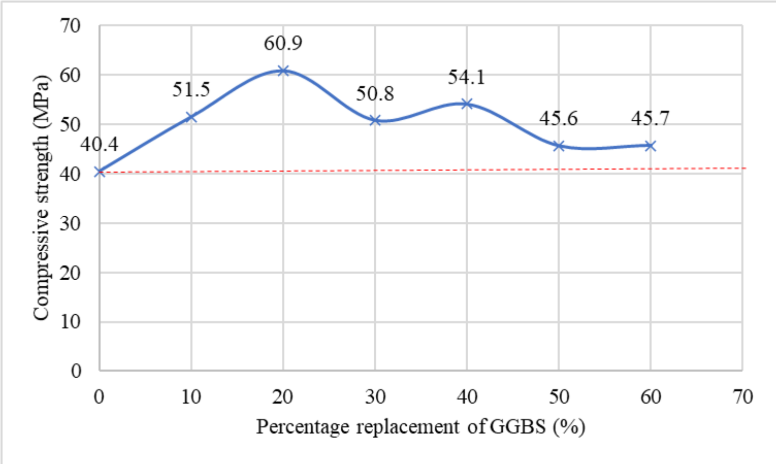


Fig. 9 - The compressive strength of brick on 56 days

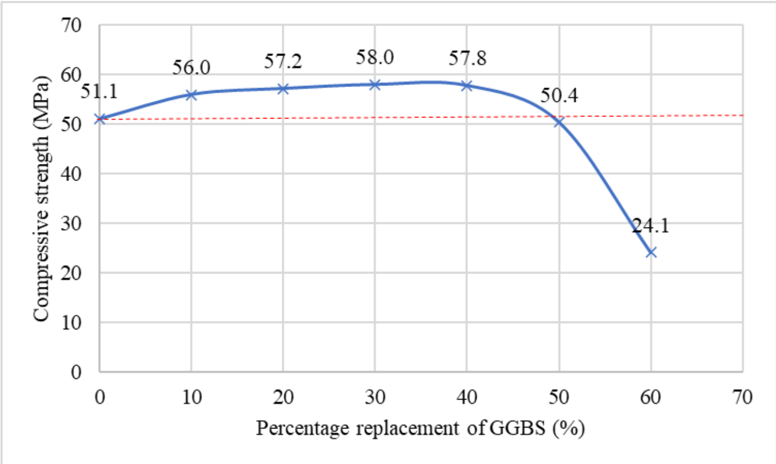


Fig. 10 - The compressive strength of brick on 90 days

3.3 Water Absorption

Figures 11, 12, 13 and 14 show the percentage of water absorption of the sand cement bricks with 0% to 60% replacement of GGBS at 7, 28, 56 and 90 days of curing respectively. Control bricks tend to absorb more water among the others especially on 7 days which is 10.95% while it decreases on 28 days. The percentage of water absorption of control bricks is closed to 13% which is closed to maximum allowable of water absorption according to ASTM C55.

The percentage absorption of GGBS-10, GGBS-20, GGBS-30, GGBS-40 and GGBS-60 is decreased at the early age and at the end of 90 days. The bricks with a lower replacement of GGBS resulted in lower water absorption. The minimum water absorption was recorded as 3.11 % with 40 % of GGBS at 90 days curing while the highest water absorption was observed in control brick which is 10.95 %. These are due to the surface characteristics of the GGBS particles having smooth dense surfaces which also tend to increase the workability of mortar mix. The effect of GGBS on workability of mortar is commonly related to the changes they cause in water demand of the mixture. The decrease in the water demand is due to the lower particle size distribution of GGBS compared to OPC.

At early ages of reaction, the porosity of GGBS is similar to that of OPC. Meanwhile, at longer ages and after reaction of the GGBS, the volume of very small pores in the nano scale range becomes larger. It has been reported that the combination of GGBS in cement paste has transformed the large pores in the paste into smaller pores. The amount of calcium hydroxide in the GGBS is lower and this can affect the deficiency of the interface. Pores in the cement paste that normally contain calcium hydroxide are partly filled with calcium silicates hydrates resulting from the hydration of the GGBS and change the total porosity and pore size distribution (Ramezanianpour, 2014).

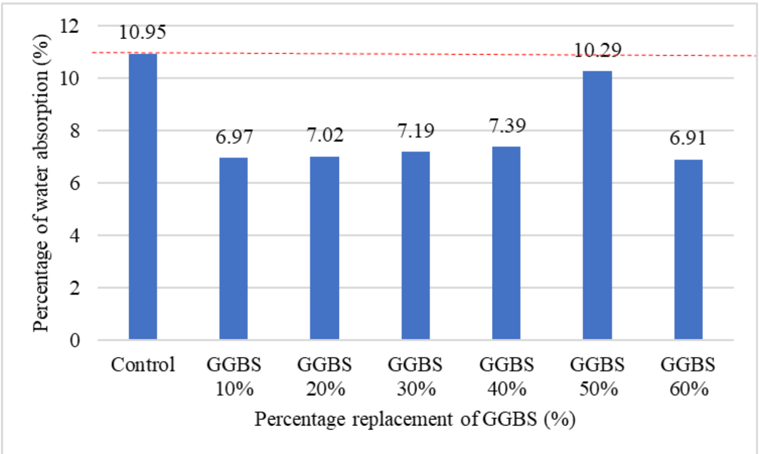


Fig. 11 - The percentage of water absorption of bricks on 7 days

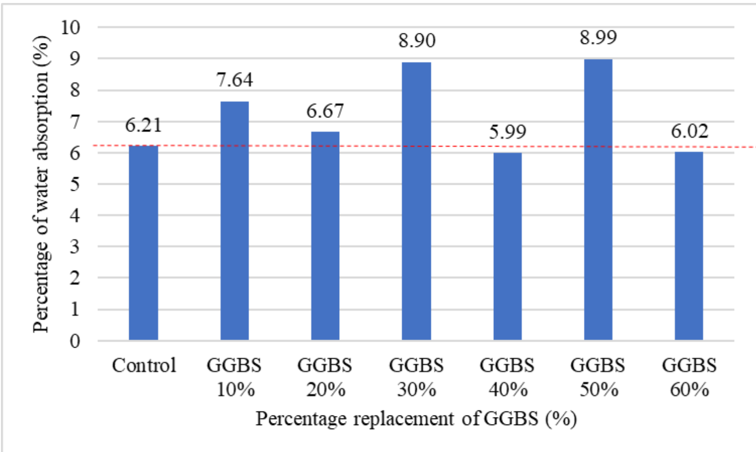


Fig. 12 - The percentage of water absorption of bricks on 28 days

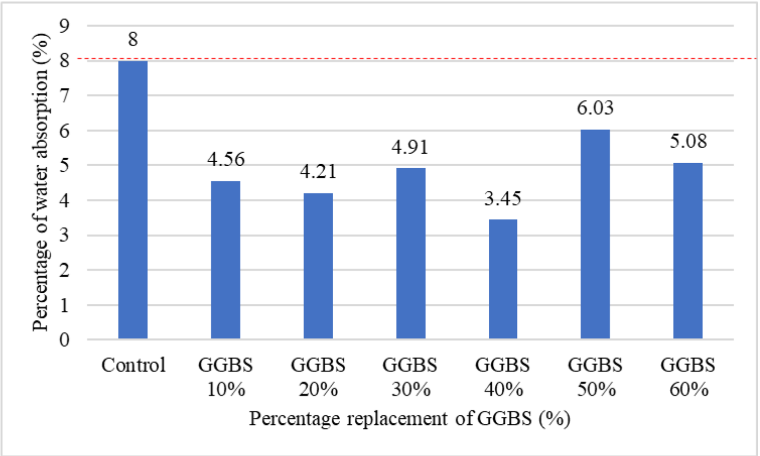


Fig. 13 - The percentage of water absorption of bricks on 56 days

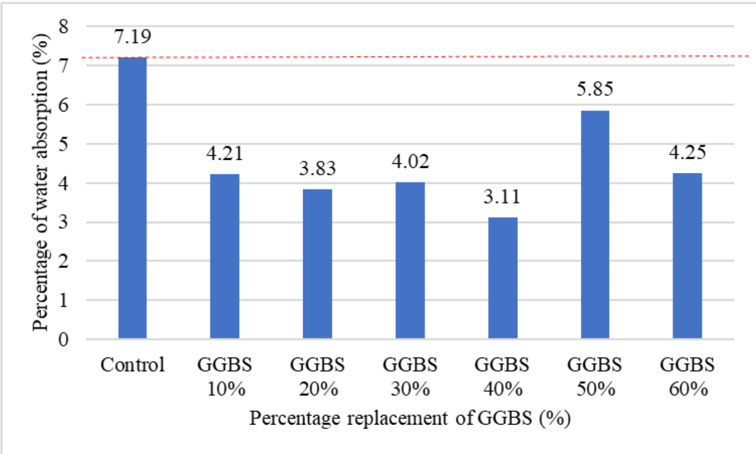


Fig. 14 - The percentage of water absorption of bricks on 90 days

4. Conclusion

- The results of physical properties of GGBS indicate that GGBS is suitable to be used as a partial cement replacement in sand cement brick due to the lower specific gravity, the particle sizes of GGBS also smaller compared to OPC and the particles of GGBS also found in angular form. The uniformly graded particle sizes enhance the flowability of mortars as well as the packing density and compressive strength development of bricks. The angular form of GGBS particles can interlock with small particles when mixed between themselves, which can gain higher strength.
- The density of control and GGBS+OPC bricks is recorded nearly same which is range 1890 to 2010 kg/m^3. The bricks can be used as the construction element in industry as their density is in range of medium weight and normal weight bricks as per ASTM C55.
- The GGBS-10 up to GGBS-60 can be classified as loadbearing brick according to ASTM C90. The GGBS+OPC bricks are potential to be applied on construction of the house without using the frame structure. This study found that the GGBS-20 brick is an optimum percentage as a cement replacement which resulted as the highest compressive strength brick which is 60.9 MPa at 56 days of curing compared to the control brick which is 40 MPa.
- Furthermore, the bricks also followed the maximum water absorption requirements. It indicates that GGBS is significantly suitable for replacing cement in brick production. This smaller microstructure offers GGBS brick substantially lower permeability and contributes significantly to its higher durability.
  It indicates that GGBS is significantly suitable for replacing cement in sand cement brick production. Thus, the usage of OPC can be reduced and help to conserve environment from CO_2 emission which one of the major causes of the greenhouse effect.

Acknowledgement

This research was supported by the Minister of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2020/STG05/UTHM/02/1). I would like to thank to YTL Cement Marketing Sdn. Bhd. for supplying GGBS for this project. I would also like to thank you Dr. Noorwirdawati Binti Ali, Prof. Madya Ts. Dr. Faisal Bin Sheikh Khalid and Dr. Zalipah Binti Jamellodin for their experimental work guidance and brick equipment's.

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