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Influence of slag and fly ash as supplementary cementitious materials on properties of concrete

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***Abstract*—This paper reports the influence of varying content of individual and combined content of fly ash and ground granulated blast furnace slag (GGBFS) as CEM-II supplementary materials on the properties of fresh and hardened concrete. The study utilized control mix without any fly ash or GGBFS. Supplementary additions of 30% separate or combined replacements of FA and GGBFS cementitious materials for ordinary Portland cement. The concrete mix C_1 was blended cement of 0FA/30GGFBS (0% fly ash and 30% GGBFS), C_2 was 10FA/20GGFBS, C_3 was 15FA/15GGFBS, C_4 was 20FA/10GGFBS and C_5 was 30FA/0GGFBS. This study confirmed the potentials of fly ash and GGBFS as supplementary materials for CEM-II blended concrete both in the plastic and hardened states. The findings showed that the workability of the control and blended cement concrete fell within the recommended range for plain and reinforced concrete. The tensile strength capacity of the concrete was enhanced by the cementitious materials with increase in curing age by immersion in water. The 28th day tensile strengths of all blended cement concrete mixtures were higher than the control value. Concrete mix C_3 had the highest tensile strength, while C_5 had the lowest tensile strengths. The compressive strength of concrete specimens with respect to control mix value increased parabolically with the mix C_3 having the maximum value of 30.8% and 59.3% higher than the 7th and 28th day control compressive strength values respectively. At 28th day, the order of increase in the compressive strength are $C_3 > C_1 > C_2 > C_4 > C_5$ which were 59.3%, 38.1%, 31.3%, 15.9% and 5.7% higher than the characteristic strength value of the control mix. Concrete mix C_3 has the greatest resistance to chloride attack with 20% strength above the control value, while C_1 (with 30% GGBFS) was the worst affected by chloride attack.**

***Keywords*—Blended cement concrete, fly ash, *ground granulated blast furnace slag,* cementitious addition, workability, compressive strength, tensile strength, chloride resistance.**

I. Introduction

Ordinary Portland cements do not completely satisfy global needs of the concrete construction industry majorly due to the fact that its primary source of raw materials is predominantly non-renewable natural resources. Consequently, blended Portland cements were conceived in the sense that they are made either by altering the compound composition of Portland cement clinker, or by blending certain additives with Portland cement, or by doing both. Ashes from the combustion of coal and some crop residues such as rice hull and rice straw, silica fume from certain metallurgical operations, and granulated slag from both ferrous and nonferrous metal industries are among the industrial and agricultural by-products that are suitable for use as mineral admixtures in Portland cement concrete. Fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans, such as calcined shale, calcined clay or metakaolin, are materials that, when used in conjunction with Portland or blended cement, contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity or both [1-2]. The energy-saving and clinker saving potentials of these cementitious materials have made them more preferred supplementary or complementary alternatives in concrete construction industry. In addition, blended cements have been reported to perform better than Portland cement in terms of the mechanical properties and durability of concrete. Presently, the production of blended Portland cements has found limestone, ground granulated blast-furnace slag, pozzolans (both industrial and agricultural fly-ashes), silica fume as useful renewable resources for classes II, III, IV and V cement.

Fly ash is a by-product of the combustion of pulverized coal in electric power generating plants. Upon ignition in the furnace, most of the volatile matter and carbon in the coal are burned off, while the coal's mineral impurities (such as clay, feldspar, quartz, and shale) fuse in suspension and are carried away from the combustion chamber by the exhaust gases. The fused material then cools and solidifies into spherical glassy particles called fly ash [1-2]. Fly ash, the most widely used supplementary cementitious material in concrete, is a finely divided powder resembling Portland cement. Most of the fly ash particles are solid spheres, some are hollow cenospheres and others are plerospheres, which are spheres containing smaller spheres [1, 3-4]. Ground clinker materials, used for Portland cement, have solid angular particles.

The particle sizes in fly ash is in the range of 1 to 100 µm, while the most common particle size is below 20 µm. Only 10 to 30% of the particles by mass are larger than 45 µm. The surface area is typically 300 to 500 m^2/kg, although some fly ashes can have surface areas as low as 200 m^2/kg and as high as 700 m^2/kg [5-7]. For fly ash without close compaction, the bulk density can vary from 540 to 860 kg/m^3, whereas with close packed storage or vibration, the range can be 1120 to 1500 kg/m^3 [7-8]. Fly ash is primarily silicate glass containing oxides of silica, alumina, iron, and calcium. Minor constituents are oxides of magnesium, sulphur, sodium, potassium, and carbon. Crystalline compounds are present in small amounts. The relative density (specific gravity) of fly ash generally ranges between 1.9 and 2.8 and the color is generally gray or tan [5,9]. Class F and Class C fly ashes are commonly used as pozzolanic admixtures for general purpose concrete. Class C fly ashes are often high-calcium (10% < CaO < 30%) with carbon contents less than 2%. Class F materials are generally low-calcium (CaO < 10%) fly ashes with carbon contents usually less than 5%, but some may be as high as 10% [1-2].

Ground granulated blast-furnace slag (GGBFS), made from iron blast-furnace slag, is a non-metallic hydraulic cement consisting essentially of silicates and aluminosilicates of calcium developed in a molten condition simultaneously with iron in a blast furnace. The molten slag at a temperature of about 1500°C is rapidly chilled by quenching in water to form a glassy sandlike granulated material. The water-quenched product is called *granulated slag* due to the sand-size particles; the material quenched by air and a limited amount of water is in the form of pellets and is called *pelletized slag*. Both products develop satisfactory cementitious properties. The granulated material, which is ground to less than 45 µm, has a surface area fineness of about 400 to 600 m^2/kg Blaine. The specific gravity for GGBFS is in the range of 2.85 to 2.95. The bulk density varies from 1050 to 1375 kg/m^3 [1-2,7].

The rough and angular-shaped ground slag in the presence of water and an activator, NaOH or CaOH, both supplied by Portland cement, hydrates and sets in a manner similar to the ordinary Portland cement. However, air-cooled slag does not have the hydraulic properties of water-cooled slag [3-5]. Granulated blast furnace slag was first developed in Germany in 1853 [10]. Ground slag has been used as a cementitious material in concrete since the beginning of the 1900s. Ground granulated blast furnace slag commonly constitutes between 30% and 45% of the cementing material in the mix when used in general purpose concrete [2, 8, 11]. Some slag concretes have a slag component of 70% or more of the cementitious material.

Cost saving was probably the original reason for the development of blended Portland cements. The common benefits of fly ash- and GGBFS-blended cement, whether as class II cement (with 6 – 35% replacement of clinker) or class III (with 36 – 65% replacement of clinker) are (1) low heat of hydration, (2) excellent durability due to its water tightness, higher impermeability and resistance to sulphate attack, (3) energy-saving, natural non-renewable resource conserving and environment protecting and (4) cost saving [1-2,5,8]. Although, extensive studies may have been conducted on the subject of cementitious additions, the production of blended cements is still in infancy in many countries. However, there is a growing interest to use pozzolanic (fly ash) and cementitious materials (GGBFS) as mineral admixtures in concrete. The strength and durability of blended cement concrete vary with the individual properties of fly ash and GGBFS which change with the processes producing them. The mainstay of Botswana economy is substantially mining and majority of the national domestic, commercial and industrial power demands in Botswana is supplied by the coal-fired power station. Tonnes of fly ash and GGBFS are the by-products of the power generation and mining activities respectively which beg for more productive management to protect the environment and the public health. Hence, the primary purpose of this paper was to investigate the influence of varying content of individual and combined content of fly ash and GGBFS as CEM-II supplementary materials on the properties of fresh and hardened concrete.

II. Description of the Study Area

Botswana is generally a mining country with the major mining activities being open cast mining. Huge amount of waste is generated from the mining sector. Processing or extraction of minerals leads to the formation of slag due to the purification processes associated with the different minerals. Located in 96 km south of the second capital city, Francistown, is the BCL Mine. Mineral processing during its operation resulted in extraction of the precious minerals but also leaves the unwanted material waste. The mine produces tonnes of waste, majority of which is slag. The slag produced is treated then piled up in stockpiles at designated areas within the mine premises. This poses a threat as it exposes the surroundings to air pollution and health hazards.

Likewise, Morupule power station is a coal fired power station near Palapye, Botswana, run by the Botswana Power Corporation. The plant provides approximately 80% of the Botswana’s domestic power generation. There are two power stations in Morupule namely Morupule A and Morupule B power stations. Morupule A has an installed capacity of 132 MW power from coal fired, steam turbine driven thermal plant with air cooled condensers and 4 turbo generators each supplying 33 MW. Morupule B produces 600 MW of power consisting of four 150 MW units. The power stations produce electricity by combustion of semi-bituminous coal to produce heat energy which in turn turns water into steam for which the kinetic energy from the steam turns turbines to generate electricity. Fly ash is produced as a by-product from the combustion of coal, which is a combination of top ash and bottom ash. Bottom ash, usually coarse, falls to the bottom of the combustion chamber and is transferred to a conveyor belt for onward transfer to a fly ash dam via trucks while fly ash is suspended in the flue gas and gathered near a chimney where it would be mixed with water to form a slurry and transferred to ash pond via a 200 mm diameter pipe. The huge quantity of fly ash generated is often disposed of at the designated ash ponds near the plant. The disposed fly ash, if not recycled or reused, poses tremendous threats to the quality of air, groundwater, surface water and soil with unprecedented health hazards, particularly, of the host and neighbouring communities.

III. Experimental Programme

A. *Materials*

Grade 32.5 ordinary Portland cement was used in this study to be blended with GGBFS and fly ash sourced from BCL Mine in Selebi Phikwe and Morupule Power Station in Palapye. The fly ash was readily processed therefore tests could be performed straight away without first having to spend time and resources on it. The GGBFS sample used in this research largely coarse lumps. The material was first pulverised using the platinery mill (pulveriser) in the Mineral Processing laboratory of the University of Botswana. The pulverised product was then sieved on the mechanical shaker and the product passing the No. 200 sieve was collected to be used as the cementitious addition.

Coarse aggregate was crushed granite of maximum nominal size of 19 mm. Fine aggregate was natural coarse sand collected from Notwane River of maximum nominal size of 4.75 mm. The particle size distribution curves of the aggregates are plotted in Figure 1. The water used as per ASTM 1602 was that similar to drinking (potable) water. This was because of the need to minimise the impurities in water that may affect the chemical reaction associated with the cementation process. Also, concrete is alkaline in nature and so is potable water (slightly alkaline).

The appearance of FA-blended and GGBFS-blended cement passing through sieve of size 50 µm , shown in Figure 2, revealed that the former is light grey and the latter is dark grey. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 1. The aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 812 [12]. The properties of fine and coarse aggregates are presented in Table 2. It is obvious that the fine and coarse aggregates employed as constituents of the concrete in the study are well-graded. Potable water of pH of 7.1 which conformed to the requirements of BS 3148 [13] was used in mixing the aggregates and cement.

Notwane river sand as fine aggregate

Crushed granite as coarse aggregate

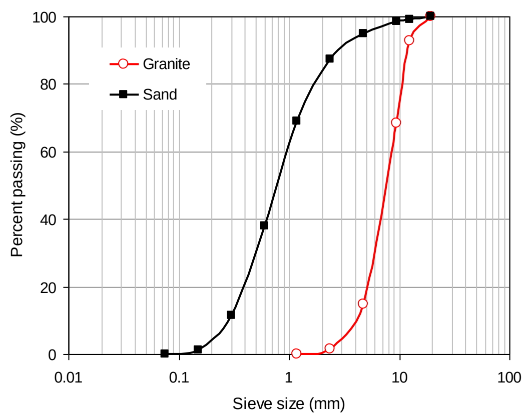

Fig. 1: Samples of particle size distribution of fine and coarse aggregates

FA blended with OPC (≤ 50 µm)

GGBFS blended with OPC (≤ 50 µm)

Fig. 2: Appearance of FA and GGBFS blended with OPC (particle sise ≤ 50 µm)

TABLE 1: PHYSICAL PROPERTIES OF CEMENT

Standard Consistency (%)	30
Specific gravity	3.15
Initial setting time (min)	290
Final setting time (min)	450
Soundness (mm)	1.0
Compressive strength (N/mm^2)	
3 days	24.5
7 days	30.8

TABLE 2: PROPERTIES OF AGGREGATES

	Sand	Crushed granite
Specific Gravity	2.64	2.70
Bulk Density (kg/m^3)	1240	1464
Moisture content	4.09	0.6
Fineness modulus	3.00	6.15
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

B. Mix proportioning and casting of concrete specimens

Six different concrete mix proportions designated C_0, C_1, C_2, C_3, C_4 and C_5 with a fixed water-cement ratio of 0.5 were considered for the study. The cementitious materials, fine and coarse aggregates were kept constant at 383 kg/m^3, 801 kg/m^3 and 1088 kg/m^3 respectively representing a concrete mix ratio of 1:2.1:2.8 in proportion of binder(s), fine and coarse aggregates respectively. The control mix C_0 with a target characteristic compressive strength of 25 N/mm^2 was purely OPC without any cementitious replacement, while other mixtures had 30% cementitious replacement of OPC. The concrete mix C_1 was blended cement of 0FA/30GGFBS (0% fly ash and 30% GGBFS), C_2 was 10FA/20GGFBS (10% fly ash and 20% GGBFS), C_3 was 15FA/15GGFBS (15% fly ash and 15% GGBFS), C_4 was 20FA/10GGFBS (20% fly ash and 10% GGBFS) and C_5 was 30FA/0GGFBS (30% fly ash and 0% GGBFS).

Each concrete mix proportion was prepared in a rotating drum mixer. The aggregates and cement were placed in the drum and mixed in parts with water to ensure a better bond between the cement paste and the aggregates. All mixing and sampling of concrete were carried out in accordance with the procedures given in BS 1881. The mix proportioning computed using arbitrary volume method is presented in Table 3.

TABLE 3: CONCRETE MIX PROPORTION

Mix proportions	C_0	C_1	C_2	C_3	C_4	C_5
Cement (kg/m^3)	384	269	269	269	269	269
FA (kg/m^3)	0	0	38	57.5	77	115
GGBFS (kg/m^3)	0	115	77	57.5	38	0
Water (kg/m^3)	192	192	192	192	192	192
Water/cement ratio	0.50	0.50	0.50	0.50	0.50	0.50
Fine aggregates (kg/m^3)	801	801	801	801	801	801
Coarse aggregates (kg/m^3)	1088	1088	1088	1088	1088	1088
Total constituents (kg/m^3)	2465	2465	2465	2465	2465	2465
Mean slump (mm)	55	67	65	62	58	53
Compaction factor	0.89	0.89	0.88	0.85	0.85	0.86

A total of thirty-six concrete cylinders of 150 mm diameter × 300 mm length f concrete mixtures C_0, C_1, C_2, C_3, C_4 and C_5 were cast, cured and tested for split tensile strength at curing ages 7 days and 28 days. Also, fifty-four 150 mm concrete cube specimens (representing nine cubes for each of the six mixtures) were cast, cured and tested for compressive strength according to BS 1881. The compressive strengths of the specimens were determined from average crushing load of 150 mm cubes at 7 days and 28 days curing age in water. Concrete specimens were cast and then covered with thin polythene membrane to minimize moisture loss. The concretes were stored and tested in the laboratory under mean air temperature of 26±1˚C. The specimens were demoulded after 24±½ hours and then transferred into a water-curing tank for the test periods. Durability assessment was determined as a function of chloride resistance by curing the cubes in 10% saline water for 28 days and testing for compressive strength.

IV. Results and Discussion

A. Properties of fresh blended cement concrete

Concrete must always be made with a workability, consistency, and plasticity suitable for job conditions. Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete. This study assessed the workability of the mix proportions using slump and compaction factor tests. Figure 3 shows the test results of workability of the six concrete mixtures. It is evident from the test results that slump fell within the recommended range for plain and reinforced concrete. Concrete mix C_1 (with 30% GGBFS) had the highest slump which was 22% higher than the control, while C_5 (with 30% FA) was 4% lower than the control. The slump linearly decreased with decrease of GGBFS (or increase of FA) in the concrete mixtures.

Likewise, the compaction factor for the control was 0.89. Concrete mix C_1 (with 30% GGBFS) had similar results as the control, while the factor slightly decreased as the GGBFS content decreased, but the mix C_5 (with 30% FA) slightly increased by 1.2% above mix C_4 (with 20% FA/10% GGBFS). Concrete mixture C_3 and C_4 has the same compaction factors. The authors could not find reasons for the non-linear parabolic relationship between compaction factor and the concrete mixture.

B. Split tensile strength of blended cement concrete

The tensile strength of concrete is about a tenth of the compressive strength. It is determined by loading a concrete cylinder across a diameter in accordance with BS EN 12390:6 [14]. The relationship between the split tensile strength of the concrete mixes and the SSA content was simply quadratic or more perfectly cubic as shown in Figure 4. Both the 7th day and 28th day tensile strength had similar trends. The 7th day compressive strength increased parabolically from C_1 (8.3% higher than the control) and reached the peak with C_3 (20.5% higher than the control) before declining to 10.8% higher than the control with C_4. Mix C_5 with (30% FA) had the lowest tensile strength which was 6.5% less than the control value.

The 28th day tensile strengths of all blended cement concrete mixtures were higher than the control value. Concrete mix C_3 (with 15% FA/15% GGBFS) was 26.5% higher than the control value, while C_5 (with 30% FA) was the lowest of the blended cement concrete with 1.9% higher than the control. It is obvious from the study the strength capacity of the concrete was enhanced by the cementitious materials with increase in curing age by immersion in water. The minimum ratio of the 7th day strength to the 28th day strength was 86% corresponding to mix C_5. It is obvious that the strength ratios for the mixtures were higher than the 70% average value.

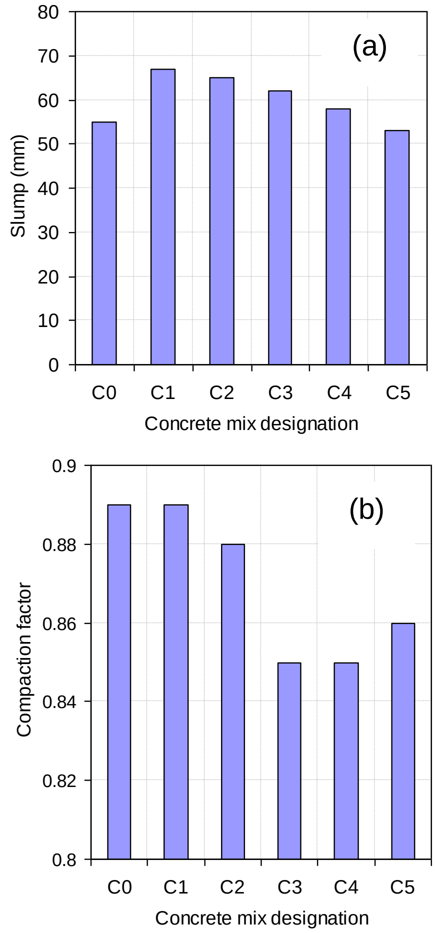

Fig. 3: Workability assessment using (a) slump test, and (b) compaction factor test.

It is obvious from the study the strength capacity of the concrete was enhanced by the cementitious materials with increase in curing age by immersion in water. The minimum ratio of the 7th day strength to the 28th day strength was 86% corresponding to mix C_5. It is obvious that the split tensile strengths are higher than the 10% of the characteristic compressive strength values.

C. Compressive strength of SSA-blended cement concrete

Compressive strength is the measured maximum resistance of a concrete specimen to axial loading. The 7th day strengths of concrete are often estimated to be about 75% of the 28th day strength [1,15]. As shown in Figure 5, the 7th day strengths of C_0, C_1, C_2,

C_3, C_4 and C_5 were 64%, 56%, 62%, 53%, 63% and 69% of the 28th strength which fell below the recommended average. The compressive strength of concrete specimens with respect to control mix value increased parabolically with the mix C_3 having the maximum value of 30.8% and 59.3% higher than the 7th and 28th day control strength values respectively. Concrete mix C_5 had the lowest strengths which were 12.9% and 5.7% higher than the 7th and 28th day compressive strength values of the control. It can be inferred from the results that the cementitious additions for all the mixes enhanced the compressive strength with increase in the curing age. At 28th day, the order of increase in the compressive strength are $C_3 > C_1 > C_2 > C_4 > C_5$ which were 59.3%, 38.1%, 31.3%, 15.9% and 5.7% higher than the characteristic strength value of the control mix C_0. This shows that the equal proportion of FA and GGBFS gave the highest compressive strength value which was similar to the split tensile strength pattern. It is also worthy of note that all the blended cement concrete mixture were higher that the threshold value of 25 N/mm^2.

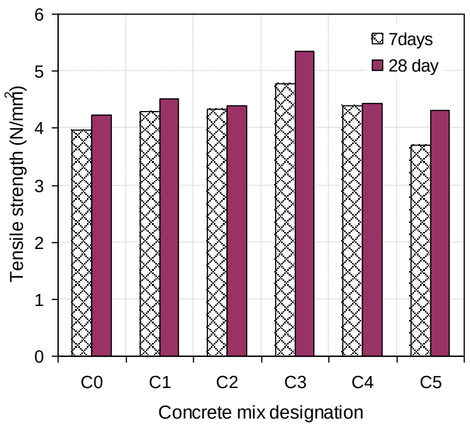

Fig. 4: Split tensile strength for blended cement concrete mixtures

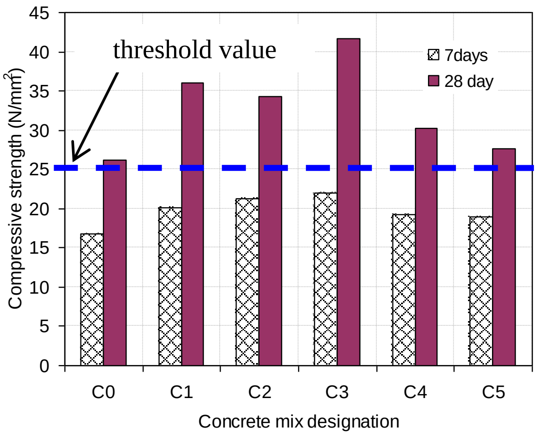

Fig. 5: Compressive strength for blended cement concrete mixtures

D. Durability assessment of blended cement concrete in saline aqueus solution

The durability of hardened blended-cement concretes was evaluated by curing the cube specimens in 10% saline aqueous solution for 7 days and 28 days. The samples were then be tested for compressive strength and compared against a control specimen made of just OPC under the same casting, curing and testing conditions. It can be seen from Figure 6 that concrete mix C_3 (with 15% FA/15% GGBFS) has the greatest resistance to chloride attack with 20% strength above the control value, while C_1 (with 30% GGBFS) was the worst affected by chloride attack with 3.9% loss of strength below the control value. Further studies of durability under medium and long-term should be conducted to property determine the behaviour of blended-cement concrete against chloride attack.

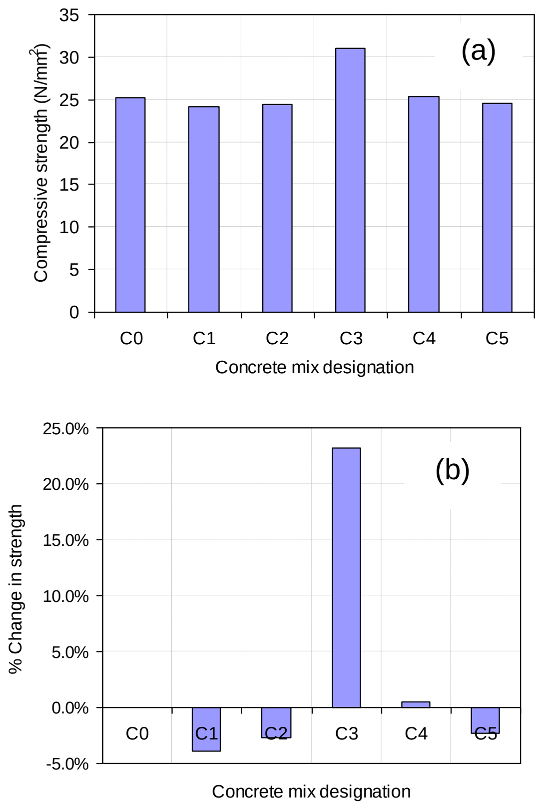

Fig. 6: Durability assessment of blended cement concrete in terms of (a) compressive strength, and (b) percentage change in control compressive strength.

V. Conclusion

This work has confirmed the potentials of fly ash and GGBFS as supplementary materials for CEM-II blended concrete. The concrete mix C_1 was blended cement of 0FA/30GGFBS (0% fly ash and 30% GGBFS), C_2 was 10FA/20GGFBS, C_3 was 15FA/15GGFBS, C_4 was 20FA/10GGFBS and C_5 was 30FA/0GGFBS. The properties of fresh and hardened blended cement concretes were investigated and the following conclusions can be drawn from the experimental study.

1. The workability of the control and blended cement concrete fell within the recommended range for plain and reinforced concrete. The slump linearly decreased with decrease of GGBFS (or increase of FA) in the concrete mixtures.
2. Concrete mix C_1 had the highest slump which was 22% higher than the control, while C_5 was 4% lower than the control. The slump linearly decreased with decrease of GGBFS (or increase of FA) in the concrete mixtures.
3. Concrete mix C_3 had the highest tensile strength, while C_5 had the lowest 7th day and 28th tensile strengths. The 7th day tensile strength increased parabolically from C_1 (8.3% higher than the control) and reached the peak with C_3 (20.5% higher than the control) before declining to 10.8% higher than the control with C_4. The 28th day tensile strengths of all blended cement concrete mixtures were higher than the control value.
4. The compressive strength of concrete specimens with respect to control mix value increased parabolically with the mix C_3 having the maximum value of 30.8% and 59.3% higher than the 7th and 28^{th} day control compressive strength values respectively.
5. Concrete mix C_3 has the greatest resistance to chloride attack with 20% strength above the control value, while C_1 (with 30% GGBFS) was the worst affected by chloride attack with 3.9% loss of strength below the control value.
6. Further studies of durability under medium and long-term should be conducted to properly determine the behaviour of blended-cement concrete against chloride attack.

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