

Effect of Ground Granulated Blast Furnace Slag as Partial Replacement in Fly Ash-Based Geopolymer Concrete

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Abstract. Replacement of Ordinary Portland cement (OPC) with geopolymer concrete (GPC) using fly ash is currently utilized in the construction industry to reduce the excessive carbon footprint. However, fly ash has lower strength development compared to OPC. Due to that reason, ground granulated blast furnace slag (GGBFS) is chosen to be blended with fly ash to produce GPC with improved mechanical strength. The analysis of the mechanical properties includes workability, compressive strength and splitting tensile strength of hardened GPC specimens have been carried out. The specimens were prepared with different percentages of GGBFS, from 0 % up to 20 %, partially replacing the fly ash-based GPC. Experimental results showed that the slump, compressive strength and splitting tensile strength of the GPC increase as the GGBFS percentage increases and found to be suitable for structural application.

1. Introduction

Fly ash is an industrial by-product produced from coal combustion, whereas ground granulated blast furnace slag (GGBFS) produced from the burning of melting iron ore [1]. Those by-products have the potential to be used as cementitious materials in reducing the excessive carbon footprint from Ordinary Portland cement (OPC) manufacturing. Recently, GGBFS is introduced in geopolymer concrete (GPC) to partially replace fly ash-based geopolymer concrete as a substitution for OPC in construction industries. It is one of the ways to reduce OPC manufacturing more effectively by reducing carbon footprint up to 9% [2]. Nowadays, there are millions of tons of those by-products generated and are unutilized or underutilized, leading to environmental issues. It may be caused by storage problem and pollution to the surrounding field [3-4]. Since the environmental problems and health issues have arisen, the concern among researchers to investigate the utilization of such by-products as potential construction materials has been drastically increased [2,4-5]. Although the application of GGBFS is still limited compared to fly ash, the durability and mechanical performances of both by-products are promising in replacing OPC as construction materials. Thus, this paper will assess the effect of GGBFS utilization as a partial replacement in fly ash-based GPC as a sustainable alternative for construction materials.

2. Experimental Methods

2.1. Raw Materials and Process of Design Mix

The base materials for manufacturing GPC were fly ash and GGBFS. They were obtained from Jimah Power Plant, Port Dickson in Negeri Sembilan and YTL Cement Malaysia, Kapar in Klang, respectively. GGBFS was utilized as a partial replacement in fly ash-based GPC. The chemical



composition of both materials was analysed through X-ray fluorescence (XRF) test at Analytical Laboratory in Universiti Teknologi Malaysia, Kuala Lumpur. Four main chemical oxides could affect the performances of both fly ash and GGBFS in GPC, known as calcium oxide (CaO), silica oxide (SiO₂), aluminium oxide (Al₂O₃) and iron (III) oxide (Fe₂O₃). From previous studies, the variations of the compositions were considerably contributed to the performance of raw materials in GPC manufacturing [3,6-7]. Figure 1 and Figure 2 show the physical characteristics of both low-calcium fly ash and GGBFS samples obtained from the manufacturers. Details on XRF results governing the performance of fly ash-based GPC will be explained further in the next section.



Figure 1. Class F fly ash sample [4]



Figure 2. Ground granulated blast furnace slag (GGBFS) sample [8]

As preparation for alkaline activator in GPC, sodium hydroxide (NaOH) solution is produced by diluting a portion of NaOH pellets with distilled water in a volumetric flask. For instance, NaOH solution with a concentration of 14 M to be achieved consists of $14 \times 40 = 560$ g, where 40 is the molar mass of the NaOH. In other words, 560 g of NaOH pellets are mixed with 1 litre of distilled water to produce 14 M concentration of NaOH solution. The solution is then left to cool down to laboratory temperature so that the dissolution of the solution took place thoroughly before mixed with sodium silicate (Na₂SiO₃). The Na₂SiO₃/NaOH ratio is fixed to 1.5, where every 150 g of Na₂SiO₃ is mixed with 100 g of NaOH [9]. During the process, an exothermic reaction took place when the solution is stirred gradually, resulting in an extreme amount of heat released. Then, the activator is left to ambient temperature for 24 hours [10-11]. As a safety precaution, safety goggles, gloves and mask are recommended to be worn during the preparation of alkaline activator. For the GPC samples preparation, fly ash, GGBFS and aggregates are dry mixed in the laboratory pan mixer for about 3 to 4 minutes. Then, the alkaline activators prepared, together with some extra water, are added to the dry mixture. The mixing continues for another four minutes. After placed in greased moulds, all the samples are subjected to oven curing at 60°C for 24 hours as optimum temperature [9]. Table 1 shows the details of the mix proportions of fly ash and slag-based GPC. The symbol C annotates concrete,

whereas the following acronym, TF, refers to Class F fly ash [12]. The following numbers 14 annotates 14 M concentration of the alkaline activator utilized whereas the last acronym, S0, S10 and S20 annotate the percentage replacement of the total binder with GGBFS consisting of 0 %, 10 % and 20 %, respectively.

Table 1. Design mix of fly ash and slag-based GPC (kg/m^3)

Name	Fly ash	GGBFS	Fine aggregates	Coarse aggregates	Alkaline activator	Additional water
C-TF-14-S0	500	-	707	1060	150	74
C-TF-14-S10	450	50	707	1060	150	74
C-TF-14-S20	400	100	707	1060	150	74

2.2. Specimens and Testing

Concrete cubes of 100 mm x 100 mm x 100 mm (27 numbers of samples) are used to evaluate the compressive strength of fly ash and slag-based GPC whereas concrete cylinders of 150 mm x 300 mm (27 samples) are used to assess the splitting tensile strength for the GPC. The compressive strength test is conducted based on BS EN 12390-6: 2009 using three cubes for each percentage of 0 % to 20 % and curing age of 7, 14 and 28 days, while splitting tensile strength are carried out in accordance to BS EN 12390-4: 2000 [13-14]. Three cylindrical specimens are tested for each age and percentage as well [10]. Figure 3 and Figure 4 show those specimens under compressive and splitting tensile test, respectively. Fly ash-based GPC without GGBFS addition (C-TF-14-S0) is considered as the control concrete specimens since there is no replacement of fly ash in the concrete.



Figure 3: Compressive strength test



Figure 4: Splitting tensile strength test

3. Results and Discussions

3.1. X-ray Fluorescence (XRF) Analysis

Fly ash is generally pozzolanic since SiO_2 content reacts with calcium hydroxide from the cement hydration process to produce calcium silicate hydrate (CSH) gel thus produced cementitious compounds suitable for GPC manufacturing. Also, fly ash with higher CaO content can increase the compressive strength of the concrete in the early ages since the calcium content present plays a significant role in developing the compressive strength [3]. The presence of calcium ions produced a quick reactivity; thus, the geopolymer will yield rapid hardening in shorter curing time under heat curing. Although the strength for the fly ash-based GPC achieved is comparable to the standard OPC strength, improvement in strength development is still yet to be achieved [15]. The addition of GGBFS in the fly ash matrix is then applied to increase CaO content in the fly ash geopolymeric gel. This will result in the enhancement of compressive strength and overall performances of the concrete. The GGBFS is contributing in compressive strength due to its compactness of microstructure and thus enhance the hardening of fly ash and GGBFS blended geopolymer through C-S-H and C-A-S-H formation. The hardening is then followed by the formation of C-S-H, N-A-S-H and C-A-S-H [6]. Table 2 shows the results of XRF from current and some of the previous studies for both fly ash and GGBFS. The differences in chemical composition show varieties in terms of the mechanical performances that will be discussed in the next subsection.

Table 2. Chemical composition of fly ash and GGBFS (%)

Oxides	Fly ash (Current study)	GGBFS (Current study)	Fly ash [5]	GGBFS [5]	Fly ash [16]	GGBFS [16]	Fly ash [3]	Fly ash [18]
SiO_2	46.8	28.7	65.6	30.6	53.6	35.2	38.8	63.4
Al_2O_3	18.4	12.3	28.0	16.2	33.0	21.4	14.7	30.5
Fe_2O_3	6.08	0.5	3.0	0.6	5.5	1.8	19.5	3.0
CaO	3.32	46.6	1.0	34.5	1.8	31.2	18.1	1.0

3.2. Slump Test

When the addition of GGBFS of 10 % and 20 % are applied, there are increments of 3.96 % and 4.90 % of the slump, respectively. Figure 5 shows the workability values are slightly increased as the replacement of GGBFS increased. Higher GGBFS content will tend to produce a higher GPC slump with a higher strength [16,17]. It was suggested that the slump value is between 65 mm and 100 mm for fresh GPC [3]. Studies performed by Abdullah et al. and Gupta and Chandrakar using fly ash-based GPC are compared with slump value in the current study. Based on Figure 5, the slump values of fly ash-based GPC observed are in line with the previous studies performed, with 3 % and 33.1 % higher in slump values for Abdullah et al. and Gupta and Chandrakar, respectively [3,18]. The variations of slump values may be attributed to the higher total of silica, alumina and calcium content in fly ash samples [19]. Table 2 shows Abdullah has 71.6 %, whereas Gupta and Chandrakar have 94.9 % in the total content, which is higher than the current study with only 68.52 %. This also proves that different chemical composition of fly ash will produce a variation of the mechanical properties of GPC, including slump values. Addition of GGBFS is then applied and found to be effective in increasing the workability of the GPC, as shown in Figure 5. However, for 10 % and 20 % GGBFS replacement, slump result data are not shown since none of them are displayed in previous studies.

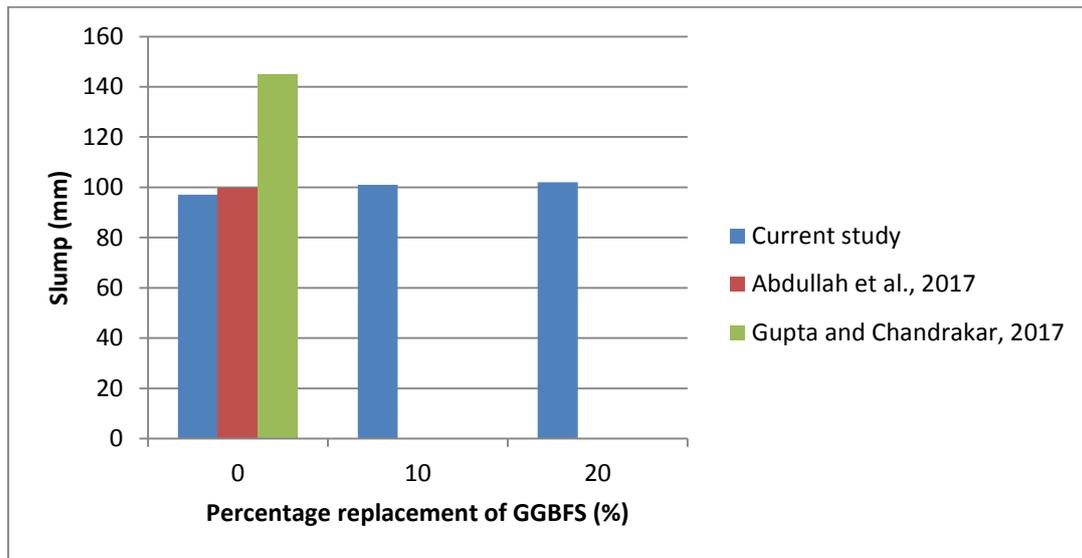


Figure 5: Relationship between slump and GPC containing a different percentage of GGBFS

3.3. Compressive Test

Table 3 and Figure 6 summarized the values of compressive strength for all mixes and the relationship between compressive strength and GGBFS percentage replacement. The database of S50, S75 and S100 annotate 50 %, 75 % and 100 % GGBFS replacement, respectively. They are collected from previous studies for comparison purpose [5]. It can be observed that the graph trend shows the strength increased significantly along with the percentage replacement of GGBFS.

Table 3. Compressive strength for the GPC mix

Mechanical property	Age (days)	Mix type					
		C-TF-14-S0 (Current study)	C-TF-14-S10 (Current study)	C-TF-14-S20 (Current study)	S50 [5]	S75 [5]	S100 [5]
Compressive strength, f_c (MPa)	7	28.4	44.1	47.7	40	44.4	52.4
	14	30.4	48.6	52.9	46.5	48.2	56.2
	28	32.8	48.9	53.2	53.5	55.5	58.6

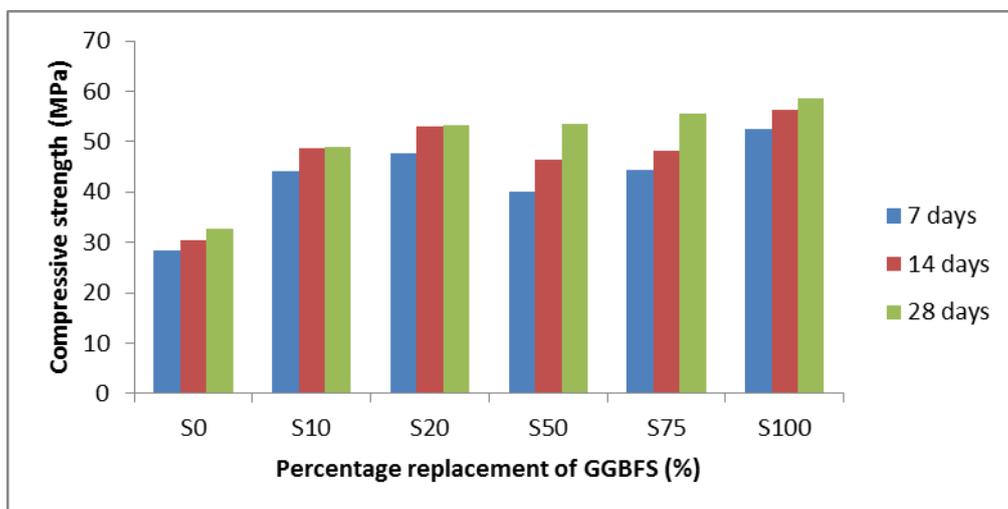


Figure 6: Compressive strength vs. GPC containing a different percentage of GGBFS

For fly ash-based GPC, there is an improvement in the compressive strength along the curing days, from 6.58 % to 13.41 %. After GGBFS replacement of 10 % to 20 % are applied on the fly ash-based GPC, the strength enhancement could be observed. Figure 6 shows 32.90 % to 37.45 % increment when 10 % GGBFS is added whereas 38.35 % to 42.53 % increment after 20 % GGBFS is added to the GPC along the curing days. The increment of GGBFS replacement in GPC for current study achieved a significant compressive strength compared to the control concrete even at seven curing days. Table 3 and Figure 6 show that the GPC for both current and previous studies achieved a range of 86.59 % to 90.18 % of the strength at 28 days, which is suitable for structural applications [5]. Besides that, setting time is an essential aspect for the fresh concrete before setting for proper compaction. Replacement of GGBFS in the fresh concrete will reduce the setting time since the calcium content increases along with the replacement percentage of GGBFS. Higher GGBFS will induce a shorter setting time which is not preferable during casting and compacting. Thus, 20% is considered as an optimum replacement percentage for the GPC casting and thus induce a higher mechanical performance for structural applications [1].

3.4. Splitting Tensile Test

Splitting tensile strength results in Table 4 indicates that the performance of GPC is comparable with conventional concrete, where they are strong in compression but not in tension [2]. Table 4 and Figure 7 display the details and graph of the relationship of splitting tensile strength with GGBFS for all ages, respectively. For the current study, the increment of splitting tensile strength is very slight compared to the studies performed by Jawahar and Mounika. This may be attributed to the higher GGBFS replacement in the study conducted by them compared to the current study and also mishandling during casting that leads to such behavior. Besides, the database for S50, S75 and S100 for seven days and 14 days are not provided, making it difficult for further analysis [5].

Table 4. Splitting tensile strength for the GPC mix

Mechanical property	Age (days)	Mix type					
		C-TF-14-S0 (Current study)	C-TF-14-S10 (Current study)	C-TF-14-S20 (Current study)	S50 [5]	S75 [5]	S100 [5]
Splitting tensile strength, f_{ct} (MPa)	7	2.11	2.31	2.54	-	-	-
	14	2.09	2.56	2.68	-	-	-
	28	2.08	2.65	2.77	3.25	3.39	3.54

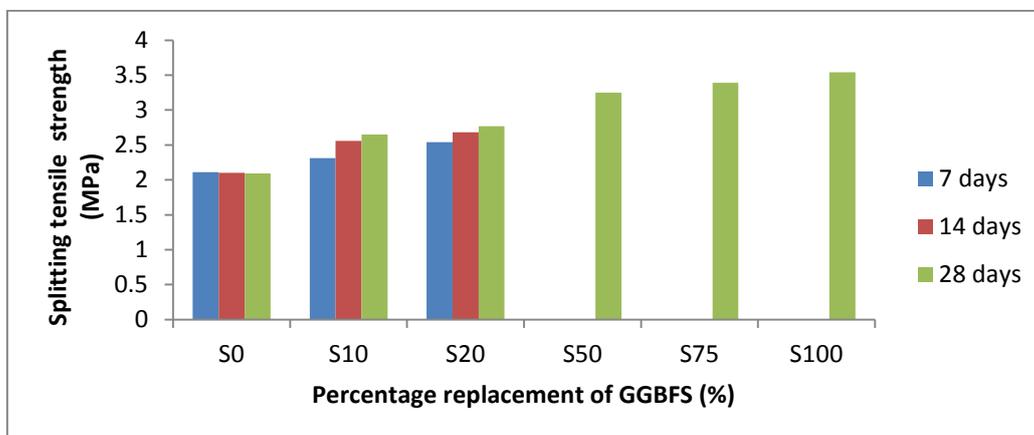


Figure 7: Effect of GGBFS percentage on splitting tensile strength

Based on Table 4, the application of 10 % and 20 % GGBFS in concrete for current study achieved 21.51 % and 24.91 % increment of splitting tensile strength compared to the control concrete, respectively. However, the strength of control concrete is decreasing along the ages for about 1.42 %, may be attributed to lesser compaction and mishandling during casting that leads to such behaviour. The strength of 10 %, and 20 % GGBFS replacement in fresh concrete, however, cannot surpass 3.0 MPa for splitting tensile strength like previous studies. There is 21.75 % higher in maximum splitting tensile strength by Jawahar and Mounika for 100 % replacement of GGBFS compared to the maximum strength achieved in the current study for 20 %. Nonetheless, the replacement percentage is capable of achieving splitting tensile strength as high as that conventional concrete for structural application [5]. The increase in GGBFS replacement level improves the microstructure of GPC, thus leads to enhancement of splitting tensile strength of GPC. From the results it is observed that GGBFS and fly ash blended GPC concretes attained enhanced mechanical properties after cured as in the case of only fly ash based GPC concrete but with more significant results [20,21] attributed to the strong bonding of geopolymer paste and aggregates that tends to increase the properties of GPC [5]. Still, the optimum percentage of GGBFS in concrete to be used as fly ash replacement is 20 % considering the workability as mentioned in the previous section.

4. Conclusion

Based on the investigations, GGBFS has the potential to be utilized in the construction industry. It is one of the ways in mitigating environmental issues, including carbon footprint and cost-saving as well. GGBFS also found to be suitable as partial replacement of cement in concrete production, especially in fly ash-based GPC. Most of the researchers suggested up to 50 % replacement of either GGBFS as cement or fly ash-based GPC replacement in the concrete production [5]. However, to achieve a comparable strength with OPC concrete for bond assessment of GPC, GGBFS replacement up to 20 % is adequate for such application. Some researchers suggested that replacement up to 50 % is recommended but the setting time should be carefully controlled [17]. It is also suggested to use water retarders to prolong the setting time before concrete casting, but still, there will be some defect on the mechanical properties [11]. Although the application of geopolymer in practical construction has already begun in some parts of the world, it will take time to understand the material and its technology and make it accepted worldwide [7,16]. For future works in sustainability enhancement, carbon footprint produced from oven curing could be eliminated as the addition of GGBFS can accelerate the hardening time of the fresh concrete of GPC. Besides, the bond assessment recommended being performed as it is crucial in determining bond behaviour and material properties of the GPC to be utilized in structural applications.

5. References

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