An Overview of Behaviour of Concrete with Granulated Blast Furnace Slag as Partial Cement Replacement

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Abstract. Ground granulated blast furnace slag (GGBFS) is one of green construction materials that held benefits in producing sustainable and high-quality concrete. GGBFS is commonly used as supplementary cementitious materials in blended cement to reduce the need for Portland cement in mortar or concrete production. An overview of the utilization of GGBFS as partial cement replacement with regards to mortar and concrete properties is presented in this paper. The fresh properties of GGBFS mixes addressed include workability and setting time. While compressive strength, porosity, shrinkage, and resistance to sulfate attack are the reviewed hardened properties. Overall, various studies showed that incorporating GGBFS in mortar/concrete mixes significantly improves mortar/concrete properties depending on the GGBFS replacement ratios. It is anticipated that this review will provide valuable information for a better understanding of the fresh and hardened properties of GGBFS-blended mortar and concrete. Moreover, as there is a growing interest in optimal utilization of GGBFS in Indonesia’s cement and construction industry, this review paper intended to raising awareness of GGBFS utility regarding its benefit for sustainable construction.

1. Introduction
Granulated blast furnace slag, GBFS, is a waste material from iron and steel production. The slag itself is a mixture of the same oxides that make up Portland cement (lime, silica, and alumina), but not in the same proportion. GBFS is obtained by rapidly cooling down the molten slag as it leaves the blast furnace. Rapid quenching converts the molten slag into a glassy granular particle having fine-aggregate size, like sand. GBFS is further processed by finely grinding it to powder, which is then referred to as ground granulated blast furnace slag or GGBFS [1].

Due to their chemical and physical properties, GGBFS is commonly used as a partial replacement of Portland cement in mortar or concrete production. The addition of GGBFS to concrete mixes improves fresh and hardened concrete properties, such as workability, strength, porosity, and durability [2]–[6]. In addition, the usage of GGBFS as a binder in concrete held economic and environmental advantages. As there is expanding infrastructure development, the increase in demand for concrete caused concrete natural material sources to be over-exploited. There is also a concern in regard to carbon dioxide emission caused by cement manufacturing which accounts for around 9.5% of global carbon dioxide releases [7]. GGBFS employment in blended cement offers environmental benefits in terms of carbon dioxide discharge reduction, natural resource preservation, and waste management while at the same time ensuring superior performance in concrete properties and characteristics.

This review study aims to provide an overview of the effect of using GGBFS as partial cement substitution on the fresh and hardened concrete properties. Fresh properties are presented in terms of
workability and setting time. Then, the effect of usage of GGBFS on mechanical properties and durability aspects, such as compressive strength, porosity, shrinkage, and resistance to sulfate attack were discussed. This review is intended to lead towards a better understanding of the properties of GGBFS-blended mortar and concrete. In Indonesia, there is an increase in government enthusiasm to encourage the utilization of GGBFS in the domestic cement industry. However, despite the growing interest, GGBFS application in the construction industry is still limited. In this regard, it is anticipated that this review will raise more awareness of the benefit of utilizing GGBFS for sustainable construction.

2. Physical and chemical properties of GGBFS
GGBFS are commonly used as binder in concrete as its latent hydraulic properties prove beneficial to the long-term compressive strength and durability of the concrete [7], [8]. Table 1 shows the chemical composition of GGBFS from Indonesia and other Asian countries. Silica (SiO₂), calcia (CaO), magnesia (MgO), and alumina (Al₂O₃) are the principal constituents of GGBFS, accounting for up to 98 percent of the total composition. Since GGBFS is a latent hydraulic resource, calcium hydroxide, the reaction products resulting from the hydration of Portland cement, or an alkaline activator must be present to accelerate the hydration process [9]. As a result, the compressive strength of the mixture decreased when Portland cement was blended with a high GGBFS percentage (> 60%). However, GGBFS can be activated with alkali solutions to entirely replace Portland cement, providing a sustainable concrete solution. This environmentally friendly alternative binder is called Alkali-activated Slag (AAS) [10], [11]. Unlike cement, GGBFS does not contain C₃A, making GGBFS concrete more resistant to sulfate attack [12]. The fineness of GGBFS is one of the important parameters since it is affecting the strength of concrete. In general, GGBFS that ground more finely has greater strength development and improved durability [13], [14]. Some typical physical properties of GGBFS are summarized in Table 1.

### Table 1. Comparison of physical and chemical properties of GGBFS

|                  | Indonesia* | Malaysia [9] | Thailand [15] | South Korea [2] | China [16] |
|------------------|------------|--------------|---------------|-----------------|------------|
| SiO₂ (%)         | 37.68      | 30.10        | 36.4          | 34.2            | 34.4       |
| CaO (%)          | 36.69      | 53.32        | 35.6          | 45.1            | 44.8       |
| MgO (%)          | 1.74       | –            | 7.1           | 3.9             | 4.43       |
| Al₂O₃ (%)        | 18.09      | 10.30        | 14.6          | 14.3            | 9.0        |
| Na₂O (%)         | –          | –            | 0.2           | –               | 0.62       |
| MnO (%)          | –          | 0.77         | –             | 0.2             | –          |
| TiO₂ (%)         | –          | –            | –             | 0.7             | –          |
| Fe₂O₃ (%)        | 0.41       | 0.57         | 1.5           | 0.5             | 2.58       |
| SO₃ (%)          | 5.43       | –            | 1.9           | 0.2             | 2.26       |
| K₂O (%)          | –          | –            | 1.3           | 0.5             | 0.5        |
| Specific gravity (g/cm³) | 2.89 [17] | –            | 2.92          | 2.9             | 2.79       |
| Blaine fineness (m²/kg) | 425 | –            | –             | 428 [18]       | 599        |
| Loss on ignition (%) | 0.01      | –            | 0.6           | –               | 1.32       |

*Sources: PT. Krakatau Semen Indonesia, September 2020

3. Workability assessment
It was known that the addition of mineral admixture in the concrete would lead to better workability. The slump test is the common workability test for fresh concrete. Several attempts have been made to
investigate the effect of incorporating GGBFS on several replacement levels on the workability of concrete or mortar. According to [2] and [3], better workability was demonstrated by GGBFS-based concrete compared to the one with Portland cement as the only binder. In addition, increasing GGBFS replacement levels would lead to increased workability enhancement. GGBFS smooth and dense particles absorb less water than Portland cement particles, making GGBFS concrete more workable than Portland cement concrete [19], [20]. However, [2] and [21] not observed a difference in the slump value of concrete with and without GGBFS when the replacement level is less than 30%. GGBFS mixes are known to have a low heat of hydration [20]. Therefore, concrete with the addition of GGBFS has low slump loss as the heat generation is lower at the initial stages. This low heat of hydration characteristic is beneficial in large concrete pouring. A study by Woo et al. [22] mentioned the high volume GGBFS replacement as a potential technique for reducing temperature rise and the risk of thermal cracking in mass concrete.

4. Setting time assessment

GGBFS have a slower reaction with water compared to Portland cement, making concrete with GGBFS have delayed setting time. Choi and Park [18] investigated the autogenous healing characteristics of GGBFS blended cement and mortars. In that study, Portland cement, GGBFS, and high-strength admixture were used as inorganic binder. Additionally, anhydrite, Na$_2$SO$_4$, and Na$_2$CO$_3$ were used as crystalline admixtures, as shown in Figure 2. The experiment has shown that increased GGBFS replacement levels result in prolonged initial and final setting times (Figure 1). Lee et al. [2] mentioned the same result where the GGBFS addition delayed the setting time of concrete. This can be an undesirable effect on the construction work where quick setting is required, for example, the manufacture of precast elements. An attempt for accelerating the hydration process of the binary binder of Portland cement and GGBFS was made by Jan et al. [23] using hardening accelerating admixtures (ACC). It was revealed that the initial setting time can be reduced by 40 to 50% depending on the admixture chemical base. The addition of crystalline admixture and gypsum also proved to reduce the setting time of GGBFS concrete [2], [18].

The setting time of GGBFS mixes also depends on the ambient temperature. At lower temperatures, the final setting time is delayed as compared with Portland cement mixes. However, the setting time of concrete with GGBFS is almost equal with normal concrete without GGBFS at higher temperatures (>30°C) [19]. To find out how fluctuating temperature will affect the setting behavior of concrete, Wade et al. [24] placed the mortar samples containing 30 and 50% GGBFS in hot and cold water baths that cycled over 24 h between temperature ranges of 32 – 41°C and 4 – 13°C, respectively. Results demonstrated that mixture containing 50% GGBFS set faster at a higher temperature than control mixture, whereas mortar with 30% GGBFS only marginally accelerated the setting process.
5. Assessment of compressive strength

The employment of GGBFS as the main supplementary cementing materials of an alternative binder contributed to its excellent cementitious properties. The performance of GGBFS on compressive strength can be related to a wide range of factors, which includes several parameters: the water binder ratio (w/b); cement dosage; GGBFS replacement level; testing age; and curing temperature [25]. Partial substitution of Portland cement with GGBFS significantly increases the compressive strength of the concrete or mortar. However, concrete with GGBFS has slow early-age strength gain caused by its latent hydraulic property. This slow development of GGBFS concrete strength proved to be beneficial for ages 28 days or later since higher strength gain occurs at later ages. Abdelli et al. [4] are investigating the influence of the pozzolanic reactivity of GGBFS on mortars. They concluded that the early-age strength gain of the mortar specimens is inversely correlated to the GGBFS replacement levels (Figure 3). At age 28 days and beyond, the compressive strength exceeds the strength of specimen control, with the strength gain increases at a higher GGBFS replacement level. However, the mortar with 80% GGBFS has low compressive strength and has not even reached the strength of mortar without GGBFS. Studies by [3] and [26] reported the slowdown of compressive strength development of the GGBFS mixes. In addition, a significant reduction of compressive strength is found in case of high-level GGBFS replacements. This can be attributed to the excess of GGBFS which remain inactive and do not contribute to the compressive strength [27]. Yüksel [19], Özbay et al. [28], and Cahyani [3] suggested the GGBFS substitution limit be controlled around 50 to 55% of total binder to maximize the excellent development in long-term compressive strength.

![Figure 3. Compressive strength of mortars containing 20, 40, 60, and 80% GGBFS [4]](image)

Strength development of GGBFS concrete is also affected by the fineness of GGBFS. Yun et al. [27] are trying to investigate the effects of fineness of GGBFS cement on compressive and flexural strength of GGBFS mortar. GGBFS was substituting Portland cement at levels of 20, 40, and 50% by the binder weight, with the GGBFS Blaine’s fineness vary between 3550 cm²/g (sample A) to 4640 cm²/g (sample B). The experiment results revealed that mortars with higher Blaine’s fineness (sample BS20, BS40, and BS60) have better performance in compressive strength, with the highest compressive strength attained in 90 days at 40% GGBFS substitution percentage (Figure 4). The finer GGBFS particles, the greater exposure of surface area for hydraulic reactions to occur. The result also indicated that the GGBFS content and particle size were more prominent at later ages (28 days and beyond) as at the early ages cement hydration reaction was dominant [15]. However, [14] mentioned that increase in GGBFS fineness does not necessarily improve the compressive strength. It was observed that the
addition of ultrafine GGBFS particles (7500 cm²/g) caused a reduction in strength compared to mortar with lesser GGBFS fineness (5560 cm²/g).

The strength development of concrete relates to the curing temperature, in which increasing curing temperature will increase the rate of cement hydration [29]. The effect of elevated temperature curing on the compressive strength of concrete with GGBFS was explored by Liu and Presuel-Moreno [30]. It was revealed that the 28-days compressive strength of GGBFS concrete under elevated temperature curing was higher than that of specimens under normal curing environment. Other researchers [31], [32] indicated that hydraulic activity of GGBFS is more responsive to the changes in curing temperature. At elevated temperatures, early strength is developing much faster and the improvement is more prominent for concrete with a greater amount of GGBFS [32], [33]. However, while the increasing curing temperature results in an advantageous high early strength development, it has negative effect on the long-term strength development, indicated with the slight strength reduction at a later age (Figure 5 and Figure 6).

**Figure 5.** Compressive strength of concrete (60% OPC + 40% GGBFS and steel slag) versus age [31]

**Figure 6.** Compressive strength development of concrete with 60% GGBFS at different high-temperature curing cycles [33]

### 6. Effect on Porosity

It is generally known that using GGBFS in the concrete mix results in lower porosity and a more refined pore structure. Choi et al. [5] experimentally investigated the porosity of GGBFS-blended cement paste with different replacement ratios at different ages. It was confirmed that the variation in the porosity is a function of GGBFS replacement ratios and specimen ages. At an early age (3 days), specimens with a higher GGBFS replacement ratio exhibited higher porosity. GGBFS is a latent hydraulic material with relatively slow reactivity, and thus, the early-age hydration is mainly affected by Portland cement's hydration. The cement content decreases at increasing GGBFS replacement ratio, resulting in a lower degree of hydration and reduced hydration products. On the other hand, the porosity of GGBFS cement paste decreased with increasing age (7, 28, and 91 days), indicating that GGBFS hydration leads to a better pore structure at later ages (Figure 7). In general, increased GGBFS replacement levels result in a denser pore structure. However, specimen with 80% GGBFS exhibited higher porosity than those with 65% GGBFS. This can be explained by the presence of unreacted GGBFS as the percentage of GGBFS replacement continue to increase, thus increasing the porosity. It was also found that the hydration of GGBFS improved the refinement of the cement paste pores. As the hydration proceeds with age, the volume of large pores gradually decreased, whereas the volume of the small pore increases (Figure 8). Other research results [3], [34] follow the same trend, reporting that the usage of GGBFS in the concrete mixes leads to reduced porosity and finer pore structure.
7. Autogenous and Drying Shrinkage

Concrete deformation is time-dependent, which means that the deformation will increase overtime under the same force. Time-dependent deformations, such as shrinkage, had a direct impact on the concrete structure's performance and serviceability since they caused contraction and crack formation within the concrete. Autogenous shrinkage and drying shrinkage are usually considered as the main component of total shrinkage [35].

Lee et al. [2] investigated the autogenous and drying shrinkage of Portland cement and GGBFS concretes. When compared to Portland cement concrete, the concrete with GGBFS addition shows greater autogenous shrinkage and it took longer to stabilize. Choi and Park [18] investigated the autogenous shrinkage of concrete with Portland cement, GGBFS, and high-strength admixture as the inorganic binder. The result shows the increase of autogenous shrinkage as the replacement ratio of GGBFS increased. The shrinkage strain of GGBFS specimens was larger than that of Portland cement specimens (Figure 9). According to these findings, GGBFS concrete has significant autogenous shrinkage that should be considered. However, contradictory results are reported on the impact of
GGBFS on the shrinkage of concretes [28]. In work [36] and [37] indicated that substituting up to 50% of the cement with GGBFS reduces the shrinkage potential of concrete (Figure 10).

8. Sulfate resistance

In the concrete durability aspect, sulfate attacks have become a major concern as they can result in loss of strength, expansion, surface spalling, and eventually disintegration [38]. The strength reduction was believed to be caused by two deterioration mechanisms. First, hydration expansion product and salt crystals from sulfate crystallization began to pressure the pore, leads to expansion and eventually microcracking. Second, sulfate attack caused decalcification of C-S-H through leaching calcium compound [39], [40]. The destruction of C-S-H will lead to loss of its binding property, and the specimen becomes severely loose and sanding. The employment of GGBFS to replace a substantial portion of Portland cement improves the concrete sulfate resistance in three ways: densification of pore structure, consumption of calcium hydroxide or Ca(OH)2 through the pozzolanic reaction, and minimizing the C3A content [28].

Atahan and Arslan [41] examined the effect of using GGBFS at various replacement ratios (20, 40, and 60%) on the resistance of mortar against sulfate attack. To observe deterioration caused by sulfate attack, all samples were submerged in a 5% sodium sulfate solution for about 3 years. The results showed a considerable improvement against sulfate attack was achieved by GGBFS-based mortar, as seen by a lower expansion value and strength reduction value when compared to standard Portland cement specimens. The resistance to sulfate attack is higher in mortar mixtures that contain a higher proportion of GGBFS (40% and 60%). The performance of Portland-limestone cement with varying amounts of GGBFS against sodium sulfate attack was evaluated by O'Connell et al. [42]. They concluded that, compared to specimens employing Portland-limestone cement alone, the inclusion of GGBFS resulted in a significant reduction in sulfate-induced expansion.

Although using GGBFS in concrete or mortar helps mitigate the effect of sodium sulfate attack, poor performance in magnesium solutions has been recorded. Investigations by [43] and [44] revealed a higher resistance for the specimen without GGBFS addition than those with GGBFS in solutions containing magnesium sulfate. This inferiority of the GGBFS specimen was believed to be caused by the development of M-S-H gel, the reaction product between magnesium sulfate (MgSO4) and secondary C-S-H gel from GGBFS pozzolanic reaction. M-S-H results in the softening of the cement matrix, thus considered as the leading cause of concrete deterioration under magnesium sulfate attack.

9. Conclusion

This paper gives an overview of the utilization of GGBFS as partial cement replacement with regard to mortar and concrete properties. The effect of GGBFS addition on the fresh and mechanical properties and the durability-related aspects were discussed. This review is anticipated to raise awareness of the benefit of utilizing GGBFS for sustainable construction, particularly in Indonesia. The general advantage of GGBFS usage as partial cement replacement can be summarized as follows:

- Enhanced workability performance especially at higher GGBFS replacement levels.
- Reducing heat of hydration which positively affects slump loss and lessens the risk of thermal cracking.
- Improving the development of long-term compressive strength with the GGBFS substitution limit suggested being around 50 to 55%.
- Reducing porosity and improve pore refinement.
- Significantly enhance sulfate attack resistance, particularly against sodium sulfate attack.

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