Civil and Environmental Research
ISSN 2224-5790 (Paper) ISSN 2225-0514 (Online)
Vol.6, No.3, 2014

Partial Replacement of Portland Cement by Granulated Cupola Slag – Sustainable Option for Concrete of Low Permeability

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Abstract

This paper presents the results of investigation on the potentials of cupola slag as a partial replacement option for ordinary Portland cement (OPC) in applications requiring low permeable concrete. The chemical analysis of granulated cupola furnace slag (GCFS), its fineness, bulk density, specific gravity, and the standard consistency and setting times of binary OPC and GCFS pastes were conducted. Furthermore, concrete mixes of 0.55 water/cement ratio were produced using 1:2:4 ratio (volume basis) at 0%, 5%, 10% and 15% replacement levels of OPC by GCFS and the workability and permeability of the fresh concrete were determined. Thirty six (36) standard 150mm cubes were cast from the various concrete mixes, cured for 7, 21 and 28 days and crushed to determine their compressive strengths. The results of the tests showed that within the OPC replacement range investigated, the compressive strength of concrete progressively increased at all curing ages as the replacement level of OPC increased and attained a maximum value of 29.8 N/mm^2 at 28 days for 15% OPC replacement, which amounted to a 31.9% increase above the compressive strength of the reference concrete. In addition, the porosity of concrete decreased as the replacement level of OPC by GCFS increased. The chemical analysis of GCFS also indicated that it has pozzolanic properties. The above results indicate the suitability of granulated cupola furnace slag for use in concrete for which reduced permeability is an essential performance requirement.

Keywords: cupola slag, low permeable concrete, compressive strength, chemical analysis, sustainable

1. Introduction

1.1 Background

Sustainable development has been defined as development which meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). It is known that concrete is one of the most popular materials employed in the construction of buildings and other civil structures (Neville, 1998). Unfortunately, although the use of OPC concrete continues to bring about socio-economic benefits, some of the activities in the life cycle of concrete are hurtful to sustainability as they negatively affect the natural environment in a number of ways. One such negative influence is the depletion of the world's natural materials reserves (limestone, sand, clay, iron ore). Furthermore, cement, the key constituent in concrete, is energy-intensive in its manufacture and accounts for 5% of the global anthropogenic carbon dioxide (CO_2 – a greenhouse gas) emissions; and greenhouse gases (CO_2 and SO_2) contribute to global warming (Altwair and Kabir, 2010). The cement plants have made efforts to reduce the CO_2 emissions arising from the de-carbonation of their raw materials, by substituting a portion of the raw materials with industrial by-products such as fly ash, silica fume, granulated blast furnace slag and pozzolans all of which are collectively referred to as supplementary cementitious materials (Mehta, 1978). In practice, variations exist in the performance of concrete produced using these by-products in different countries due to the differences in the quality of the by-products, other concrete components, and the interactions among the various constituents. It is consequently imperative that local materials be tested in order to truly optimize concrete mixtures.

Premature deterioration of concrete structures is an important concern to those responsible for maintaining them as well as to the public. It is however known, that nearly all concrete deterioration processes are driven in some manner by the penetration of water and water-borne agents such as chloride and sulfate ions. One way of minimizing these problems is by making concrete less permeable by for example, densifying the cementitious paste. The densification is achieved by using lower water-cement (w/c) ratio and supplementary cementitious materials (Horst, 2001).

The objective of this research is to determine the suitability of cupola furnace slag for partial replacement of ordinary Portland cement (OPC) in order to obtain a relatively environmentally friendly concrete for use in applications for which low permeability (relative to conventional concrete) is an essential requirement.

1.2 Cupola Furnace Slag

A cupola furnace is a vertical shaft furnace used to produce cast iron by high temperature melting of metallic and mineral charge materials (Naik *et al.*, 1994). The furnace contains a continuous melting shaft which can accept a wide range of raw materials including oily, wet and contaminated scrap. Molten iron is tapped from the bottom of the furnace while slag is removed in a molten state via a slag hole. A number of research works had been conducted on the successful use of cupola furnace slag to partially or wholly replace native coarse aggregate in concrete (Naik *et al*., 1998; Tesch and Jeff, 2006). Cupola furnace slag has also been reported suitable for use as aggregate in asphalt mixtures (Lenahan, 2010) and as roadbed, base course, or sub-base material for highways. However, of greater interest is the possibility of the use of the granulated form of the slag for concrete production (Baricova *et al*., 2010; Ceccato *et al*., 2009). This is because it is only in its use for concrete production that its pozzolanic or hydraulic property can be utilized and this means using less Portland cement which ultimately translates to the reduction in the various harmful effects that result from the use of Portland cement. Other works on the use of granulated foundry furnace slag for partial replacement of Portland cement in concrete include those of Xinghua *et al*. (2000) and Naik (2005). Elsewhere, Aderibigbe and Ojobo (1982) had reported on the use of cupola slag for partial replacement of Portland cement in mortar.

Portland cement is manufactured by mixing sources of calcium oxide, silica, alumina and iron oxide in the proper proportions in a kiln. These ingredients are found in natural rock such as shale, dolomite and limestone. Cupola furnace slag can be a substitute for calcium oxide, alumina, and iron in Portland cement. One of the issues that typically limit the use of cupola furnace slag as a raw material in the manufacture of Portland cement is that it is often not available in commercial quantities. Although the quantity of the slag produced annually in Nigeria is not known, it is nonetheless known that there is an abundance of metal scraps from engines and other parts of unserviceable vehicles and such other metal scraps which are melted in the various foundry furnaces scattered across the country. Cupola slag results as by-product from these furnaces and is mostly bagged and dumped as refuse, adding to existing environmental concern. If found suitable for concrete production, the use of granulated furnace slag will reduce environmental problem caused by dumping it as refuse, reduce the cost of concrete production by partially replacing the single highest cost component (Portland cement) and reduce concrete permeability thereby improving durability of concrete constructions.

2. Materials and Methods

2.1 Materials

The cement used in this study was *Elephant* brand of ordinary Portland cement that satisfies the requirements of British standards BS 12 (1978). The fine aggregate used was river sand while the coarse aggregate was crushed granite of 25 mm maximum nominal size. In this investigation, cupola furnace slag was sourced from a dumpsite within St. Daniels foundry site in Akure, Nigeria, where it is dumped as waste product.

The slag was dumped in large lump forms. It was first dusted and isolated to remove the visible earth impurities. It was then crushed to sizes less than 20 mm with the use of jaw crusher. It was later pulverized to sizes less than 4 mm diameter with the use of a pulverizer and was afterwards ball-milled to achieve the powdered granulated form of the slag. It was sieved through 75 µm size sieve and was finally sieved through 45 µm (No. 200) in order to get a particle size similar to the 45 µm size of a Portland cement particle size.

The mix components of the materials used for the production of the test concrete is as shown in Table 1.

2.2 Methods

2.2.1 Chemical Test on Cupola Furnace Slag

The chemical test was conducted at the central research laboratory of the Federal University of Technology, Akure (FUTA). X-ray fluorescence analysis was carried out to determine the percentage oxide composition of the slag, for which purpose the sample was ground to sizes less than 75 µm and the test was run through the tube-sample-detector assembly. A computer system was connected to the equipment for automated data collection. Loss on ignition of cupola furnace slag was done by firing the sample in a crucible to 950^0c for 1 hour and the weight loss of the sample was subsequently taken.

2.2.2 Natural Moisture Content of the Fine Aggregate

The oven-drying method was used; consequently, a test portion was taken in a container and dried at a temperature of 105 ± 5 °C until it attained a constant mass. The moisture content was determined as the mass of the total moisture in the sample expressed as a percentage of the mass of the dry sample. Details of the procedure were in accordance with BS 812-109 (1990).

2.2.3 Grading of the Aggregates and Cupola Furnace Slag

The dry sieving method was used for the test. The sieve analysis of coarse aggregate (granite), fine aggregate (river sand) and granulated cupola furnace slag used for casting the concrete mixes under investigation was performed in the Geotechnical Laboratory of the Civil Engineering Department, FUTA. The sieves were arranged from 25 mm – 4.76 mm for granite, 4.75 mm – 72 µm for river sand and 500µm – 45 µm for granulated cupola furnace slag. The percentage retained on each sieve was computed by dividing the weight retained on each sieve by the original sample mass while the percentage passing (or percentage finer) was computed by starting with 100% and subtracting the percentage retained on each sieve as cumulative procedure. The entire procedure used was in accordance with BS 812 – 103.1 (1985).

2.2.4 Bulk Density

The bulk density test was carried out for granite, river sand and granulated cupola furnace slag in accordance with the provisions of BS 812 – 2 (1995). The test was performed in a weighed metal cylinder of prescribed diameter and height. In order to find the compacted bulk density, the container was filled in three layers, tamping each layer with a rod. The overflow was removed and the bulk density was computed as the ratio of the net mass of the sample in the cylinder to its volume.

2.2.5 Specific Gravity

The specific gravity test was conducted on the granite, river sand and granulated cupola furnace slag based on the guidelines given in BS 882 (1992). The specific gravity was calculated as the ratio of the mass of the sample to the mass of equal volume of water.

2.2.6 Standard Consistency

The test was conducted on the locally used Elephant brand of ordinary Portland cement and on each of the cementitious materials resulting from the various percentage replacements of OPC with granulated cupola furnace slag, in accordance with the provisions of BS EN 196 (1995). The standard Vicat apparatus was used. In the test, the plunger of the apparatus was allowed to penetrate 33 mm from the top of each of the cementitious pastes in the mould. The ratio of the mass of water required to obtain a paste that permits the 33 mm penetration to the mass of cementitious material (in percentage terms) was recorded as the standard consistence for each paste.

2.2.7 Setting Time

This test was conducted according to the recommendations of BS EN 196 (1995). The initial and final setting times were determined both for the OPC and for each of the pastes obtained by partially replacing OPC with granulated furnace slag. The initial setting time was determined as the time that elapsed from the moment water was added to the paste to the time the paste started losing its plasticity. The final setting time was determined as the time that elapsed from the time water was added to the paste to the time the paste completely lost its plasticity and obtained sufficient firmness to resist certain definite pressure.

2.2.8 Fineness

This test was performed using the dry sieving method, according to BS EN 196 – 6 (1992). Weighed OPC with varying mass quantities of granulated cupola furnace slag was poured in 45 μm sieve and shaken carefully for 8 minutes. The fineness was expressed in terms of the percentage weight of residue on the 45 μm sieve and calculated as the ratio of mass of sample retained on the 45 μm sieve to the total mass of the sample.

2.2.9 Slump

This test was carried out in accordance to BS 1881 – 102 (1983). Concrete mix ratio of 1:2:4 was batched by volume and prepared with water / cement ratio of 0.55. The decrease in the height of the slumped concrete was taken as the slump.

2.2.10 Compacting Factor

The test was carried out in accordance to BS 1881 – 103 (1993). The degree of compaction called the compacting factor was measured by the mass ratio, i.e. the ratio of the mass of the partially compacted concrete to the mass of the same concrete fully compacted.

2.2.11 Air Entrainment (Porosity)

This test was carried out according to the recommendations of BS 1881 – 106 (1993). Accordingly, freshly mixed concrete was placed in the requisite pressure air meter and compacted in 3 layers. Each layer received 50 blows and the equipment was well clamped. Water was poured in the calibrated tube up to the zero mark. Air pressure was applied by means of a bicycle pump into the concrete and measured by a pressure gauge. Due to the increase in pressure above the atmospheric pressure, the volume of air in the concrete decreased and this caused a fall in the level of the water above the concrete. The air content was read directly. This procedure was repeated for various replacement levels of OPC by granulated cupola furnace slag.

2.2.12 Compressive Strength

Cement, sand and granite were properly mixed together in the ratio 1:2:4 by volume before water was added, properly mixing together to achieve homogenous material. Ordinary Portland cement was replaced in percentages of 0, 5, 10 and 15 with granulated cupola furnace slag and 150 × 150 × 150 mm^3 moulds were used for casting. Compaction of concrete was achieved by placement in three layers and rodding each layer with 16 mm rod. The concrete was left in the mould and allowed to set for 24 hours before the cubes were demoulded and placed in curing tank. The concrete cubes were cured by complete immersion in water for 7, 21 and 28 days. Thirty six cubes were cast for 0.55 water/cement ratio and crushing tests were carried out using compression machine in accordance with the procedure of BS 1881 – 116 (1983).

3. Results and Discussions

3.1 Chemical Test of Cupola Furnace Slag

The result of the chemical test of cupola furnace slag is presented in Table 2. American Society for Testing and Materials ASTM C618 (2005) specified that for a material to be regarded as pozzolan, the addition of Al_2O_3, SiO_2 and Fe_2O_3 must give at least 70% of the total oxide composition. From the result obtained in and shown in Table 2, Al_2O_3 + SiO_2 + Fe_2O_3 for cupola furnace slag gave 85.2%. This satisfies the ASTM C618 (2005) requirement. The loss on ignition (LOI) obtained for cupola furnace slag was 9.93%. This value is less than the 10% maximum required for pozzolan as given in ASTM C618 (2005). Consequently, based on the chemical test results, cupola furnace slag can be considered a pozzolana.

3.2 Physical Properties of Aggregates and Cupola Furnace Slag

The results of the tests on the physical properties of the aggregates and the furnace slag, for the test concrete, are shown in Table 3. The table shows that the natural moisture content, bulk density and the specific gravity of the aggregates are appropriate for making normal concrete. Although the specific gravity of the granulated furnace slag is similar to that of the ordinary Portland cement used, the bulk density of the slag at 2359 kg/m^3 is higher than that of OPC which ranges from 830 kg/m^3 to 1650 kg/m^3. The implication is that partial replacement of OPC with furnace slag should result in densification of concrete.

3.3 Grading of the Aggregates and Granulated Cupola Furnace Slag

The gradings of the coarse aggregates, fine aggregates, and furnace slag are shown respectively in Tables 4, 5 and 6. Table 4 indicates that the sample was purely granite with 19 mm nominal size, confirming the suitability of the aggregate for use in concrete for construction work (BS 882, 1992). Table 5 shows that the river sand used was well graded, and ranges from fine to coarse sand thereby recommending the aggregate for use in concrete for construction work (BS 882, 1992). According to ASTM C618 (2005), the percentage of a supplementary cementitious material retained on BS 45 µm sieve must not exceed 5%. The result above gave a value of 1.14% for granulated cupola furnace slag which is less than 5%. This meets the requirement and therefore, it is a good supplementary cementitious material.

3.4 Standard Consistency

The result of the standard consistence test is presented in Table 7 for OPC and for the relevant replacement levels of OPC by granulated furnace slag. The table shows that the amount of water needed to achieve the desired consistence increases as the replacement level of Portland cement with granulated furnace slag increases. This is as expected because of the presence of carbon in the furnace slag which as it is known, increases the water absorption capacity of the material.

3.5 Setting Time

The results of the setting times test for OPC and various OPC/GCFS mixes are shown in Table 8 and presented graphically in Figure 1. Although both the initial and final setting times of the OPC/GCFS pastes were longer than those of the control OPC paste, the initial setting times were greater than the 45 mins recommended minimum while the final setting times were less than the maximum 600 mins recommended maximum according to BSI EN 196 (1995). Therefore at the replacement levels used in this work, the addition of cupola furnace slag to OPC did not adversely affect the setting time of concrete binder.

3.6 Fineness

The result of the fineness test is presented in Table 9. The result shows that as the replacement level of OPC by GCFS increases; the resulting mix contains lesser amount of material (in percentage terms) coarser than 45 µm sieve. Consequently, increase in the percentage replacement of ordinary Portland cement by cupola furnace slag improved the fineness of cement.

3.7 Tests on Fresh Concrete

The tests conducted on the fresh concrete include workability (measured by slump and compacting factor), air entrainment (for measurement of porosity) and compressive strength. The results of these tests are shown in

Table 10. The table shows that both the workability and the porosity of concrete decrease with increase in the replacement level of OPC by GCFS. In order to use this cupola furnace slag more effectively, more water needs be added to achieve a more workable fresh concrete. The air entrainment (porosity) test result showed a decrease in the void of the concrete with increase in percentage of cupola furnace slag replacement. This agreed with the fineness test result in table 9 which showed that increase in the percentage replacement of ordinary Portland cement by cupola furnace slag improved the fineness of cement. This was due to the fact that the granulated cupola furnace slag was finer than the cement alone. The cupola furnace slag contents helped to fill up the voids in the concrete and absorbed water that might have formed part of the void volume in the concrete, making the concrete less permeable with the potential to increase the compressive strength of the concrete. The low permeability has the potential to reduce the ingress into the concrete of chloride and sulphate ions thereby increasing concrete durability.

3.8. Compressive Strength

Figure 2 shows the results of the compressive strength test of concrete. From the figure, concrete strength increases with curing age. Furthermore, there is a progressive increase in strength with increase in the percentage replacement of cement with cupola furnace slag. Taking the strength at 28 days curing with 0% OPC replacement as reference (22.6 N/mm^2), 5% GCFS replacement gave a compressive strength value of 26.5 N/mm^2, which is a 3.9 N/mm^2 or 17.3% increase over the reference; 10% GCFS gave a compressive strength value of 27.2 N/mm^2, resulting in a 4.6 N/mm^2 or 20.4% increase over the reference. Finally, 15% GCFS gave a compressive strength value of 29.8 N/mm^2, which is a 7.2 N/mm^2 or 31.9% increase over the reference. The strength activity indices of the 5%, 10% and 15% replacement levels are respectively 117%, 120% and 132%.

4. Conclusions

All the concretes with the various percentage replacements tested have greater compressive strength values at 28 days curing than that at 0% replacement. The compressive strengths of the test cubes increased with age and with percentage replacement, with the control having the least value and 15% cupola furnace slag replacement having the highest value. Compressive strengths for 5%, 10% and 15% replacements with cupola furnace slag were above 25 N/mm^2. This shows that partial replacement of ordinary Portland cement with cupola furnace slag as new construction material can be utilised for structural concrete with satisfactory strength. In addition, the porosity / permeability of concrete decreased with increase in percentage replacement of OPC by GCFS throughout. All these point to high potential and possibility of use of furnace slag in concrete production, especially in aggressive media because of its low permeability compared to 100% OPC concrete.

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Table 1. Mix Components for Test Concrete

Percentage Replacement (%)	Number of Cubes	Portland Cement Used (kg)	Granulated Cupola Furnace Slag (kg)	River Sand (kg)	Granite (kg)
0	9	9.37	-	18.74	37.48
5	9	8.90	0.47	18.74	37.48
10	9	8.43	0.94	18.74	37.48
15	9	7.96	1.41	18.74	37.48
Total	36	34.66	2.82	74.96	149.92

Table 2. Oxides Composition of Granulated Cupola Furnace Slag (GCFS)

Compound	Al_2O_3	SiO_2	SO_3	CaO	MnO	Fe_2O_3	CuO	Eu_2O_3	HfO_2	TiO_2	Cr_2O_3	SrO	ZrO_2	La_2O_3	Total	LOI (%)
Oxides (%) in GCFS	-	16	-	0.75	6.27	69.20	0.95	0.90	2.90	0.37	0.83	0.53	1.10	0.08	99.88	9.93

Table 3. Physical Properties of Aggregates and Granulated Cupola Furnace Slag

Type of Test	River Sand	Granite	Granulated Cupola Furnace Slag
Natural moisture content (%)	6.82	-	-
Bulk density (kg/m^3)	2102	1491	2359
Specific gravity	2.64	2.74	3.15

Table 4. Particle Size Distribution for Granite Sample

Sieve Size (mm)	Mass of sieve (g)	Mass of sieve + sample (g)	Mass Retained (g)	Percentage retained (%)	Percentage Passing (%)
25	490.6	490.6	0	0	100
19	521,5	654.7	133.2	26.64	73.36
14	410.0	720.4	310.4	62.08	11.28
12.75	630.0	669.8	39.8	7.96	3.32
9.5	377.7	392.8	15.1	3.02	0.3
6.7	515.4	515.7	0.3	0.06	0.24
6.3	401.9	402.0	0.1	0.02	0.22
4.76	618.9	619.0	0.1	0.02	0.2
Pan	276.7	277.7	1.0	0.2	0
Total			500	100	

Table 5. Particle Size Distribution for River Sand Sample

Sieve Size (mm)	Mass of sieve (g)	Mass of sieve + sample (g)	Mass Retained (g)	Percentage retained (%)	Percentage Passing (%)
4.75	381.8	405.0	23.2	4.64	95.36
2.36	480.1	512.9	32.8	6.56	88.8
1.70	417.3	448.6	31.3	6.26	82.54
1.18	444.4	494.0	49.6	9.92	72.62
0.60	334.9	495.5	160.6	32.12	40.5
0.50	365.7	374.1	8.4	1.68	38.82
0.425	353.2	358.4	5.2	1.04	37.78
0.212	311.4	446.7	135.3	27.06	10.72
0.18	370.0	385.7	15.7	3.14	7.58
0.15	263.7	282.7	19.0	3.8	3.78
0.075	312.7	327.3	14.6	2.92	0.86
Pan	276.7	281.0	4.3	0.86	0
Total			500	100	

Table 6. Particle Size Distribution for Granulated Cupola Furnace Slag

Sieve Size (mm)	Mass of sieve (g)	Mass of sieve + sample (g)	Mass Retained (g)	Percentage retained (%)	Percentage Passing (%)
0.5	365.7	405.7	40	8.0	92.0
0.425	353.2	357.1	3.9	0.78	91.22
0.212	311.4	433.0	121.6	24.32	66.9
0.15	263.7	504.5	240.8	48.16	18.74
0.075	312.7	397.6	84.9	16.98	1.76
0.045	420.0	425.7	5.7	1.14	0.62
Pan	276.7	279.8	3.1	0.62	0
Total			500	100	

Table 7. Standard Consistency Test Result

Replacement of OPC by GCFS (%)	0	5	10	15
Mass of cement (g)	400	380	360	340
Mass of GCFS (g)	0	20	40	60
Penetration of plunger from the top of the mould (mm)	33	33	33	33
Mass of water (g)	112	112	120	128
Water content (%)	28	28	30	32
Time of mixing (minutes)	4	4	4	4

Table 8. Setting Time Test Result

Replacement of OPC by GCFS (%)	0	5	10	15
Initial setting time (minutes)	113	160	220	267
Final setting time (minutes)	188	250	341	423

Table 9. Fineness Test Result

Replacement of OPC by GCFS (%)	0	5	10	15
Mass of cement (g)	50	47.5	45	42.5
Mass of GCFS (g)	0	2.5	5	7.5
Fineness (%)	10.0	6.0	5.0	4.6
Time of sieving (minutes)	7½	7½	7½	7½

Table 10. Test Results on Fresh Concrete

	Granulated Cupola Furnace Slag			
Percentage replacement (%)	0	5	10	15
Average Slump (mm)	12	11	11	9
Compacting Factor	0.93	0.91	0.89	0.88
Air Void (%)	1.2	0.8	0.7	0.6

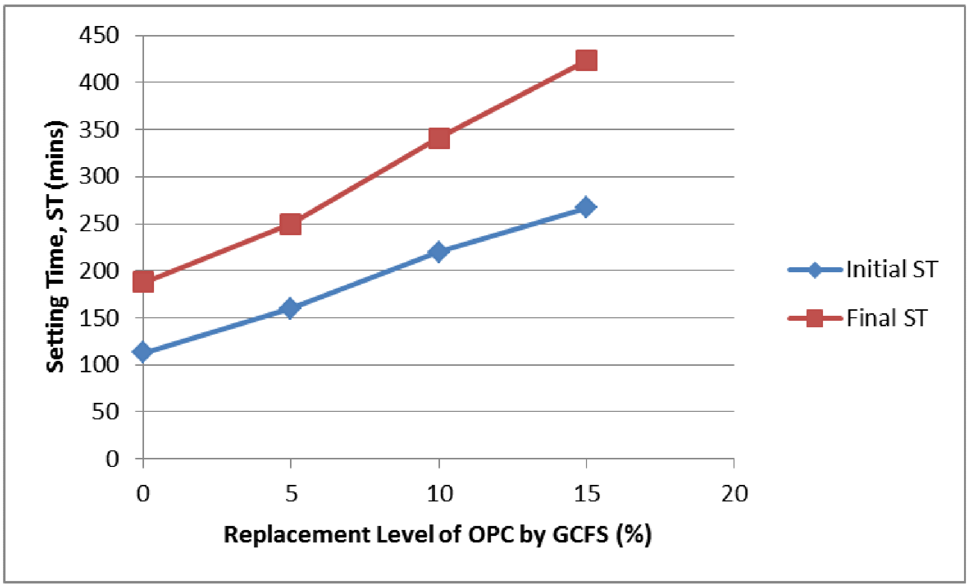

Figure 1. Curves of Setting Times for Different OPC/GCFS Mixes

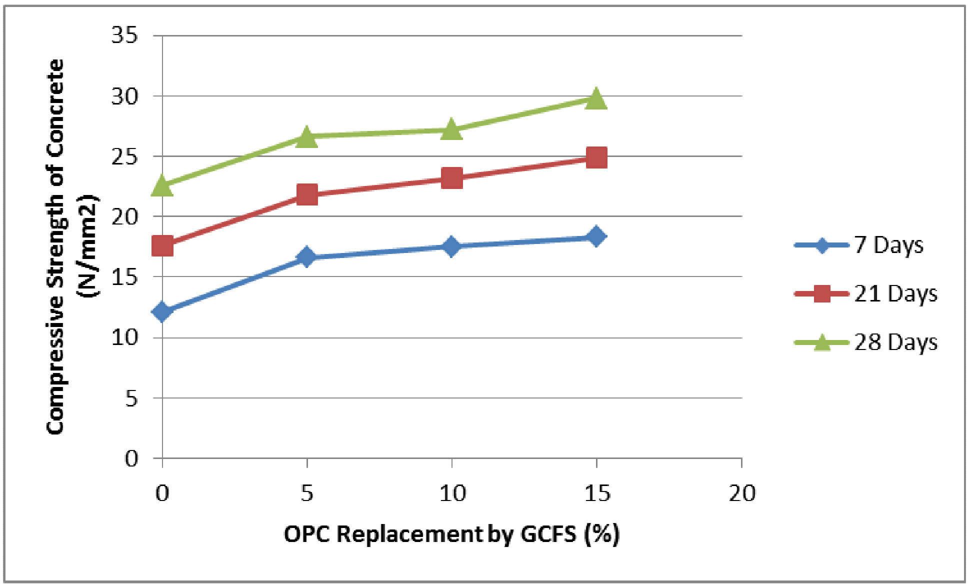

Figure 2. Curves of Compressive Strength of OPC/GCFS Concrete