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An Investigation Of The Compressive Strength Of Plain Concrete Produced With Calcium Aluminate-Treated Pulverized Steel Slag As Partial Replacement For Ordinary Portland Cement

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***Abstract:** This study aimed at investigating the compressive strength of plain concrete produced with calcium aluminate-treated pulverized steel slag as partial replacement for Ordinary Portland Cement. The study considered constant water: cement ratio and curing conditions. A maximum water absorption capacity of 152% was observed for the concrete cubes, irrespective of mix proportion and this occurred after 120 h. An optimal value of 30.44 N/mm2 was obtained at 10% replacement after 60 days for the 1:2:4 concrete samples. Again, the optimal value of approximately 30 N/mm2 was obtained at 10% replacement after 60 days for both the 1:3:6 and 1:4:8 concrete samples. This showed that a maximum replacement of 10% is needed for an optimal compressive strength value when using blast furnace slag as partial replacement for the Ordinary Portland Cement at constant water: cement ratio and curing conditions. The study recommended that steel slag should be recycled or re-utilized for plain concrete production so as to reduce overall cost of concrete.*

I. INTRODUCTION

Steel slag is a steel-making waste from the steel industry and is reused as it is in many engineering fields, including transportation and highway engineering, environmental engineering, and geotechnical engineering. It is used as either an additional or substitute material in road construction, filter or soil stabilizer in these cases. Indeed, soil stabilization using steel slag is popular in Europe and Asian country as a result of a concerted effort towards reducing wastes and optimizing resources.

Steel slag can be produced from two different processes, namely, from the conversion of iron into molten iron and from the manufacturing process to modify the components of molten iron in making strong steel. The byproducts of the processes can be categorized as the blast furnace slag and steel-making slag. There are two types of blast furnace slag, that is, the air-cooled slag and the granulated slag. Steel-making slag includes the converter slag and electric arc furnace slag.

Regardless of the processes to produce the slags, their size and shape are similar, though they have different chemical and mechanical properties. For instance, steel-making slag has a lower specific gravity than blast furnace slag, while electric arc furnace slag is usually darker than the other types of steel slag.

In the production of iron, blast furnace slag and basic oxygen furnace slag are generated. Both types of slag are produced in the blast furnace, where it rises above molten iron due to its specific gravity of being less than that of molten iron. This enables ease of separation of the slag from the furnace. Upon removal from the furnace, the cooling method used determines the type of slag produced. If the natural cooling process is used, with water being sprayed over the slag, it is categorised as an air-cooling slag.

On the other hand, if a pressurized jet is used to make it cool rapidly, a granulated slag is formed. The molten iron from a blast furnace will be processed to make strong steel. If a converter is used in the steel-making process, with water being sprayed on the slag for cooling purpose, the slag generated is termed a converter slag. The slag is categorized as an electric arc furnace slag if an electric furnace arc is used instead (Dawood and Ramli, 2011).

The cementing properties of activated steel slag using alkaline are higher than those of raw steel slag due to the chemical reactions between the steel slag and sodium hydroxide (NaOH). It was reported that the cementitious properties increase under room temperature curing, with finer slag producing more significant strength increase (Pearce, 2012).

The most commonly used alkaline activators are sodium hydroxide, potassium hydroxide, sodium water glass, and potassium water glass. All these activators have some common properties: caustic, corrosive, and highly hazardous. Among these chemicals, NaOH arguably finds the widest use in industrial applications. This is attributed to both the low price and availability in various forms, that is, granules, flakes, or pellets.

Wang and Yan recommended the NaOH: steel slag ratio of 30%, based on steel slag in dry condition and the NaOH in liquid form for mixing. Calcium aluminates are a range of minerals obtained by heating calcium oxide and aluminium oxide together at high temperatures. They are encountered in the manufacture of refractories and cements.

The stable phases shown in the phase diagram (formed at atmospheric pressure under an atmosphere of normal humidity) are: Tricalcium aluminate, $3CaO{\cdot}Al_2O_3$ (C3A); Dodecacalcium hepta-aluminate, $12CaO{\cdot}7Al_2O_3$ (C12A7) (mayenite); Monocalcium aluminate, $CaO{\cdot}Al_2O_3$ (CA); Monocalcium dialuminate, $CaO{\cdot}2Al_2O_3$ (CA2); Monocalcium hexa-aluminate, $CaO{\cdot}6Al_2O_3$ (CA6). In addition, other phases include: Dicalcium aluminate, $2CaO{\cdot}Al_2O_3$ (C2A), which exists only at pressures above 2500 MPa.

The crystal is orthorhombic, with density 3480 $kg{\cdot}m^{-3}$; Pentacalcium trialuminate, $5CaO{\cdot}3Al_2O_3$ (C5A3), forms only under an anhydrous and oxygen free atmosphere. The crystal is orthorhombic, with a density of 3067 $kg{\cdot}m^{-3}$. It reacts rapidly with water; Tetracalcium trialuminate, $4CaO{\cdot}3Al_2O_3$ (C4A3), is a metastable phase formed by dehydrating $4CaO{\cdot}3Al_2O_3{\cdot}3H_2O$ (C4A3H3).

This study aimed at investigating the water absorption properties of plain concrete produced with calcium aluminate-treated steel slag as substitute for Ordinary Portland Cement.

II. MATERIALS AND METHOD

A. MATERIALS

Ordinary Portland Cement: Dangote brand of ordinary Portland cement with properties conforming to BS 12 was used in this study.

Steel Slag: Steel slag was obtained as a by-product of the production of iron.

Calcium aluminate: This was bought from marketers of industrial chemicals.

Aggregates: The coarse aggregate from crushed granite was collected from igneous origin. The particle size used ranged between 5 to 20 mm (Croney, 2008). River sand as fine aggregate was used to mix the concrete conforming to BS 882 and the ASTM Standard C33 (2006). All particles passed through ASTM sieve No. 4 aperture 4.75 mm but were retained on sieve No. 230, aperture 63 µm (Porter,2011).

Water: The Potable drinking water was collected from the laboratory stand post and conformed to the specification of EN 1008

B. METHODS

Preparation of the test specimens: Concrete cube sizes of 150x150x150 mm and prisms having dimension of 100x100x300 mm were cast for plain steel slag/OPC concrete for the determination of different water absorption properties and compressive strengths of the concrete samples. The mix proportions of 1:2:4, 1:3:6 and 1:4:8 by the weight of binder, river sand and crushed stone were used to cast the specimens (Alexander and Milne, 1995).

The water/cement ratio used was 0.4 for all the mixes. The water/cement ratio was maintained constant at all different volume percentages of OPC and slag. Seal frost adhesive was also used for quick setting of concrete. 70 grams seal frost was used per 1 kg binder. In preparing the specimens, at first, sand and binder were properly mixed in the machine and then crushed stones were added. All ingredients were mixed properly with use of concrete mixing machine.

Fresh concrete workability was investigated immediately after the final mixing of the concrete using slump test. To avoid void, hammer and vibrator were used for compaction. The cubes and prisms were cast by filling each mould in three layers; each layer had been compacted normally with 25 blows from a steel rod of 16 mm diameter before the next layer was poured and for the prisms, vibrator was used (Packer, 2007). An average slump value of 72 mm was achieved for the plain concrete, which represented high workability. All specimens were left in the moulds for 24 h to set under ambient temperature. They were removed from the mould and transferred into a curing tank. The curing temperature was 30±2°C. The concrete mixes and the specimens were prepared in accordance with the provisions of ASTM C330 (2009), ASTM C469, (1987) and BS 8110-1 standards.

Water absorption of concrete cubes: The concrete cubes were air dried and their weights were measured and recorded. They were then immersed in drinking water in a curing tank in the laboratory for 24 h and their weights were also measured and recorded. This weight measurement was carried out on the samples every 24 h until the average wet concrete weight was constant (a point of saturation). The water absorption capacity "W" was calculated using equation 1:

$$W = \frac{W_{sw} - W_{ad}}{W_{ad}} \times 100\% \qquad (1)$$

where, W_{sw} and W_{ad} were the weight of saturated wet concrete cubes in drinking water and weight of air dried cubes, respectively. The measurements were carried out at 24 h intervals for 7 days. Experimental data showed that the maximum water absorption of the concrete cubes occurred during the first 24 h and increased up to 120 h.

Compressive strength test: Two types of universal testing machine were used to determine the compressive strength of Slag: OPC concrete. Avery Denison testing machine is manufactured in the United Kingdom. The rate of loading of this machine is 10-3000 kN min^{-1}. Experiments were done using this machine with a loading rate of 136 KN min^{-1}. Dartec testing machine was also used to determine the compressive strength of Slag: OPC concrete. This machine can plot automatically a graph of load vs. remote. From the given graph or data, it is possible to make stress- strain graph of a specific sample. The loading capacity of this machine is up to 500 KN.

The compressive rate of this machine is from 0.00015 to 2.0 mm sec^{-1}. The experiment has been done using this machine with a compressive rate of 0.00015 mm sec^{-1}. Compressive strength test of plain Slag: OPC concrete was carried out to find out the ultimate failure load and compressive strength. Static loading tests were done with use of DARTEC testing machine.

III. RESULTS AND DISCUSSION

A. RESULTS

Sample No.	Time (h)	Water absorption (%)
1	24	116
2	48	120
3	72	130
4	96	138
5	120	152
6	144	152
7	168	152

Table 1: Water absorption capacity of 5% steel slag concrete cube samples

Sample No.	Time (h)	Water absorption (%)
1	24	119
2	48	124
3	72	136
4	96	142
5	120	152
6	144	152
7	168	152

Table 2: Water absorption capacity of 10% steel slag concrete cube samples

Sample No.	Time (h)	Water absorption (%)
1	24	130
2	48	136
3	72	141
4	96	148
5	120	150
6	144	152
7	168	152

Table 3: Water absorption capacity of 15% steel slag concrete cube samples

% Replacement of OPC	7 days	14 days	21 days	28 days	60 days
0	13.88	17.44	20.88	25.42	33.46
5	13.55	16.53	20.74	24.81	31.65
10	12.46	15.85	20.21	23.54	30.44
15	11.87	14.20	18.85	22.13	28.62
20	11.22	13.51	17.62	21.62	26.58
25	10.34	12.86	17.25	20.44	25.11

Table 4: Compressive strength of 1:2:4 concrete samples (N/mm^2)

% Replacement of OPC	7 days	14 days	21 days	28 days	60 days
0	13.88	17.44	20.88	25.42	33.46
5	12.87	15.11	18.86	23.22	30.12
10	11.75	14.24	17.95	22.64	29.51
15	11.21	13.87	16.33	20.74	26.42
20	10.75	12.53	15.11	18.72	24.86
25	10.10	11.32	14.73	18.10	23.44

Table 5: Compressive strength of 1:3:6 concrete samples (N/mm^2)

% Replacement of OPC	7 days	14 days	21 days	28 days	60 days
0	13.88	17.44	20.88	25.42	33.46
5	12.96	15.22	18.73	23.14	30.21
10	11.55	14.20	17.74	22.58	29.47
15	11.19	13.75	16.41	20.70	26.40
20	10.68	12.48	15.00	18.66	24.79
25	10.00	11.28	14.71	18.00	23.38

Table 6: Compressive strength of 1:4:8 concrete samples (N/mm^2)

B. DISCUSSION OF RESULTS

During mixing and drying of matrix, the concrete cubes absorbed water and expanded due to the slag content. The swelling of the Slag: OPC matrix was observed, initially, at least at the micro-level. Then at the end of the drying process, the concrete samples lost their moisture and shrank back almost to their original dimensions leaving very fine voids around themselves. The cubes then continued to absorb water over time until a point of saturation.

A maximum water absorption capacity of 152% was observed for the concrete cubes, irrespective of mix proportion and this occurred after 120 h. Specifically, from Table I, the 5% steel slag concrete samples had 116,120,130 and 138% water absorption at 24, 48, 72 and 96h, respectively but had a constant 152% from 120h. Again, from Table II, the 10% steel slag concrete samples had 119,124,136 and 142% water absorption at 24, 48, 72 and 96h, respectively but had a constant of 152% from 120h.

From Table III, the 15% steel slag concrete samples had 130,136,141,148 and 150% water absorption at 24, 48 and 72 but had a constant value of 152% from 144h. From Table IV, the compressive strengths of the 1:2:4 concrete samples were 24.81, 23.54, 22.13, 21.62 and 20.44 N/mm^2 for 5,10,15,20 and 25% OPC replacements, respectively, at 28 days. These gradually increased to 31.65, 30.44, 28.62, 26.58 and 25.11 N/mm^2, respectively at the age of 60 days. An optimal value of 30.44 N/mm^2 was obtained at 10% replacement after 60 days. From Table V, the compressive strengths of the 1:3:6

concrete samples were 23.22, 22.64, 20.74, 18.72 and 18.10 N/mm^2 at 28 days for 5,10,15,20 and 25% replacements, respectively. These improved to 30.12, 29.51, 26.42, 24.86 and 23.44 N/mm^2, respectively at 60 days. The optimal value of approximately 30 N/mm^2 was obtained at 10% replacement after 60 days. From Table VI, the 1:4:8 concrete samples had compressive strengths of 23.14,22.58,20.70,18.66 and 18.00 N/mm^2 for 5,10,15,20 and 25% replacements, respectively at age 28days. These gradually improved to 30.21, 29.47, 26.40, 24.79 and 23.83 N/mm^2, respectively at 60 days of age. The optimal compressive strength of approximately 30 N/mm^2 was obtained at 10% replacement after 60 days.

IV. CONCLUSION AND RECOMMENDATIONS

A maximum water absorption capacity of 152% was observed for the concrete cubes, irrespective of mix proportion and this occurred after 120 h. An optimal value of 30.44 N/mm^2 was obtained at 10% replacement after 60 days for the 1:2:4 concrete samples. Again, the optimal value of approximately 30 N/mm^2 was obtained at 10% replacement after 60 days for both the 1:3:6 and 1:4:8 concrete samples. This showed that a maximum replacement of 10% is needed for an optimal compressive strength value when using blast furnace slag as partial replacement for the Ordinary Portland Cement at constant water: cement ratio and curing conditions. Granulated slag is often used in concrete in combination with Portland cement as part of blended cement.

Granulated slag reacts with water to produce cementitious properties. Concrete containing granulated slag develops strength over a longer period, leading to reduced permeability and better durability. Since the unit volume of Portland cement is reduced, this concrete is less vulnerable to alkali-silica and sulfate attack. This previously unwanted recycled product is used in the manufacture of high-performance concretes, especially those used in the construction of bridges and coastal features, where its low permeability and greater resistance to chlorides and sulfates can help to reduce corrosive action and deterioration of the structure. The slag can also be used to create fibers used as an insulation material called *slag wool*.

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