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Utilization of Ground Granulated Blast Furnace Slag and Flue Gas Desulfurization Gypsum on Concrete Properties

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Abstract

The production of cement is a significant source of carbon emissions in the industrial sector. An important aspect of environmental management involves utilizing industrial waste materials to create value-added building products. This study focuses on evaluating the performance of two such waste materials: ground granulated blast furnace slag (GGBFS), generated by the steel manufacturing industry, and flue gas desulfurization gypsum (FGDG), a byproduct of coal-fired power plants. The objective is to investigate the impact of partially replacing Ordinary Portland Cement (OPC) with GGBFS and FGDG on the mechanical properties of self-compacting concrete, specifically its compressive strength and splitting tensile strength. Different proportions of GGBFS and FGDG (10%, and 20% of the cement content) were used to assess the concrete's properties. UPV test was conducted to test the quality and soundness of the concrete. The strength development of the concrete was evaluated at curing ages of 7 and 28 days. FGDG achieved the greatest 28-day compressive strength of 30.4 MPa with 10% substitution. At both 7 and 28 days, GGBFS had diminished strength in comparison to control mix. At 28 days, the GGBFS mix with 10% substitution had a compressive strength of 95.76% of the control mix. The UPV values between 3674 and 4470 m/s showed concrete of good quality.

Keywords: *Mechanical Properties; Blast Furnace Slag; Flue Gas Desulfurization Gypsum; UPV Test.*

1 Introduction

Modern construction materials like concrete are frequently used in a variety of civil engineering applications. Over time, its popularity has steadily grown. Concrete has advanced significantly, as seen by the creation of self-compacting concrete (SCC). SCC has gained a lot of respect in the building industry thanks to its wide variety of applications and various advantages over traditional concrete. Greater volumes of cement, mineral additive, and superplasticizer are used in SCC. SCC has the major benefit of eliminating the need for vibration or outside energy during compaction. SCC has proven to be effective over time at enhancing concrete's durability (Sharma R, 2018). SCC exhibits excellent resistance to segregation, ensuring the uniformity and consistency of concrete during transportation and placement (Khayat, 1999). The main base component of concrete manufacture is cement, yet producing cement has environmental consequences. Cement manufacturers throughout the world currently produce more carbon dioxide than 5% of all global emissions (H. Okamura, 2003). Industrial waste can be used as a cementitious material as a feasible alternative to cement in order to address the environmental issues related to cement production. The generation of waste and greenhouse gas emissions could both be greatly reduced as a result of this swap. Concrete can be made more affordable, with lower hydration heat, and with better durability by substituting mineral admixtures for PC(Abdul Razak H, 2019). In order to find sustainable alternatives that are both eco-friendly and functionally equivalent to traditional cement, significant efforts are being conducted worldwide to develop environmentally friendly building materials. Multicomponent binder materials can use a variety of industry leftovers for a variety of applications. Both Flue Gas Desulfurization Gypsum (FGDG) and Ground Granulated Blast Furnace Slag (GGBFS) are workable cement substitutes in a variety of applications. FGDG is a byproduct created when coal-fired power stations' flue gas desulfurization (FGD) systems remove sulfur (S) from fuel combustion gases (Liu XM, 2011). By 2016, the total production of FGDG China had reached 550 million tons. (*National Bureau of Statistics, People's Republic of China, 2017. National Report on Cement Production in Chinese*, 2016). It is vital to recycle FGDG and lessen its negative impacts. A sustainable alternative, FGDG has been used more frequently lately in the manufacturing of building products like cement retarder and plasterboard (C.L. Hwang, 1986; G. Peng, 2014; P.X. Duan, 2012). GGBFS, a byproduct of iron extraction in blast furnaces, has latent hydraulic qualities that enable it to interact with water to generate cementitious compounds. Granulated slag, when finely powdered, exhibits outstanding cementitious properties and can be used with Portland cement or alkali-activated materials (C.L. Hwang, 1986). Due to their high percentage of silica content, Fly Ash (FA) and GGBFS are frequently employed as cement replacement materials. (Manjunath R, 2018). FA is constantly utilized in concrete as a cement substitute to some extent. This substitution lowers the heat of hydration of the concrete, which lowers the thermal gradient. Utilizing GGBFS reduces the heat of hydration during the early phases, which reduces the possibility of early-stage cracking even though it may result in lower initial strength (Liwu M, 2006). FA is frequently used in concrete as a partial cement alternative. This substitution reduces the concrete's heat of hydration, which also reduces the thermal gradient. Even though it may result in reduced initial strength, using GGBFS lessens the heat of hydration during the early stages, which lowers the likelihood of early-stage cracking (Bougara A, 2010; Oh, 2014). This paper focuses on examining the viability of using FGDG and GGBFS as partial substitutes for cement in concrete.

2 Materials and Method

2.1.1 Cement

Ordinary Portland Cement (OPC), a hydraulic cement, is the type of cement that is used the most frequently worldwide. OPC is used in the building industry and goes through a hardening process when coupled with water. Portland cement (PC) of type I, made locally and in accordance with BDS EN 197-1 standard, was used for this study. The chemical composition percentages of OPC are provided in Table 1.

2.1.2 Ground Granulated Blast Furnace Slag

In this investigation, GGBFS, obtained from a neighboring iron extraction factory, was used as a partial cement substitute. After coming into contact with water, ground-granulated blast furnace slag transforms into calcium silicate hydrates (C-S-H), a latent hydraulic binder. It is a substance that gives concrete more strength and durability. Table 1 lists the percentages of GGBFS's chemical makeup.

2.1.3 Flue Gas Desulfurization Gypsum

This study's source for the flue gas desulfurization gypsum (FGDG) was a local coal-fired power station. It was used in the inquiry as a partial cement replacement. Gypsum can be found in large quantities in flue gas desulfurization gypsum (FGDG). FGD gypsum has a strong potential for uses in building constructions because of its extremely low cost and wide availability. Table 1 lists the percentages of FGDG's chemical composition.

2.1.4 Fly Ash

Fly ash, a finely split byproduct of pulverized coal combustion, can be utilized to improve the strength and workability of concrete while lowering permeability. A local distributor's fly ash (FA) of category class F was employed as a mineral additive in Portland cement. Concrete gains strength, durability, and chemical resistance by including fly ash. Table 1 lists the chemical component percentages of FA.

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2.1.5 Superplasticizer

Plasticizer Sikament®-2014 NS was applied. Concrete's workability is improved, and it is sustained over time. This plasticizer's chemical foundation is modified naphthalene formaldehyde sulphonate. It helps the concrete become stronger and more resilient. Sikament® NN considerably improves the concrete's plasticity and maintains a healthy slump by acting as a superplasticizer or high-range water reducer.

2.1.6 Coarse and Fine Aggregate

The majority of the coarse sand, or Sylhet sand, used for this investigation was procured from the neighborhood. The sand was meticulously sieved to remove any pebbles, using a sieve size of 4.75mm, to guarantee its appropriateness. For the coarse aggregate, it was decided to use locally accessible crushed natural stone with a nominal maximum size of 19mm. In accordance with ASTM C127 (2015), a number of experiments were performed to evaluate the physical properties of both coarse and fine aggregates. These tests comprised unit weight measurements, sieve analysis, specific gravity, and moisture content. Table 2 displays the outcomes of these examination

2.1.7 Water

In the laboratory, clean and uncontaminated pipeline water of pH 7.35 was utilized for all the mixtures.

Table 1. Chemical composition by using X-ray Fluorescence (XRF) analysis

Constituents	OPC (%)	Fly Ash (%)	GGBFS (%)	FGDG (%)
Silica (SiO_2)	20.24	59.40	33.20	4.01
Alumina (Al_2O_3)	4.9	28.58	14.44	2.61
Ferric oxide (Fe_2O_3)	3.36	3.02	0.58	0.31
Calcium oxide (CaO)	63.78	3.56	47.39	33.15
Magnesium oxide (MgO)	1.29	1.18	3.22	1.34
Sulfur trioxide (SO_3)	1.24	0.27	0.14	39.30
Sodium oxide	1.23	0.43	-	-
Potassium oxide	1.61	0.51	-	-
IR	0.32	-	0.24	-
LOI	1.12	3.05	0.03	-
Free lime	0.91	-	-	-
Combined Water	-	-	-	18.11

Table 2. Physical properties of sand and stone chips.

Properties	Sand	Stone Chips
Moisture content (%)	4.41	4.29
Fineness Modulus	2.52	6.39
Specific gravity	2.51	2.70
Absorption (%)	1.67	1.15
Loose bulk density (kg/m^3)	1413.2	1566.5
Void Ratio (%)	44.68	36.2

2.2 Mix Proportion

To prepare the self-compacting concrete (SCC) for the experimental program, a total of five concrete mix proportions were selected, with partial replacements of GGBFS and FGDG in the coarse aggregate. Through numerous trial combinations, where the water-to-binder ratio and the amount of superplasticizer (SP) were changed, the mix design was developed. Mixing process is shown in Figure 1. Cement, coarse sand, and coarse aggregate weights were used to determine the mix ratio, which was set at 1: 2.1: 1.9. A 0.38 water-to-binder ratio was chosen

Figure 1. Mixing process.

Table 3. Mix proportion of all SCC mixes.

Mix ID	**Cement (kg/m^3)**	**Fly ash (kg/m^3)**	**Fine aggregate (kg/m^3)**	**Coarse aggregate (kg/m^3)**	**GGBFS (kg/m^3)**	**FGDG (kg/m^3)**	**Water (kg/m^3)**	**W/B ratio**	**Super plasticizer (kg/m^3)**
MB0F0	410	123	860	780	0	0	202.5	0.38	6.15
MB10F0	369	123	860	780	41	0	202.5	0.38	6.15
MB20F0	328	123	860	780	82	0	202.5	0.38	6.15
MB0F10	369	123	860	780	0	41	202.5	0.38	6.15
MB0F20	328	123	860	780	0	82	202.5	0.38	6.15

Throughout all concrete formulations, fly ash and SP were added at a constant rate of 30% and 1.5% of the cement weight, respectively. As a mineral additive, fly ash was used. The different mixtures were designated as MB0F0 for the control mix and MB10F0 and MB20F0, respectively, for the ones that had GGBFS substitutions of 10% and 20% of the cement weight. The mixes with 10% and 20% of the cement weight replaced with FGDG were labeled as "MB0F10" and "MB0F20," respectively. Table 3 lists the particular mix proportions for the SCC in this study. Initially, the dry components—cement, sand, fly ash, coarse aggregate, FGDG, and GGBFS—were dry mixed for about a minute. After another 2 minutes of mixing, 70% of the projected amount of water was progressively added. Subsequently, the remaining 30% water, along with the superplasticizer, was added, and mixing was continued until the concrete exhibited visible flowability. The overall mixing process adhered to the guidelines specified in ASTM C192/C192M-18.

2.3 Specimen preparation and curing

Compressive and splitting tensile strength tests were conducted using cylindrical molds with dimensions of 100 x 200 mm. Fresh concrete was poured into the mold without using any strokes after the mold had been prepared with lubricating oil. The concrete was then allowed to compact evenly under its own weight. The molds were carefully removed and then numbered for easier identification after a 24-hour hardening time. The specimens were cured for 7 and 28 days in a plastic curing tank while completely submerged in water.

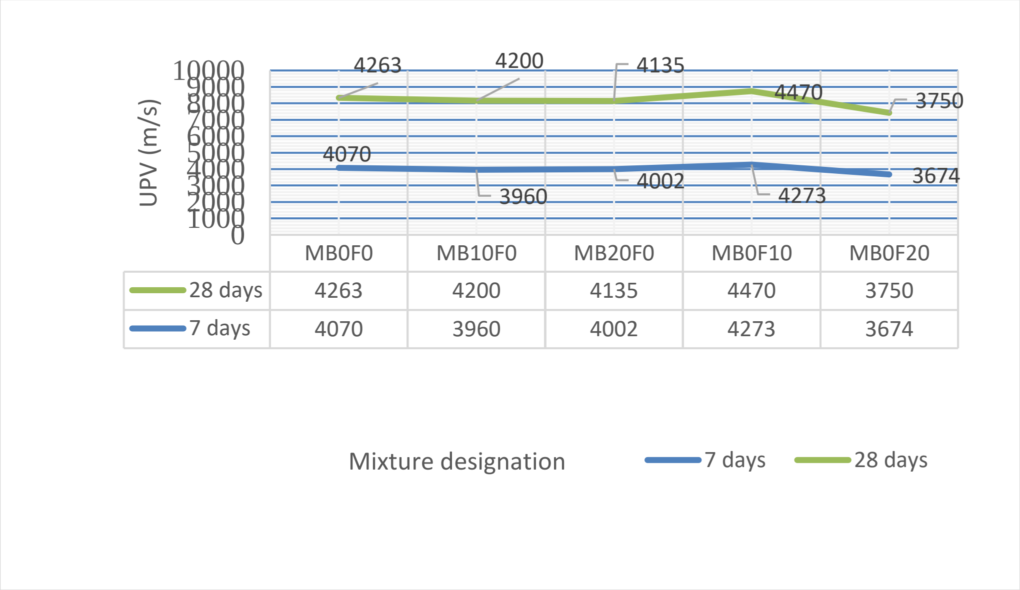
2.4 Test Method

Following the testing procedure outlined in ASTM C597-16 (2016), the Ultrasonic Pulse Velocity (UPV) test was carried out at 7 and 28 days to assess the qualities of the concrete. The UPV test makes use of tools that can spot and map many types of concrete flaws, including voids, fractures, honeycombs, and other oddities. Cylindrical specimens were created and put through testing at 7 and 28 days for the hardened concrete tests, which included the Splitting Test and Compressive Strength Test. The ASTM-C39/C39M-18 (2018) standard was followed in conducting the compressive strength test. Following the instructions of ASTM C496 (2017), the cylinder specimens were subjected to a tensile force along the diameter using the same testing apparatus as for the compressive strength test, delivering a constant compressive force until failure occurred. The tests performed are shown in Figure 3 and processes are shown in Figure 4.

3 Result and Discussion

3.1 Ultrasonic Pulse Velocity (UPV) Test

The UPV technique uses the theory of wave propagation to assess the depth of materials, identify fractures and concrete damage, ascertain mechanical parameters like Young's modulus and Poisson's ratio, and calculate the compressive strength of concrete (Mills, 1998; Naik TR, 2004). The table in Figure 2 displays the UPV results that have been examined.



	MB0F0	MB10F0	MB20F0	MB0F10	MB0F20
28 days	4263	4200	4135	4470	3750
7 days	4070	3960	4002	4273	3674

Figure 2. Variation of UPV with different mix proportions.

By computing the mean of the UPV measurements in the three spatial directions (X, Y, and Z-axis), the UPV value for each specimen was determined. The UPV measurements were between 3774 and 4470 m/s. Each UPV value fell within a respectable, acceptable range. MB0F10 had the highest UPV value at 28 days of curing, whereas MB0F20 had the lowest at 7 days. As curing days increased from 7 days to 28 days, UPV values for all samples rose. A 10% or higher addition of FGDG reduces the UPV score. Less pulse velocity was seen in the MB10F0, MB20F0, and MB0F20 UPV values compared to the control. The UPV values clearly reflected the compressive strength as higher UPV values amounted to higher compressive strength.

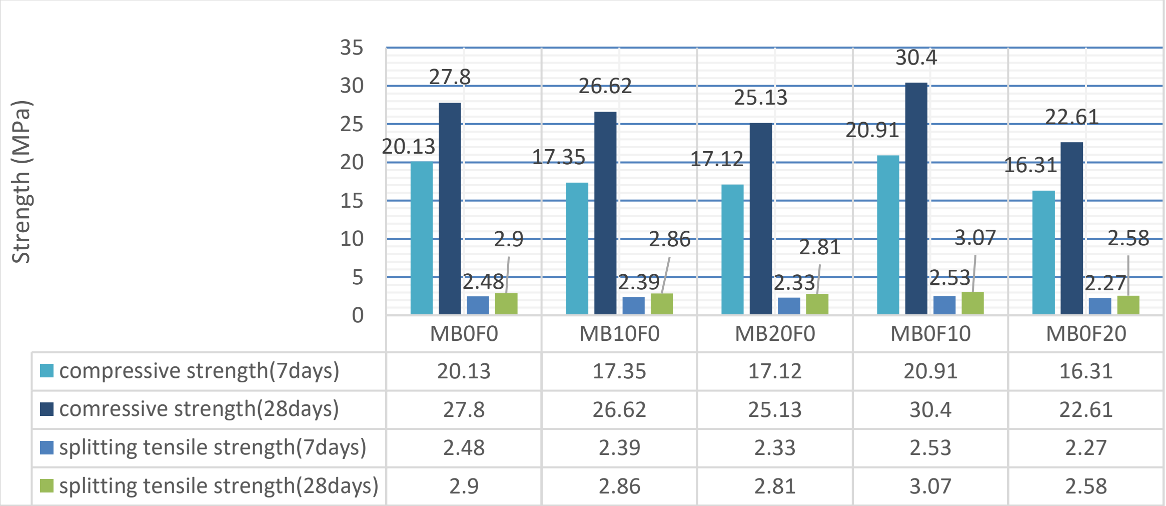
3.2 Hardened State Tests

3.2.1 Compressive Strength Test

At all levels of cement replacement, GGBFS decreased the compressive strength of concrete. Reduction was greater after 7 days, but as the curing period prolonged, the reduction dwindled. For 10% and 20% GGBFS replacement of cement, respectively, the compressive strengths of the GGBFS mixes were 86.19% and 85.05% of the control mixes at 7 days. Whereas, with 10% and 20% BFS replacement of cement, respectively, the compressive strengths of the GGBFS mixes at 28 days were 95.76% and 90.39% of the control mixes. After 7 days of curing, the compressive strength starts to decline due to a decreased rate of pozzolanic hydration (Bougara A, 2010). At both 7 and 28 days, the compressive strength of MB0F10 with a 10% substitution of FGDG for cement was higher than control mixes by 103.87% at 7 days and 109.35% at 28 days. This improvement can be ascribed to GGBFS and cement having a more favorable pozzolanic reaction, which increases the stability of the concrete. Compressive strength was negatively impacted by FGDG with a 20% cement replacement at both 7 and 28 days. At 7 and 28 days, MB0F20 demonstrated 81% and 81.33%, respectively, strength of control mix. Gypsum has no strength-contributing properties, therefore increasing the replacement of gypsum powder will diminish the amount of calcium silicates C3S and C2S, which are responsible for both the short- and long-term strength of concrete.

3.2.2 Splitting Tensile Test:

The splitting tensile strength of the samples was assessed after 7 days and 28 days of curing. The findings revealed that there was no improvement in the strength of mixes containing GGBFS compared to the control mix. In fact, the tensile strength decreased for mixes containing BFS at both 7 days and 28 days.



	MB0F0	MB10F0	MB20F0	MB0F10	MB0F20
■ compressive strength(7days)	20.13	17.35	17.12	20.91	16.31
■ comressive strength(28days)	27.8	26.62	25.13	30.4	22.61
■ splitting tensile strength(7days)	2.48	2.39	2.33	2.53	2.27
■ splitting tensile strength(28days)	2.9	2.86	2.81	3.07	2.58

Figure 3. Compressive and splitting tensile strength test results.

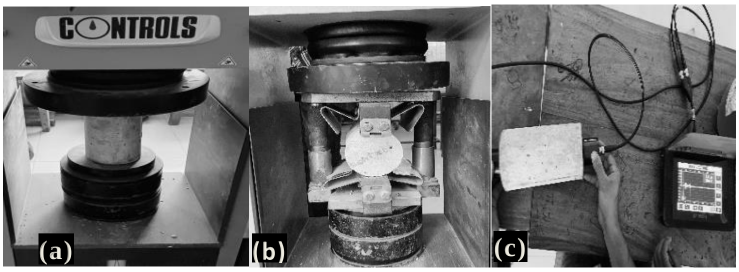


Figure 4. (a) Compressive Strength Test (left) (b) Splitting Tensile Strength Test (middle) (c) UPV Test (right).

At 7 days, the tensile strength of MB10F0 and MB20F10 was 96.37% and 93.95% respectively, compared to the control mix. However, as the curing period increased, the reduction in strength became less pronounced. This can be attributed to the slower rate of the pozzolanic hydration process mentioned earlier. Furthermore, when FGDG admixtures were used, the splitting strength initially increased with partial replacement for MB0F10, but then decreased for MB0F20. The results indicated that the highest splitting tensile strength values were observed for MB0F10, reaching 2.53 MPa (102.02% of the control mix) after 7 days and 3.07 MPa (105.86% of the control mix) after 28 days. In terms of the splitting tensile strength of the SCC mixes, an increase was observed from 7 days to 28 days of curing.

4 Conclusions

The UPV values indicated that all concrete samples were of satisfactory quality. Based on the laboratory results and the accompanying discussion, it can be concluded that FGDG and GGBFS exhibit favorable characteristics as supplementary materials in SCC. Although a decrease in strength gain was observed in GGBFS mixes, the disparity in strength between GGBFS mix concrete and the control mix was reduced at the 28-day curing mark for both 10% and 20% GGBFS samples. This reduction in strength gain can be attributed to the lower calcium oxide content in GGBFS compared to cement, which may slow down chemical reactions during the early stages of curing, resulting in a gradual decline in strength with higher GGBFS content. On the other hand, FGDG at a 10% replacement of cement was found to be the most suitable option, as it achieved better compressive and splitting tensile strength than the control mix. However, when FGDG was used as a 20% replacement, a notable decrease in UPV, compressive strength, and splitting tensile strength was observed compared to the control mix.

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