Incorporation of High Volume Ground Granulated Slag From Blast Furnaces in Pavement Quality Concrete

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ABSTRACT

Supplementary cementitious materials (SCMs) are commonly introduced into the concrete mix to increase their properties, addressing the current need for durable and robust pavements. With every ton of Ordinary Portland Cement (OPC) produced through processes such as fossil fuel combustion and limestone fermentation, carbon dioxide is released into the atmosphere. Conversely, Ground Granulated Blast-furnace Slag (GGBS), being abundantly available, presents a viable more environmentally friendly alternative to cement for various concrete applications. This work studies the influence of GGBS, in combination with chemical admixtures, on M40 grade binary blended concrete mixtures. The aim of the study was to improve the strength characteristics at various stages of concrete curing. The results indicated that the GGBS-incorporated concretes (replacing 60%, 65%, and 70% of the cement) exhibited an increase in compressive strength after prolonged curing. The average density of fresh concrete mixes containing GGBS did not exhibited a noticeable increase. A marginal disparity in air content was observed in the replacement mix. Minimal length changes were observed in the drying shrinkage test after a curing duration of 360 days compared to conventional concrete mixtures.

Keywords-GGBS; cementitious materials; concrete; portland cement

I. INTRODUCTION

The most common building material used by civil engineers is concrete. Concrete is indeed a remarkable material made by mixing various components. Its versatility makes it indispensable in construction. Whether it is for buildings, bridges, roads, or other infrastructure, the strength and flexibility of concrete are hard to beat. In addition, its durability ensures that structures built with concrete can withstand a long time and various environmental factors. Concrete does not dry immediately after mixing and putting; instead, hydration occurs, a slow chemical interaction between water and cement. By combining cement and water, a powerful paste is created that not only fills in the gaps left by fine particles, but also effectively binds all particles together. This process is crucial to creating a strong and durable concrete mixture [1]. The concrete mixture in the mold dries to a stone-like hardness after curing due to the chemical processes between the water and the binding components.

Due to the increasing demand for concrete and the shortage of fine aggregate supplies, the price of cement is increasing. A viable approach that provides several benefits to the long-term growth of the construction industry is the substitution of Portland cement with other cementitious materials such as fly ash, Ground Granulated Blast-furnace Slag (GGBS) and silica dust. The Supplementary Cementitious Material (SCM) that is used most as a replacement for cement is GGBS, which is a byproduct of the iron and steel industry. The GGBS is generally available everywhere in the world [2].

Authors in [1] studied the mechanical properties of light weight vermiculite concrete of M30 grade when employing dolomite and GGBS instead of some amount of cement. Vermiculite was used as the aggregate due to its strength, and the durability quality of light-weight concrete was examined. In that study, two different concrete mixtures were made, one with 30% dolomite instead of cement and the other with GGBS serving as a 40% fractional cement substitution. Fine aggregates were used in amounts of 0%, 5%, 10%, 15%, 20% and 25%. The results indicated that the maximum strength was obtained when GGBS was used. Using dolomite instead of cement or GGBS resulted in a significant improvement in flexural and split tensile strength, but to a decrease in compressive strength. However, using GGBS instead of cement increased the compressive strength [1]. Authors in [2] examined the mechanical performance of mortars using high-volume GGBS over an extended period of time. By substituting a large volume percentage of GGBS for cement, the initial and final setting periods were reduced. Moreover, a significant correlation was found between the Ultrasonic Pulse Velocity (UPV) values and the compressive strength. Despite a small decrease in strength of the mortal for 50% and 70% GGBS after 550 days, all GGBS ratios can be deemed adequate from the environmental viewpoint, thus an environmentally friendly mortar was developed [2].

The effects of using GGBS and partially carbonized alum sludge ash (ASA) ablated at a temperature of 200–300 °C instead of cement were studied in [3]. Ten combinations of ASA and GGBS up to 6.0% by weight and the highest possible replacement rates of Ordinary Portland Cement (OPC) were examined. The critical parameters of the OPC, that is, density, compressive strength, flexural strength, water absorption coefficient, porosity, and water absorption, were evaluated after two curing ages of 7 and 28 days. Fresh concrete was used for the setting time and flow table tests. The findings proved that while the setting time increased with an increase in ASA content, the mechanical strength, workability, and thickness of cement generally decreased when the partial substitution with ASA of OPC increased. Furthermore, the GGBS and ASA enhanced the concrete's coefficient and water absorption properties. After 28 days of curing, the mortar produced had a maximum compressive strength of 20.6 MPa. A partial replacement of OPC was achieved by using 2.0% by weight of ASA and 4.0% by weight of GGBS to create the mortar with a workability of 156 mm [3]. In [4] is proposed an optimal mix design for cryogenic concrete considering its durability performance, the mechanical and thermal properties [4].

Sewage water has been shown to affect concrete pavement more severely than freshwater. The proper drainage and adequate supplemental sewerage systems are necessary to maintain the desired strength of the pavement throughout its useful life [5]. Therefore, the incorporation of GGBS and selecting the curing conditions can increase the durability of concrete pavement [6]. The flexural strength of concrete mixtures developed from different combinations of glass fiber-reinforced concrete pavement mixes based on GGBS was examined in [7]. 15% of the fine aggregate was replaced with M sand. GGBS was used in place of cement for up to 30% and 0.5% or 0.75% of glass fibers were added to the mixture. Conplast SP-430, a superplasticizer, was used to improve workability. The flexural strength was found to increase with the amount of GGBS and fiberglass in the mixture. The optimized mixture containing 30% GGBS and 0.75% fiberglass showed an increase in flexural strength of 24% compared to the reference [7].

Roller Compacted Concrete (RCC) is used mainly in heavy duty asphalt pavement and multiple industrial applications. In [8], 0%, 20%, 40%, and 60% of the OPC was replaced with GGBS and various RCC combinations were developed. The optimal water content for each mixture was identified by compaction tests. The strength and microstructural characteristics of RCC after the incorporation of GGBS were evaluated. The results showed that fresh RCC mixes containing GGBS show a higher compressive strength than standard OPC, which increases as the samples age. The test results also showed that replacing OPC with GGBS could result in a 40% increase in the strength characteristics of the RCC. The morphology revealed by Scanning Electron Microscopy (SEM) consisted of dense, compact, and uniformly dispersed C-S-H gel in the RCC mix comprising 40% GGBS [8]. GGBS was also implemented on M50 concrete using several proportion combinations (0%, 10%, 20%, 30%, 40%), replacing the fine aggregate with quarry sand (which was kept constant at 30%), and infusing 1% of steel fiber by volume in the mixture. A variety of prisms, cylinders, and cubes were cast and tested after curing periods ranging from 3 to 28 days. The mixture containing 30% GGBS, 30% quarry sand and 1% steel fibers gave the best results regarding compressive strength, split tensile strength, and flexural strength, which increased by 2.1, 0.65, and 1.4% compared to control, respectively. The investigation discovered that the addition of 30% GGBS to cement significantly increased the workability of fresh concrete [9]. GGBS instead of cement of up to 60% has been used for the preparation of concrete pavements with very good results [10]. In [11] the authors studied the strength properties of concrete, produced by partially replacing cement with GGBS. The maximum strength increase was found when 15% GGBS was added [11].

Falling Weight Deflectometer (FWD) measurements were employed to evaluate the deflection and elastic modulus of pavement subgrades modified with tire scrap [12]. The analysis revealed a notable reduction of 37.5% in deflection and 2.68 times increase in elastic modulus for the tire scrap modified subgrade pavement compared to the standard clayey soil subgrade pavement. The authors in [13] produced Geopolymer Concrete (GC) by adding fly ash and GGBS and varied the binder content. The effect of temperature curing was studied. Ambient cured GC with 70% fly ash and 30% GGBS showed comparable compressive strength to M20 concrete. However, the temperature-cured specimens exhibited a higher strength than the ambient-cured. The mechanical properties of M20 and M40 grade concrete specimens with a 30%, 40%, or 50% replacement of cement by GGBS were studied in [14]. Hydrochloric and sulfuric acid durability tests were also carried out. The GGBS containing cements exhibited better mechanical properties and chemical stability to acids compared to reference samples. Following a different approach, the authors in [15] devised a Neural Network (NN) concept to predict the compressive strength of GGBS-based concrete and compared their findings with experimental results. The study has shown that NN methods can be effective in evaluating the strength of GGBS mixed cement concrete. The use of this method opens the door to designing GGBS concrete with the desired strength by predicting the appropriate percentage of GGBS and aging [15].

The mechanical characteristics of bending specimens employing GGBS were studied in [16], showing that replacing cement with GGBS increases the cement's strengths, but the GGBS concrete bending specimen's mechanical performance was essentially on par with ordinary concrete. The results further indicated that 20% replacement of cement with GGBS in concrete samples is the optimal proportion of slag for good girder performance. The authors in [17] conducted an experimental investigation into the effects of GGBS on the compressive strength of concrete and the binding properties between steel and concrete bars. The effect of GGBS mix proportions on binding strength was examined. The results show that increasing the GGBS content decreases the bonding strength of concrete and steel bars. However, this behavior is dependent on the GGBS amount and the type of steel bars. The study provides a reference for the application and distribution of GGBS concrete.

Previous studies demonstrate the substantial social and economic benefits of replacing cement with GGBS, which results in reduced costs per cube, improved performance, and utilization of industry residual waste. Therefore, from a technical, economic, and environmental perspective, the use of GGBS as a reinforcing ingredient should be prioritized.

II. RESEARCH METHDOLOGY

The research methodology that was followed in this work was divided into the following steps:

- First, was conducted the determination of the exact ratio of cement replacement to GGBS. Then, Pavement Quality Concrete (PQC) mixtures were made by mixing different proportions of cement and GGBS. A superplasticizer was added to the mixtures with a water/cement (w/c) ratio of 0.4 to achieve the necessary workability. To produce a highly durable concrete, the GGBS and water mixture was optimized. The cement was replaced by GGBS at 60%, 65% and 70% by the cement mass.
- Next, was performed the development of the chemical admixture in the lab to add in into the concrete mix. The superplasticizer to be added to the mixture was developed by the MAPEI Concrete R&D Lab.
- Then followed the design of the mixture proportions. The mix design for the PQC M-40 grade concrete followed the IS 10262:2009 guidelines. It was completed in the laboratory using the following materials: cement, sand, aggregates, GGBS, chemical additive, and water. 0.4% of PC-based superplasticizer was added to the concrete mix with a w/c ratio of 0.40 to ensure adequate workability. Specific gravity, apparent specific gravity, water absorption, and fineness modulus are among the physical characteristics that were measured.
- Experimental procedure. Following IS 10262:2009, the mix design was used for casting concrete cubes. The mechanical characteristics of the M40 PQC mixtures, incorporating GGBS, were examined after 7, 28, 56, 90 days of aging. Furthermore, we examined the workability and drying shrinkage (length change) of the M40 PQC samples when GGBS and chemical admixture were added.
- Finally, the experimental results were interpreted. The compressive strength, drying shrinkage (length change), air content, and density of the GGBS were measured and compared with those of the control samples.

III. MATERIALS AND METHODS

GGBS has a high calcium silicate content and exhibits good cementitious characteristics. The chemical composition of GGBS is illustrated in Table I.

TABLE I. CHEMICAL COMPOSITION OF GGBS

Material	Content (%)
Silicon dioxide	34.04
Aluminium oxide	18.8
Ferric oxide	0.7
Calcium oxide	32.4
Magnesium oxide	10.75
Sulphur trioxide	0.85
Potassium oxide	0.98
Sodium oxide	0.31
S	0.65

GGBS, a byproduct of the iron-making process, has long been used in the construction sector as an alternative to OPC. GGBS can suppress temperature rise in massive concrete pours; thus, it is used in massive concrete placements when temperature control is an issue. Compared to OPC, GGBS cement produces less heat because of its more progressive hydration. GGBS has less free lime and more calcium silicate hydrates, which boost concrete strength. The physical properties of GGBS are shown in Table II. The GGBS was evaluated to determine whether it can be utilized as a pozzolana. These experimental results can then be compared with the IS-3812 Part 1 guidelines, which outline the requirements for a substance to be utilized as a pozzolana.

The primary component of concrete, mortar, and plaster is Portland cement, the most common type of cement. It is composed of calcium, aluminum, and silicon oxides. After heating clay and limestone, a supply of sulphate is added to create Portland cement. When combined with water, the fine material will form a thick paste and eventually solidify. The physical properties such as specific gravity, fineness, strength activity index of GGBS and cement are illustrated in Table II.

Chemical admixtures are commonly used to produce the desired properties of concrete mixtures. In this research, we used the Dynamon NRG 9040 superplasticizer. It is a superplasticizer formulated by MAPEI Construction Products India Pvt. Ltd. and is based on second-generation polycarboxylic ether (PCE) polymers. The physical properties, specific gravity, solid content, pH, and dosage in % of Dynamon NRG 9040 are illustrated in Table II.

Aggregates, which are basically inert elements, make up about 70–75% of concrete. The two significant functions of aggregates are to reduce the number of voids that require cement paste filler and to provide concrete with a strong skeleton. In India, materials such as granite, quartzite, sandstone, basalt, and limestone are commonly used as aggregates. River sand is used as a fine aggregate on a large basis. The 4.75 mm IS sieve size is the line that separates fine and coarse particles. Grading is sometimes described as the total percentage of aggregate mass that flows through a given IS sieve. Coarse aggregates are categorized as single-sized, which is primarily retained between neighboring sieves, or graded, which indicates that they comprise particles of various sizes. The physical properties of the coarse aggregates are illustrated in Table III. The Fineness Modulus (FM) of the aggregates can vary.

TABLE II. PHYSICAL PROPERTIES OF CONCRETE INGRADIENTS

GGBS	Cement	Dynamon NRG 9040
Specific gravity: 2.88	Specific gravity: 3.13	Specific gravity: 1.115
Fineness: 372 Kg/m^3	Standard consistency: 27%	Solid content: 43.37%
Strength activity index (at 28 days): 110 min	fcm (7-Days): 39.57 MPa fcm (28-Days): 49.23 MPa	pH: 7.81

TABLE III. PHYSICAL PROPERTIES OF AGGREGATE

Property	Coarse aggregates		
	20 mm	10 mm	Standard
Specific gravity	2.94	2.87	
Water absorption	0.40%	0.60%	<2% (MORTH 2013)
Impact value	16.06	15.55	<20% IS: 2386 Part-4 (1963)
Abrasion value	18.01	16.24	
Crushing value	15.55	14.76	
Flakiness index	27.65%	-	

The mixture design for M-40 grade PQC was based on the IS 10262:2009 guidelines and the following materials were used: cement, sand, aggregates, GGBS, chemical additive, and water, as illustrated in Table IV. 0.4% of PC-based superplasticizer was added to the concrete mix with a w/c ratio of 0.40 to ensure adequate workability.

TABLE IV. MIX PROPORTION OF CONCRETE SPECIMEN (WT. IN KG)

Ingredients	Control	60% GGBS	65% GGBS	70% GGBS
Cement	330	176	157	138
Fly Ash	80	0	0	0
GGBS	0	264	293	322.5
10 mm	485.43	467.77	459.16	457.03
20 mm	688.08	720.22	706.96	703.68
River sand	768.32	777.4	763.08	759.55
Water	167.69	152.79	164.76	163.68
Superplasticizer	1.64	1.76	1.8	1.84
Density (kg/m^3)	2521.17	2559.94	2545.76	2546.27

IV. RESULTS AND DISCUSSION

With respect to the workability of PQC, the inclusion of a large number of water-reducing admixtures, preferably a PCE-based superplasticizer, is necessary to make PQC workable. For this experiment, a dose of 0.4 % by mass of the binder was added. The values of the standard slump test (Figure 1), which was used to determine the workability of PQC, are illustrated in Table V.

TABLE V. WORKABILITY OF PQC MIXTURES

Value	Control	60% GGBS	65% GGBS	70% GGBS
w/c ratio	0.40	0.35	0.37	0.35
Slump	30	25	25	25
Density	2487.26	2482.73	2498.8	2514.87
Air Content	1.20%	1.00%	1.00%	1.00%

The average density of the fresh concrete mixtures containing 60%, 65% and 70% GGBS was measured at 2482.73, 2498.80, and 2514.87 Kg/m^3, respectively. The density of the control concrete mixture was estimated at 2487.26 Kg/m^3, suggesting that there was no significant change in density with the addition of GGBS. The air content of fresh concrete mixes containing 60%, 65% and 70% GGBS was 1.00%, while 1.20% for the control, indicating a slight reduction in air content in cement with the addition of GGBS.

Fig. 1. Performance of experimental work in the lab.

Standard cube samples of 150 mm × 150 mm × 150 mm were produced (Figure 2) and subjected to axial compression tests using 3000 KN and following the IS 516:1999 guidelines. The mean compressive strength was derived from three cube specimens after 7, 28, 56, 90, and 180 days of aging.

Fig. 2. Casting of PQC cubes.

Table VI shows the results of the experimental procedure described in Section III. The increase in length of the GGBS containing samples compared to the control is not significant. Therefore, replacing cement up to 70% with GGBS does not have any impact on the physical dimensions of the final product.

Figure 3 shows the evolution of compressive strength over time for the PQC mixtures containing the three percentages of GGBS and the control. The average compressive strength of concrete mixtures containing GGBS exhibits a continuous increase after 28 days of curing. A slight decrease in compressive strength of 6.6% and 8.6% is observed at 7 and 28 days. The average compressive strength of the M40 grade

PQCs containing 60%, 65% and 70% GGBS shows an increase of 7.6%, 12.78%, and 13.03%, respectively, after 56 days, compared to the control. After 90 days, the compressive stress increases by 7.06%, 12.78%, and 13.03% for 60%, 65%, and 70% GGBS containing PQCs, respectively, and 31.43%, 44.15%, and 43.83% after 180 days. The evolution of compressive stress over aging time indicates that concrete with a high GGBS content gains strength over time due to the high concentration of calcium and silicon oxides of GGBS.

TABLE VI. EXPERIMENTAL RESULTS OF DRYING SHRINKAGE TEST [M40]

Sample	W (mm)	D (mm)	Δ (mm)	L (mm)	Length change (%)	Increase over control (%)
Control	281.12	277.68	3.44	274.5	1.253	
	281.073	277.762	3.311	274.5	1.206	
	280.875	277.53	3.345	274.4	1.219	
60% GGBS	280.01	276.569	3.441	274	1.256	0.003
	279.155	275.857	3.298	274	1.204	0.002
	280.533	277.177	3.356	275	1.22	0.001
65% GGBS	280.75	277.32	3.44	274.6	1.253	0.004
	279.58	276.26	3.32	274.7	1.208	0.002
	280.56	277.2	3.36	275.2	1.221	0.001
70% GGBS	281.496	278.064	3.432	275	1.246	0.005
	279.996	276.659	3.337	275.5	1.208	0.002
	280.596	277.231	3.365	275.5	1.221	0.002

W and D are the lengths of wet and dried PQC cubes, respectively. Δ is defined as the difference between the length of the wet and dried PQC cube (Δ=W-D). L is the dry length revolving in length change. The length change percentage is calculated by the equation: 100*Δ/L.

Compared to previous studies, our results show that cement replacement with GGBS can reach 70% with proper curing. In [1] GGBS was used up to a 25% cement replacement, but we achieved an increase in this proportion to a maximum of 70%. Similarly, the authors in [3] limited the use of GGBS to 6%, focusing on curing ages of 7 and 28 days. In contrast, our investigation encompasses a wider range of curing ages, spanning from 7 to 180 days. Furthermore, although the authors in [6] used a 60% replacement of GGBS in PQC, our study shows a 70% proportion of GGBS. Furthermore, while the authors in [8] demonstrated a 40% increase in strength characteristics by replacing OPC with GGBS, we achieved a more substantial enhancement in strength characteristics. Lastly, in [10] satisfactory results were achieved, showing an increase in flexural strength by using up to 50% of the GGBS cement replacement. Nevertheless, our research endeavors to utilize a higher maximum proportion of 70%.

V. CONCLUSIONS

Incorporating high volumes of Ground Granulated Blast-furnace Slag (GGBS) in Pavement Quality Concretes (PQCs) offers enhanced durability, strength, and resistance to chemical attacks. It also contributes to reducing the carbon footprint associated with concrete production. This study demonstrates the potential of replacing a large amount of cement with GGBS without compromising the structural integrity of the final product. PQCs were constructed by replacing 60, 65, and 70% of the cement with GGBS and the samples were evaluated against the control. Control specimens were cast alongside GGBS incorporating concretes to ensure comparable results using identical amounts of cement and aggregates under consistent environmental conditions for enhanced precision. The experimental results indicated negligible length changes in the drying shrinkage tests of the concrete mixtures containing GGBS compared to the control. Similarly, the fresh control and GGBS concrete mixtures exhibited a comparable average density. However, the fresh GGBS concrete mixtures exhibited air content of 1.00%, which is lower than the 1.20% air content of the fresh control mixture. Regarding the compressive strength of the PQCs samples incorporating GGBS, it is evident a significant increase in the compressive strength of the GGBS containing samples compared to the control after 50 days of curing. The average compressive strength of concrete mixtures containing 60%, 65%, and 70% GGBS increases steadily for 180 days of curing. The average compressive strength of the M40 grade concrete mixes containing 60%, 65% and 70% GGBS increased, compared to the control, by 31.43%, 44.15%, and 43.83%, respectively, after curing for180 days. This increase in compressive strength is attributed to the high content of GGBS in calcium oxide.

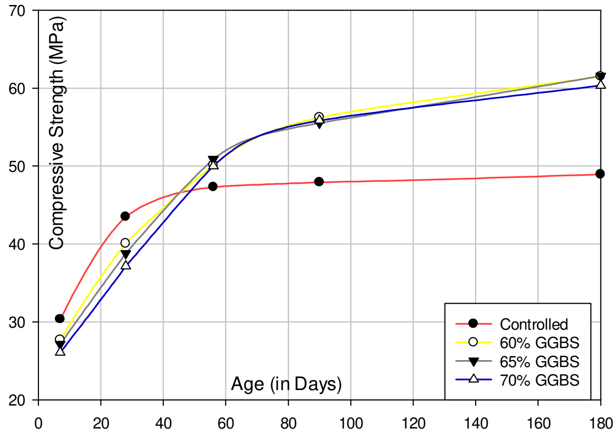

Fig. 3. Compresice strength over time for the control and GGBS incoporating PQC samples.

However, there remains a need for further research to fully understand the long-term performance and potential drawbacks of using high volumes of GGBS in PQC. This includes evaluating the impact on numerous factors such as long-term durability, environmental sustainability, and economic feasibility. The contribution of incorporating GGBS into PQC lies in its potential to revolutionize traditional concrete mix designs. By leveraging this industrial byproduct, the construction industry can significantly enhance the sustainability and performance of pavement structures. This approach offers a novel solution to reduce the environmental impact of concrete production while simultaneously improving the durability and strength of PQC. This approach aims to minimize the reliance on Ordinary Portland Cement (OPC), thereby enhancing the sustainability and efficiency of concrete production.

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