

Properties of Concrete made with Portland Cement Partly Replaced with Ground Granulated Blast Furnace Slag (GGBS)

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ABSTRACT: The use of pozzolan for cementation in concrete production has become common all over the world. When incorporated in accordance with the New European standard, British standard and other international standards, they can significantly enhance both the fresh and the hardened properties of concrete. Laboratory based experimentation was conducted to investigate the properties of concrete made by partial replacement of Portland Cement (PC) as the binder with Ground Granulated Blast-furnace slag (GGBS) as the pozzolana. Concrete cubes and cylinders were cast at a constant water/binder ratio of 0.542 and moist cured for 7, 14 and 28 days using the cementing materials. Measurements of compressive strength and porosity were determined. The results showed that the use of binary blend of PC and GGBS produces concrete with improved strengths and permeability at all replacement levels in comparison to that of PC concrete. It was established that PC-GGBS concrete properties have very good qualities, and for up to 30% replacement PC with GGBS, the concrete made become compact and less porous, with improved engineering properties. The porosity of the concrete containing pozzolana (GGBS) decreases with an increase in slag level up to 30% when compared to the control.

Keywords- Portland cement (PC), Ground Granulated Blast Furnace-slag (GGBS), Durability, Porosity and Compressive Strength, Pozzolana.

1.0 INTRODUCTION

Pozzolanic cementing materials such as fly ash, blast furnace slag, silica fume, rice husk ash and metakaolin have been used as partial replacements for portland cement. These materials can improve concrete durability, reduce the risk of thermal cracking in mass concrete and is less CO₂-intensive than cement [12]. Previous investigations on the use of high volumes of GGBS as a pozzolanic material result in more durable and sustainable concrete [13]. As a result, GGBS concrete is becoming of increasing interest for use as aggregate in structural concrete and recent research has examined its performance [14].

The need to improve construction practices worldwide and the growing environmental apprehension towards energy conservation and resources, researches globally have been directed towards the utilization of both industrial and agricultural by-products as building materials [7]. Pozzolanas from industrial and agricultural by-products such as rice husk ash, pulverized fuel ash, condensed silica fume and ground granulated blast furnace slag are receiving more attention now since their uses generally improve the properties of both fresh and hardened concrete. This, reduce heat of hydration and improve concrete's resistance to a range of durability threats, such as sulfate attack, alkali aggregates reactivity and increase demand for low cost and environmental friendly construction materials, thus strengthening economic growth and competitiveness [5]. Ground granulated blast furnace slag is an industrial by-product from the manufacture of iron. GGBS is a pozzolan by characteristics obtained by quenching molten iron slag from a blast furnace in water or steam to produce a glassy granular product. This is then dried and ground into fine powder. Investigation of the additions of GGBS in concrete noticed improved strength and reduced permeability [4]. There is a decrease in porosity of concrete paste as a result of the incorporation of GGBS with the reduction of the average pore size, thereby resulting in a less permeable paste [6]. Pozzolan are Siliceous or aluminous material, which in itself possesses little or no cementing value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide Ca (OH)₂ to form compounds possessing hydraulic cementing properties [13]. In GGBS, the amorphous glass content is considered to be the most significant variable and certainly the most critical to its hydraulicity [5]. The rate of quenching, which influences the glass content, is thus the predominant factor affecting the strengths of slag cements. The presence of alkaline activators improves the hydraulic activity in GGBS based systems [2]. At constant basicity the strength increases with the aluminium oxide (Al₂O₃) content, and a deficiency in calcium oxide (CaO) can be compensated by a larger amount of magnesium oxide (MgO). Hydraulic activity increases with increasing calcium oxide, aluminium oxide and magnesium oxide and decreases with increasing silica (SiO₂) content.

This research used GGBS as a base material for studying binary blended cement. The influence of this material on the compressive strength and permeability of concrete is discussed and the results are compared with those obtained with control Portland cement concrete. The knowledge in terms of strength and porosity would be beneficial to the understanding of the microstructures as well as for future applications of these materials in more severe and aggressive environment in which concrete is subjected to during its service life.

2.0 EXPERIMENTAL PROGRAM

A. Materials

The materials used in the research consisted of Portland cement, pozzolan as slag and natural sea-dredged sand.

Portland Cement (PC)

The PC used for this investigation is of strength class 32.5R [22] in 25 kg supplied by Lafarge Group Plc UK, complying with the European Standard [19]. Some of the other oxide and chemical composition of PC can be seen in Table I, the physical properties of the PC in Table II.

Table I: Oxide and Some Chemical Composition of PC

Oxides	PC
SiO ₂	21.0
Al ₂ O ₃	6.0
CaO	66.0
Fe ₂ O ₃	2.0
MgO	4.2
MnO	0.03 – 1.11
K ₂ O	3.5
Na ₂ O	1.5
Na ₂ O Equivalent	3.81
SO ₃	3.0
TiO ₂	1
Cl	0.01
Free Lime	-
L.O.I	4.9
Insoluble Residue	-

Table II: Physical Properties of PC.

SAMPLE	MEDIAN SIZE (µm)	COLOR	BULK DENSITY	BLAINE FINENESS
PC	14	Grey	1400.000 (kg/m ³)	3500 cm ² /g)

The Pozzolan (GGBS)

The slag used as GGBS was obtained from the Civil and Marine slag Cement limited Ltd, Newport, UK. It was in compliance with [18]. A replacement level of 10%, 20% and 30% was used. The oxide and chemical composition of GGBS is shown in Table III, the physical properties of the PC in Table IV.

Table III: Oxide and Some Chemical Composition of GGBS.

Oxides	GGBS
SiO ₂	36.6
Al ₂ O ₃	10.4
CaO	37.6

Fe ₂ O ₃	1.16
MgO	12.8
MnO	0.45
K ₂ O	0.33
Na ₂ O	0.07
Na ₂ O Equivalent	-
SO ₃	0.87
TiO ₂	-
Cl	-
Free Lime	-
L.O.I	1.72
Insoluble Residue	-

Table IV: Physical Properties of GGBS.

SAMPLE	MEDIAN SIZE (µm)	COLOR	BULK DENSITY	BLAINE FINENESS
GGBS	-	off-whit	1200.00 kg/m ³	5100 cm ² /kg.

The Sand

The sand throughout this study was natural sea-dredged sand from Bristol Channel (UK), and was in compliance with mortar composition for fine aggregate [4], with specific gravity of 2.62, fineness modulus of 2.83 and water absorption of 0.82%.

The Coarse Aggregates

The coarse aggregate used is medium graded sand combination of 10 mm and 20 mm natural round uncrushed gravel and was made available by a local quarry. It has a specific gravity of 2.73 and water absorption of 1.10%. The rough and angular surface of the 20mm crushed aggregate gives a good bond and the dust in the present in the 10mm helps to produce a good density concrete.

B. Mix Design, Sample Preparation and Testing of the Fresh Concrete

The control mix for the concrete in this work adopted a mix used on various occasions in previous researches. However it was modified for the current investigation by the authors. Cementing materials used in the study comprises of binary mixes of cement and pozzolana. The water to binder ratio used is 0.542.

Based on this control mix for the concrete, the current investigation used GGBS to replace the PC in the control mix (M1). The intention was not to maintain a specified consistency but to obtain a less porous concrete, irrespective of consistency, using GGBS aggregate and, if possible, without using super-plasticisers, for cost-effectiveness. After several trials with wide range of mixes, four mixes (M2-M4) were selected, in which GGBS aggregate was used to replace the PC aggregate in the control mix. Table V shows the various mix combinations.

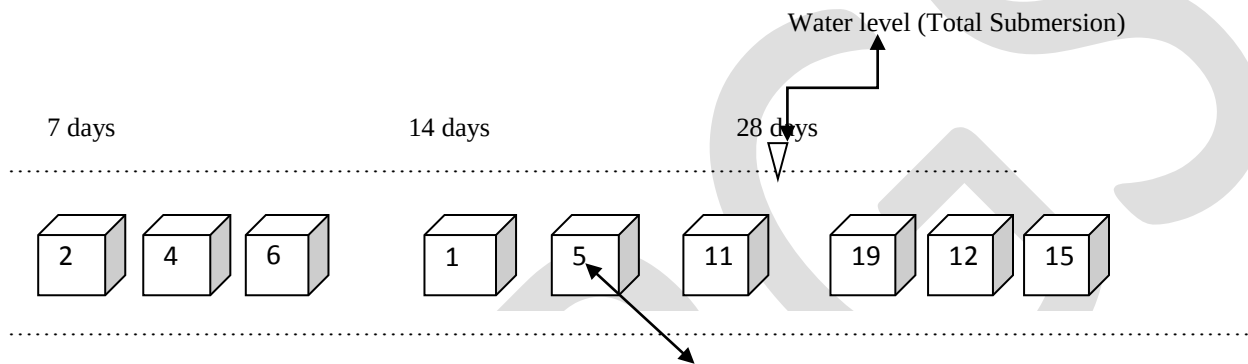
Table V. The Fresh Concrete Mix Design

Mix Code	Material	Cement (Kg/m ³)	Coarse Aggregates: (kg/m ³)		Sand (kg/m ³)	Water (kg/m ³)	GGBS (kg/m ³)
			20/10	10/4			
M1	Concrete	420	210	230	880	189	0
M2	Concrete	378	210	230	880	189	42
M3	Concrete	336	210	230	880	189	84
M4	Concrete	294	210	230	880	189	126

For the first mix using GGBS aggregate (M2), the PC aggregate in the control concrete mix was replaced with 10% GGBS aggregate. For the second mix (M3), the PC aggregate in the control concrete mix was replaced with 20% GGBS aggregate. The final mix was designated M4 and the mix was produced by replacing the PC aggregate in the control concrete mix with 30% GGBS aggregate.

The concrete samples were casted following the standard procedure. Cast samples were kept in steel moulds in a room where the temperature was controlled at $22 \pm 20^\circ\text{C}$ and were de-molded at the age of 24 ± 4 hours after casting. The aggregates were added in the mixer with a third of the water. After 5 minutes of mixing, the cement and the GGBS were added along with the rest of the water and permitted to fully hydrate. In an attempt to evade segregation and bleeding in the concrete, the fresh mixes were cast in moulds and a vibration process was introduced to homogenize the mix for one (1) minute. A method generally adopted, however it was modified in accordance with [25].

The concrete specimens cast were cubes of $100 \times 100 \times 100$ mm for the compressive strength, the rate of absorption (porosity) was carried out on all samples for the curing period ranging from 7 days, 14 days and 28 days.



Sample number (the variance in the numbering system of the sample was as a result of differences in casting dates)

Figure 1. Curing Process Illustration.

Compressive Strength of the Hardened Concrete.

The samples of size $100 \times 100 \times 100$ mm concrete cube mould for compressive strength were tested at the age of 7, 14 and 28 days respectively. The test was done in accordance with [20], and the strength was calculated as follows:

$$\text{Where: } R_c = \frac{F}{A_c}$$

R_c = The compressive strength in (N/mm^2)

F = Maximum strength in (N)

A_c = Cross sectional area of the specimen in (mm^2)

Porosity Tests of the Hardened Concrete.

Porosity of concrete is regarded as a measure of the voids (empty spaces) in the concrete, and is a fraction of the volume of voids over the total volume. The percentage of void test determines the water absorbing capacity of the specimen indicating the porosity. For this investigation the density and percentage of voids were determined using a density rig with a 32kg weighing scale based on the [21]. The specimens were then placed in water tank at a temperature of $\pm 20^\circ\text{C}$ with the capacity to submerge the whole specimen. At the end of the curing period, the specimens were removed from the tank, and the surface water wiped off with a damp cloth. The mass of the specimen in water (M_w), in air (M_a) and the actual density were directly measured using a hydrostatic weighing in accordance with BS EN [19]. The percentage of voids of each specimen determined was checked against the design mix density of concrete. The percentage of voids for each specimen was calculated as:

$$\text{Percentage of Voids (V \%)} = \left[\frac{B - A}{A} \right] 100$$

Where:

Th A = Actual density of the sample. B = Design mix density of concrete.

3.0 RESULTS AND DISCUSSION

Compressive Strength Results

Compressive strength results of the studied concrete are shown in Figure 2. The strengths of the concrete containing GGBS at the binary blended mixes were all higher than the control OPC (M1) at all ages. The incorporation of GGBS produces filler and dispersing effects and increases the nucleation and precipitation site, with increased compressive strength when compared with the control Portland cement concrete [7]. The incorporation of GGBS also produces the filler effect due to its fine particle size.

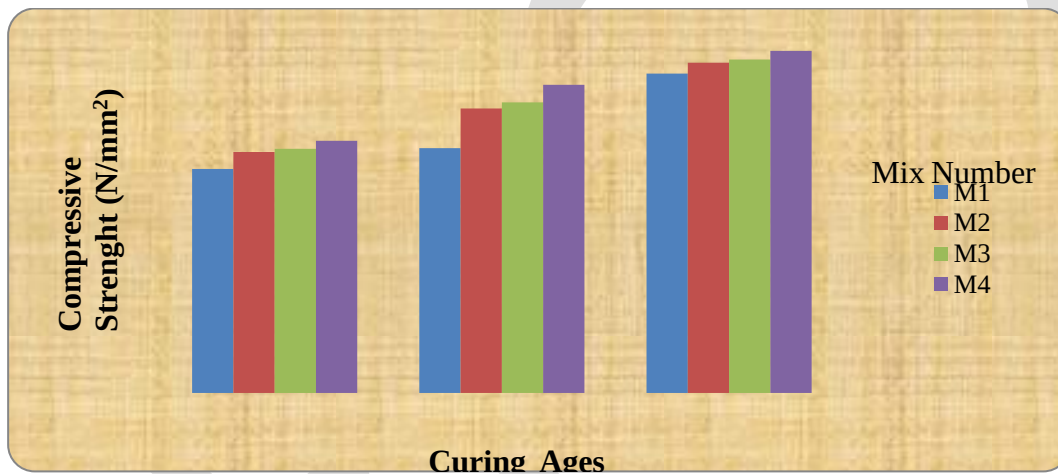


Figure 2: Compressive Strength Results for the Mixes at Different Curing Age.

Effect of GGBS on Compressive Strength of the Hardened Concrete.

The effects of different replacement levels of GGBS on the compressive strength for all the various mix composition are discussed as follows. The compressive strength of the PC used the control mix (M1) at all ages was lower than the strength of other mix composition. This is shown in Figure 2. The strength values of the mixtures prepared with GGBS mixes (M2– M4) were higher by a magnitude, which is depended on the distribution of GGBS particle sizes within the microstructure of the concrete prepared with GGBS. The higher compressive strength shown in mix (M2-M4) with the concrete containing GGBS can be attributed to the superior bonding of PC-to-GGBS interlock cementing system [15]

Compressive strength dependent mainly on the type of cement in the mortar paste and the type of aggregates; the cement/aggregate bond [12]. A good understanding of concrete's compressive strength can assist in the appropriate selection of material to minimize or possibly maximize the heat of hydration, which is influenced by the proportion of the calcium silicate hydrates (C_3S) in the cement that causes an increase in the rate of heat of evolution at early ages of the hardened concrete. The compressive strength increases as the replacement level in the concrete increases from 10% to 30%. This trend was however expected [10].

The presence of GGBS on all the blended concrete showed positive effect on strength increase up to 28 days, since GGBS contains highly reactive siliceous and aluminous materials in a finely divided form. These materials, in the presence of water react with calcium hydroxide liberated during hydration of cement to form compounds (C–S–H gel), which possess cementing properties. In addition to

this, GGBS contains Calcia (CaO) which undergoes pozzolanic reaction with silica and alumina resulting in gel formation, also the fines and large surface area which allow GGBS to be involved more in the hydration process thereby filling the pore spaces which are left unfilled by the less fine cement particles. The characteristics strength of concrete is based on the 28 days strength test; the new European Standard minimum for characteristic cube test for various mixes as required [26] the strength obtained for M1 – M4 was all above the minimum characteristic value cube strength at 28 days curing. Therefore the results are in conformity with the acceptable engineering standard. The mix is classified as C40/50. The incorporation of blend of fine pozzolanas improves the strength of concrete due to synergic effect [9]

Influence of GGBS on Porosity Results

The results of the porosity of studied concrete at 7, 14 and 28 days in terms of percentage of voids 10%, 20% and 30% of GGBS at M2, M3 and M4 respectively are shown in Figure 3. The porosities of concrete containing blend are lower than that of the control concrete M1 at all ages. The addition of fine particles of GGBS causes segmentation of large pores and increases nucleation sites for precipitation of hydration products in cement paste [1]. This results in pore refinement and a reduction of calcium hydroxide (Ca (OH)₂) in the paste as a result of dilution effect and pozzolanic reactions. The concrete containing GGBS gives less porous concrete. In other word, GGBS is effective in modifying pore and reducing the porosity of concrete.

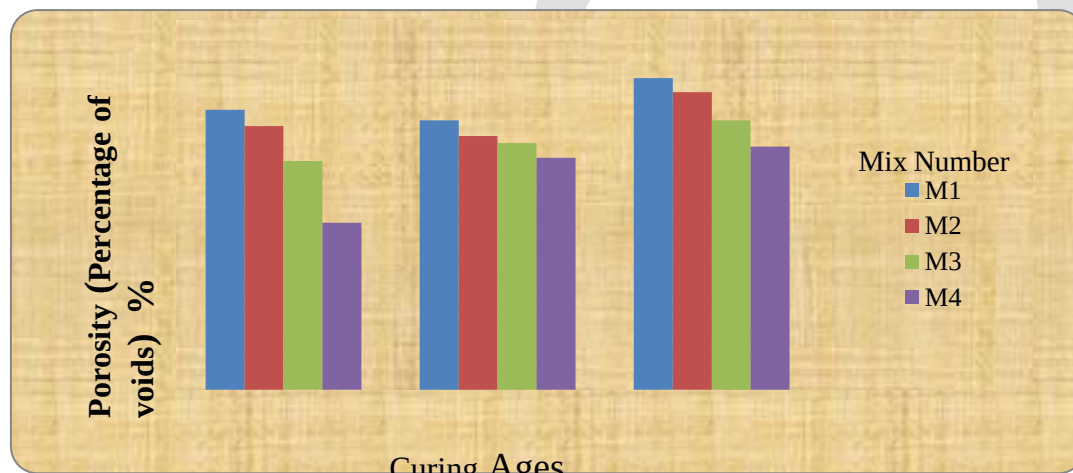


Figure 3: Porosity Results for the Mixes at Different Curing Age.

From the results, it is apparent that the percentage of voids present in the final product of concrete specimen has both direct and indirect effects on the overall performance of the concrete in service life. For instance the mechanical strength of the mixes (M2, M3 and M4) increases as curing age's progresses up to 28 days, but the percentage of void space decreases as the percentage of GGBS increases from 10% up to 30%. it was anticipated that pro-long curing (beyond 28 days) of the pozzalanic concrete of the mix (M2 – M4) will further improve the strength development. The results generally showed that, the incorporation of 10% to 30% of GGBS results in the decrease in void of the internal structure of the concrete, thereby making the concrete less permeable, [11]. Permeability is the baseline for concrete durability; a concrete with higher pore structure results in high rate of absorption, producing reduction in durability which can later lead to unbalanced tensile, excessive cracking and water ingress, and finally loss of durability when exposed to harsh environment.

This present study shows concrete containing GGBS is less permeable and chemically more stable than convectional PC concrete. This enhances its resistance to cracking and disintegration due to sulphate attack as a result of concrete exposure to aggressive water environment. The reactions between GGBS, PC and water are complex with regards to percentage of voids. This findings correlate with the result of a study, [8]. The main hydration product of PC–GGBS based system is calcium silicate hydrates. Additionally, the GGBS reacts with the excess of calcium hydroxide to form a finely dispersed gel, which fills the larger pores. The result is a hardened cement paste, containing far fewer calcium hydroxide crystals and therefore has fewer large capillary pores.

The reduction in free calcium hydroxide makes the concrete mix chemically more stable, and the finer pore structure (as a result of pore structure refinement) limits the ability of pore development and prevents chemicals diffusing through the concrete surface. Whereas in the case of mix M1, containing PC only, the PC reacts with water and creates insoluble hydration products (mainly calcium silicate hydrates). The more soluble product of hydration (calcium hydroxide) migrates through the pore solution and precipitates as discrete crystals, surrounded by large pores with expansive potential, making the PC based concrete with more pores and vulnerable to external attack.

CONCLUSIONS

The results obtained suggest that there is potential for using GGBS as partial substitutes for cement, which will facilitate more sustainable construction. The use of binary blend of PC and GGBS significantly improves the concrete in terms of strength and porosity at later age. Specifically, strength was improved at replacement levels up to 30% and porosity at higher replacement level comparable to the control Portland cement mixture. In addition, by incorporating GGBS in concrete, there is a reduction in the porosity of the concrete compared to the control Portland cement mixture. This is perhaps as a results of reduced $\text{Ca}(\text{OH})_2$ in the interfacial zone compared to the control Portland cement. Furthermore, besides meeting the strength criteria, the parameter for the concrete specimen related to porosity, (percentage of voids) upon curing was within the acceptable limits for the durability of the final concrete product to ensure sustainable development.

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