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ABSTRACT

This paper presents results of an experimental research project into the effect of using pulverised copper slag (CS) as partial replacement for ordinary Portland cement (OPC). Cement was replaced in the following proportions; 2.5, 5, 10 and 15% compared to the control (0%) specimen. Test performed included X-ray diffraction (XRD) and X-ray Fluorescence (XRF) respectively for mineralogical and chemical oxide composition. The compressive and flexural strength developments of samples concrete were determined for up to 90 days of water curing. Oxygen permeability, water sorptivity and chloride conductivity tests were performed to assess the long term durability performances.

In assessment of the hydraulic properties of slags, the hydraulic activity index of the copper slag was found to be approximately 0.5, less than the requirement for usage as constituent for cement as per SANS 55167-1:2011. The results of the strengths tests of the concrete cubes and beams showed a reduction in strength with increasing copper slag content. However, there was observed an improvement in the durability properties of the concrete samples with increase in copper slag content.

Keywords: Pozzolan, hydraulic index, compressive strength, oxygen permeability, water sorptivity, chloride conductivity index

Figure 1.1: Slag Heap Adjacent To A Farm Plantation in Democratic Republic of Congo

Figure 1.2: A Slag Dumping Site In Likasi, Democratic Republic of Congo

Figure 1.3: Metallic Trace Elements Dispersed into the Katamanda River

Figure 1.4: Slag Mountain Seen In The Background Close To Residential Area in DRC

1. INTRODUCTION

South Africa like many other countries, is witnessing a rapid growth in the construction industry, involving the use of natural resources for the development of infrastructures. This growth is jeopardized by the lack of natural resources that are available. Natural resources are depleting worldwide, while at the same time the generated wastes from the industry are increasing substantially (Al-Jabri, 2009). Slag, the glassy materials left when metals are either hydrometallurgical or pyrometallurgical extracted from their ores, in the metallurgical industries have traditionally been considered a waste product (Gorai et al., 2002). Waste from extractive industries are therefore to be properly managed, in order to ensure in particular the long term stability of disposal facilities and to prevent or minimise any water and soil pollution arising from acid or alkaline drainage, as well as, the leaching of heavy metals (European Commission, 2012). Current management options of slags are recycling and recovering of metal, production of value added products and the disposal in slag dumps, stockpiles or tailing dams.

Over the years, rigorous environmental impacts have been associated with copper tailings dam failure. According to Grimalt et al., (1999) approximately 2 million m^3 of mud containing heavy metals were spread over 4 286 ha of land and surface water during the 1998 Aznalcollar tailings pond failure in Spain. Lungu (2008) also highlighted that, the year 2000 tailings spillage at Nchanga Copper Processing Plant in Zambia released high concentrations of heavy metals into the nearby surface water, thereby contaminating the local source of water supply. Similar contamination of the Katamanda River in Lubumbashi, Democratic Republic of Congo (DRC), was also observed by Mutombo et al., (2011). According to the authors, metallic trace elements such as Cu, Co, Cd, Pb, and Zn shown in Figure 1.3, are frequently dispersed into the Katamanda River due to an adjacent heap of slag tailings produced by Electronic Foundry Panda (FEP) copper plant in Lubumbashi.

A case study of the slags from the copper mining areas of the Democratic Republic of Congo was presented by Mutombo et al., (2011). After about 40 years of mining large quantities of copper, the Authors concluded that, significant amount of slag has been generated. Figure 1.1 shows a slag mountain in the background adjacent to a farm and the Katamanda River used by the locals in DRC.

2. EXPERIMENTAL PROCEDURE

2.1 Materials Used

OPC, CEM 52.5 N procured from PPC Ltd was used for this research study. Coarse aggregates (granite) of nominal sizes between 18-20 mm and fine aggregates (crushed granite) between nominal sizes of 75 μm-4.75 mm were used. The properties of the cement conformed to the requirements of BS EN 197-1:2000, whiles the sampling of the aggregates was done in accordance with BS 812: Part 102. The copper slag (CS) used for this experiment was brought from Katanga, Democratic Republic of Congo. Katanga is a province with several mining companies producing copper and cobalt. The physical appearance of the CS is black, glassy and granular in nature, with particle size range similar to conventional sand used for concrete production.

2.2 Chemical Composition

The mineralogical and glass content of the CS sample were obtained using the Rietveld X-Ray Diffraction (XRD) method. The elemental oxide composition of the CS sample was obtained using the X-Ray fluorescence spectrometer to determine all the major oxides present in the sample. The XRF of both the CS sample and cement were analysed in South Africa by Lafarge's Chemical laboratory, whiles the XRD was performed in Germany by Heidelberg Technology Centre.

2.3 Blaine Air Permeability Test

The fineness of both slag and cement has a significant effect on the physical properties when used in concrete. Generally the finer the slag powder, the more rapid the concrete will set, as there is an increase exposure of the surface area, consequently increasing the rate of micro reaction. The Blaine air permeability apparatus was used to determine the fineness of Portland cement and pulverized CS in terms of the specific surface, expressed as total surface area in square centimetres per gram as per EN196-6. The Blaine apparatus draws a defined volume of air through a prepared bed of compacted cement powder of defined porosity. The resistance to air flow is directly proportional to the fineness of the sample grain, as long as the same testing conditions are observed.

2.4 Setting Time Determination

Cement paste were prepared with pulverized slag replacing cement at percentages 0, 2.5, 5, 10 and 15% under standard laboratory conditions with relative humidity of approximately 50% as per EN 196-3:2005. The water requirements for standard constituency were determined for each percentage replacement, prior to preparing the paste for the setting time test. The penetration depth of the plunger and the base-plate was within the required range of 6 ±2 mm. The initial and final setting time measurement was performed using the manual Vicat apparatus and the penetration depth between the needle and the base-plate was within the distance of 8 ±3mm in accordance with EN 196-3:2005.

2.5 Compressive Strength Determination

A series of concrete mixtures were cast in cubic moulds of nominal size 100 mm for control and with different proportions of pulverised CS ranging from 2.5, 5, 10 and 15% respectively replacing Portland cement. Activation of the pozzolanic reaction of the pulverized CS was done using 1.5% hydrated lime i.e. $Ca(OH)_2$ by weight of OPC. The materials constituents are shown in Table 2.

The slump of the fresh concrete mixes was determined to study the effect of different percentages of CS used on the workability of the concrete mixture as per SANS 5862-1. The mixes were compacted using a vibrating table and afterwards, the specimens were covered with polyethylene sheet, cured under ambient laboratory conditions of temperature 23 ±2ºC and demoulded after 24 hours. The demoulded cubes were moist-cured in a water tank at temperature of 21 ±2ºC and tested at the required curing age. All specimens were cured for 3, 7, 14, 21, 28 & 90 days before compressive strength tests were conducted. The maximum load at failure of three specimens at a loading rate of 1.0 kN/sec was recorded and the average value computed in accordance with SANS 5863 for compressive strength determination.

Copper slag replacement (%)	0	2.5	5	10	15
Cement (kg/m^3)	352	343	334	317	299
Fine aggregate (kg/m^3)	758	758	758	758	758
Coarse aggregate (kg/m^3)	995	995	995	995	995
Copper slag (kg/m^3)	0.0	8.8	17.6	35.2	52.8
Ca(OH)2 kg	5.3	5.3	5.3	5.3	5.3
Water (kg/m3)	170	170	170	170	170
Water to binder ratio	0.5	0.5	0.5	0.5	0.5

Table 2: Concrete Mix Design

2.6 Flexural Strength Determination

For flexural strength determination, concrete beam specimens of cross sectional length 300 mm, breadth 100 mm and width 100 mm were cured in water for 3, 7, 14, 21, 28, 60 and 90 days. The dimensions of the beams were determined to the nearest mm and the mass of each specimen were determined before testing. The rollers of the compression testing machine were wiped cleaned and the concrete beams were placed centrally on the supporting rollers, with orientation of the casted face perpendicular to the loading face. The axis of the beams were aligned with the centre of thrust of the spherically seated top roller holder(s), whiles ensuring that the axes of both the top and the supporting rollers were normal to the longitudinal axis of the specimen in accordance with SANS 5864:2006.

Demoulded prism specimens were water cured and tested at the required curing age at a loading rate of 0.6 kN/s until failure. For both the control samples and for each percentage replacement of the Portland cement with CS, three beams were tested at the required curing age for flexural strength under two loads at third point conditions in accordance with SANS 5864:2006. The average modulus of rupture (flexural strength) was determined using the expression for a third-point loading method as per SANS 5864:2006. The results of the modulus of rupture of all mixtures showed similar trend to the compressive strength results as the replacement level of copper slag increased.

2.7 Concrete Durability Test

Three standard test methods were used to investigate the durability properties of CS admixed concrete cored samples, namely: oxygen permeability, water sorptivity and chloride permeability tests.

For the oxygen permeability index (OPI), cored disc samples of average diameter 70 ±2 mm and depth 30 ±2 mm were placed unto the compressible collar within a rigid sleeve, with the test face at the bottom and resting against the lip of the collar. The thickness and diameter of each disc specimen was measured with a vernier calliper at 4 points equally spaced around the perimeter of the disc specimen and

Figure 2.1: OPI Measuring Setup

Figure 2.2: A Computer Data Logger

recorded. The samples, collar and rigid sleeve were placed on top of the permeability cell so that it covers the hole in accordance with SANS 516-2. Afterwards, the cover plate was partially tightened with the top screw to ensure that it was centred. The time and pressure readings in the permeability cell were then recorded in 15 minutes time steps by a computer data logger shown in Figure 2.2, connected to the oxygen permeability index setup for about 3 hours.

For the water sorptivity test, the vertical curved sides of the cored disc specimen were sealed with a packing tape which extends to the extreme edges of the sides towards the test face. 10 layers of paper towel were then placed on a tray and a solution of $Ca(OH)_2$ poured into the tray, the paper towel was saturated with water visible at the top surface. The specimens were weighed at 3, 5, 7, 9, 20 and 25 minutes, after patting it once on the damp piece of absorbent paper not longer than 15 seconds and replaced each time after weighing until the maximum time of 25 minutes as per SANS 516-4. The concrete discs were vacuum saturated in water to determine the effective porosity.

The chloride permeability test was conducted to assess the concrete quality as per SANS 516-3. 2.93 kg of NaCl was added to 10L of water to form a brine solution in a container. The connecting points of the conduction cells were unscrewed and the lugging capillaries of the chloride cell connected to both chambers of the cell were filled with NaCl solution. With the flexible collar in the central ring portion of the cells, the concrete disc samples were placed within the collar with one face against the plastic lip of the rigid ring. The central portion of the cathode section of the cell was screwed ensuring that the solid plastic lip pressed against and compressed the flexible collar. Both parts sealing the sample were tightened to ensure that there were no signs of leakage. Both the ammeter and voltmeter were connected and the DC power supply was adjusted until the voltage applied across the specimen was approximately 10V. The current and voltage readings were simultaneously recorded. Testing was completed within 15 minutes of removing the specimen from the suspended NaCl solution. All other concrete discs waiting testing were stored in the NaCl solution in accordance to SANS 516-3.

Figure 2.3: Cored Discs Samples Stored in a Desiccator

Figure 2.4: Cored Discs Samples Being Tested For Water Sorptivity

3.0 RESULTS AND DISCUSSIONS

3.1 Mineralogical Composition of Copper Slag

The X-ray diffraction (XRD) results in Figure 3.1 shows that, the mineralogical composition of CS are quartz-(SiO_2) and augite-Ca(Mg, Fe)Si_2O_6 similar to CS used in literature which contains fayalite, magnetite and quartz Gorai et al., (2002). The glass content of the CS is approximately 99.3%, similar to Ground Granulated Blast Furnace Slag (GGBS) glass content between 85 and 90% Saddique et al., (2011). The glassy nature of a slag is responsible for its cementitious properties, with a linear relation to the late compressive strength development of concrete (Smolczyk, 1980). However, slag with completely vitreous glass may lead to strength reduction (Frigione, 1986).

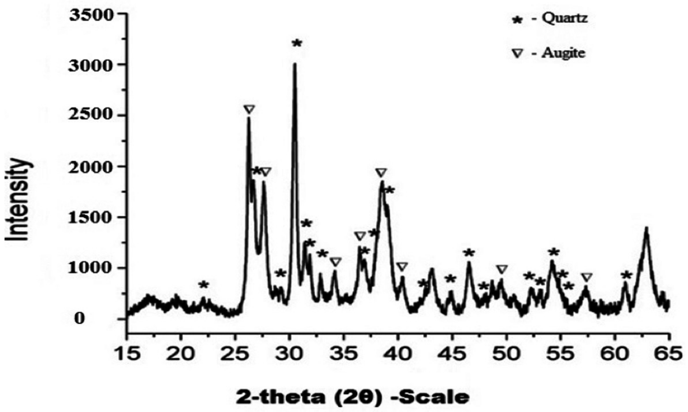

Figure 3.1: Mineralogy Composition of Copper Slag

3.2 Chemical Composition of Copper Slag

The chemical composition of the 52.5 N CEM I, procured from PPC Ltd and CS are presented in Table 3.1. It can be seen from Table 3.1 that, the calcium oxide (CaO) contribute to nearly 63% of the chemical composition of the Portland cement, whereas CS has a very low lime content of approximately 12%. This indicates that CS is not chemically a very reactive material to be used as a cementitious material since sufficient quantity of lime must be available in order to reach the required rate of hydration and to achieve the required early-age strength. On the other hand, CS has high concentrations of SiO_2 and Fe_2O_3 compared with OPC.

Table 3.1: Chemical Composition of Portland cement and Copper Slag

Components	**PC%**	**CS%**
SiO_2	19.85	38.31
Al_2O_3	4.78	7.28
Fe_2O_3	2.38	25.91
CaO	63.06	12.31
MgO	2.32	6.41
K_2O	0.94	1.08
Na_2O	0.22	0.91
TiO_2	0.25	0.61
Mn_2O_3	0.05	0.14
P_2O_5	0.26	0.20
SrO	0.3	0.02
ZnO	-	0.36
SO_3	2.48	0.42
Loss on Ignition (LOI)	2.83	2.38
$SiO_2 + Al_2O_3 + Fe_2O_3$	27.01	71.5
$(CaO + MgO)/SiO_2$	3.29	0.49

3.3 Pozzolanic Characterisation

In comparison with the chemical composition of natural pozzolans in accordance to ASTM C618-99, the summation of the three oxides (silica, alumina and iron oxide) in CS is nearly 72%, which exceeds the 70% percentile requirement for Class F fly ash and pozzolans. Therefore, the CS used is expected to have good potential to produce high quality pozzolans. Moreover, the CS has an LOI of 2.38% which falls below the maximum value of 6.0%, as per ASTM C618-99, therefore can be categorized as a Class F fly ash.

In the assessment of hydraulic properties of slag as per SANS 55167-1:2011, the slag chemical composition should consist of at least two-thirds by mass the sum of calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO_2). The remainder shall be aluminium oxide (Al_2O_3), together with small amounts of other compounds. The most popular related formulae used to indicate the hydraulic value of a slag according to SANS 55167-1:2011 is shown in equation 3.1 below.

$$\text{Hydraulic value} = \frac{CaO + MgO}{SiO_2} \qquad (3.1)$$

The result for CS is approximately 0.5, which is less than 1, the recommended requirement to be used as constituent for cement as per SANS 55167-1:2011.

3.4 Results of the Fineness Test

The minimum Blaine air surface area requirement respectively for slags and cement in accordance to SANS 55167-1:2011 are 275 m^2/kg and 300 m^2/kg. The average Blaine air surface areas determined were 4000 m^2/kg and 3968 m^2/kg respectively for the CS and OPC. The results obtained above represented below in Table 3.2, indicate that the CS used for this study is in the same range of fineness as the Portland cement and conforms to the requirement as per SANS 55167-1:2011.

Table 3.2: Surface Area results for Slag and Cement

Material	Blaine Air Surface Area (m^2/kg)	Specific Gravity
CS	4000	3.13
OPC	3968	3.14

The increased surface area of the slag may lead to pronounced strength effect at early stages of reactivity. This behaviour is typical of pozzolans and at later curing ages other factors, such as influence of pore structure and diffusion controlled processes, become more significant.

The specific gravity results for both CS and OPC are represented in Table 3.2. In general, the specific gravity varies with the iron content in the slag, from a low value of 2.8 to as high as 3.8 (Gorai et al., 2002). The results of the specific gravity shown in Table 3.2 confirm that, CS used for this research lies within the aforementioned range and slightly less than that of the Portland cement.

3.5 Setting Time

The setting time results are shown in Table 3.3. As required by SANS 55167-1:2011, the initial setting time of a combination (by mass) of 50 % of a slag with 50 % of test cement, shall not be more than twice as long as that of the test cement on its own. For all percentage replacement of Portland cement with CS, the results of the initial setting time values complies with the requirement as per SANS 55167-1:2011.

Table 3.3: Summary of the Initial and Final Setting Time Results

Mix Design	Initial Setting Time (min)	Final Setting Time (min)
Control	207	270
2.5% Replacement	333	402
5% Replacement	355	436
10% Replacement	385	480
15 % Replacement	412	512

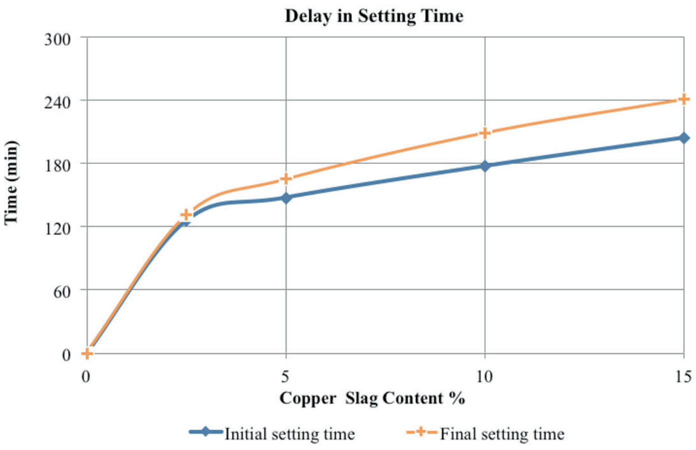

Figure 3.2: Delay Initial and Final Setting Time for Cement Paste

Figure 3.2 also highlights the delay in the setting time of the cement paste as the substitution level of pulverized CS increases. This observation could be due to delayed hydration induced by the heavy ions contained in the CS. This postulation is supported by Hashem et al., (2011). According to the authors, the presence of Cu (II) ions retards cement hydration. Zain et al., (2004) were also of the opinions that, the presence of Cu, Pb and Zn compounds in CS increases cement paste setting times

3.6 Slump Test Results

Fresh concrete properties are presented in Table 3.4. The trend of the slump test results shows CS does affect concrete workability. Slumps of all samples increased significantly with an increase in the CS content.

Table 3.4: Slump Properties of Fresh Concrete

Copper slag replacement	0%	2.5%	5%	10%	15%
Slump (mm)	90	100	125	130	160

Since CS is very similar to fly ash as a less dense material compared to Portland cement and having spherical particle shape, the improvement in workability was expected (Sri Ravindrarajah and Tam, 1989). This improvement would enable the reduction of water to cement ratio leading to possible increase in the characteristics strength of concrete specimen for the same slump, as compared to the control sample.

3.7 Compressive Strength Test Results

The measured compressive strength for concrete specimens up to 15% CS replacement is shown in Figure 3.3. The compressive strengths reduction for 2.5, 5, 10 and 15% CS replacement are 92, 87, 86 and 84% respectively of the value for control specimen at 28 days of curing. Moreover at 90 days of curing, the compressive strengths reduction for 2.5, 5, 10 and 15% CS replacement are 94, 90, 89 and 87% respectively of the value for control specimen.

The overall decrease in the ultimate compressive strength for CS admixed concrete compared to control samples could be due the low hydraulic activity index of the slag. Moreover, the high glass content of the CS (99.3%) could have led to the overall reduction of the compressive strength development of the CS admixed concrete.

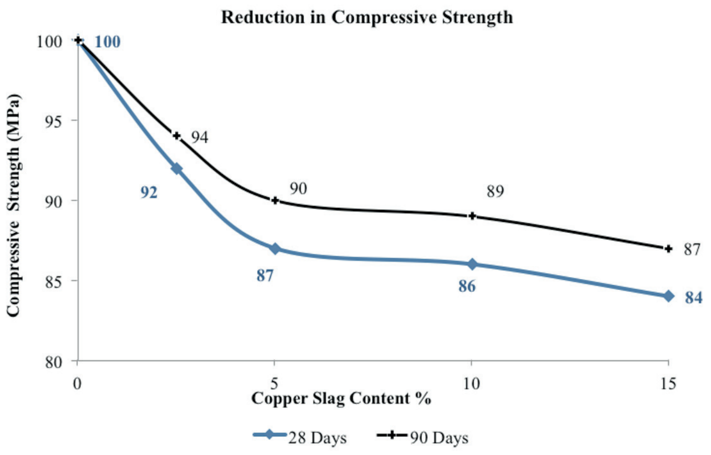

Figure 3.3: Compressive Strength Results of Copper Slag Admixed Concrete

Demoulian et al. (1980) reported in a similar study that, slag concrete with high glass content in excess of 95% significantly reduces in compressive strength. Frigione (1986) admitted that, a low percentage of crystallization between 3–5% in mass of slag is found to be beneficial to the compressive strength development of slag concrete.

3.8 Flexural Strength Test Results

Table 3.5 shows the results of the flexural strength results up to 90 days of water curing. The flexural strength generally shows a decreasing strength trend as more CS is added to replace the cement, analogous to the trends of the compressive strength. At 90 days, the reduction in the flexural strength for 15% replacement is about 14%. However, the strength reduction is lower for the other samples with lesser replacements. The decline of the flexural strength as shown in Figure 3.4 could be due to the increased in porosity of the concrete induced by trapped excess water. The porous internal structure causes the concrete to be prone to failure in tensile cracking at the weak bonds between the concrete components.

Table 3.5: Flexural Strength Results of Prisms Up to 90 Days

	Percentage Replacement (%)				
Curing Days	0	2.5	5	10	15
3	3.36	3.10	2.86	2.65	2.46
7	4.36	4.08	3.78	3.56	3.28
14	4.62	4.37	4.00	3.68	3.60
21	5.05	4.58	4.32	4.08	3.98
28	5.41	4.88	4.64	4.45	4.30
60	5.94	5.66	5.48	5.01	4.92
90	6.25	6.10	5.86	5.59	5.40

3.9 Results of Durability Test

According to Alexander et al., (1999), the suggested ranges of index values for durability classification of concrete for three index tests namely: Oxygen permeability index (OPI), water sorptivity and chloride conductivity are shown in Table 3.6

The test results of both the oxygen permeability index (OPI) and water sorptivity are shown in Table 3.7. The results of the water sorptivity trends are more consistent than the results of the oxygen

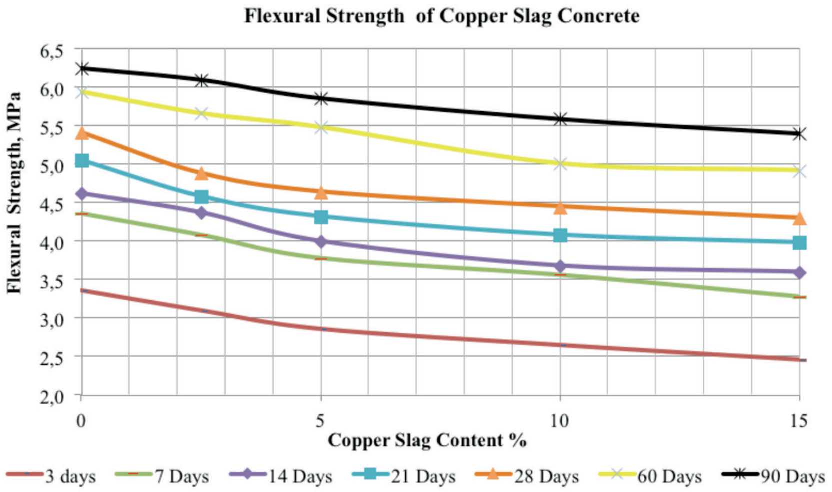

Figure 3.4: Flexural Strength of Pulverized Copper Slag Concrete Up To 90 Days of Water Curing

permeability. This observed trend could probably be due to the fact that bleed voids and other macro-defects have a smaller effect on the rate of water absorption than on air permeability. From the coefficient of oxygen permeability results shown in Figure 3.5, it is observed that, the CS can be effectively used in concrete to reduce the pore size of the concrete matrix.

As shown in Figure 3.6 the water sorptivity of the concrete sample decreases as the percentage of CS content increases. For all percentage replacement of cement with CS, the concrete samples generally performed better than the control sample; this is probably due to the pore refining effect of CS on Portland cement concrete because of its finer particle size and pozzolanic effect. Higher CS percentage replacement produced denser structure and prevents concrete from water penetration.

Moreover, the CS reacts with water in the highly alkaline environment of the concrete pore matrix and then with calcium hydroxide to form cement hydration product through pozzolanic reaction which forms extra C–S–H gel in the concrete paste and slows down the strength development at early age.

This conjecture is supported by a similar research by Daube and Bakker (1986) on the addition of Ground Granulated Blast furnace Slag (GGBS) in concrete. The Authors indicated that, the addition of GGBS modifies the products and the pore structure in a hardened cementitious material. Table 3.8 below shows the average results of chloride conductivity of two concrete discs.

Table 3.6: Suggested Ranges for Durability Classification Using Index Values

Durability Class	Oxygen Permeability Index (Log Scale)	Water Sorptivity (mm/hr0.5)	Chloride Conductivity (mS/cm)
Excellent	> 10.0	< 6.0	< 0.75
Good	9.5–10.0	6.0–10.0	0.75–1.50
Poor	9.0–9.5	10.0–15.0	1.50–2.50
Very poor	< 9.0	>15.0	> 2.50

Table 3.7: The Results of Oxygen Permeability Index and Water Sorptivity

	Durability Indexes	
Mix Design	Coefficient of Oxygen Permeability (mm/s)	Water Sorptivity Test (mm/hr$^{0.5}$)
Control	10.0	11.5
2.5% Replacement	10.0	11.0
5% Replacement	10.1	10.7
10% Replacement	10.1	10.5
15% Replacement	10.2	10.2

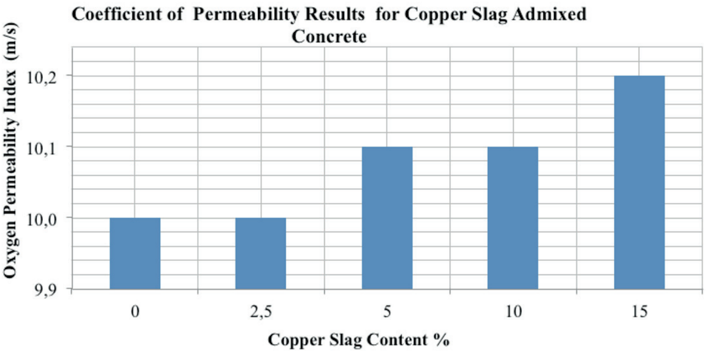

Figure 3.5: Coefficient of Oxygen Permeability Test Results

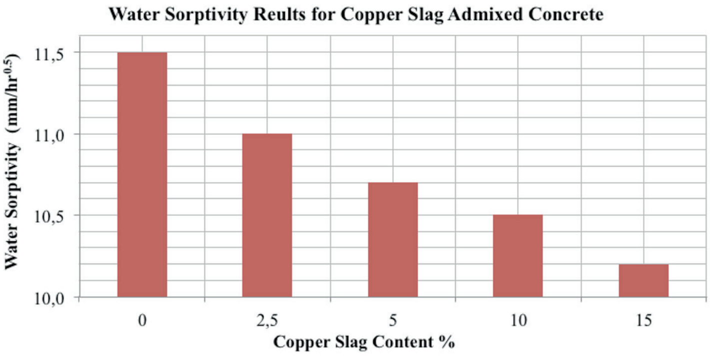

Figure 3.6: Water Sorptivity Test Results

As observed in Figure 3.7, the chloride conductivity of the concrete sample decreases with percentage increase of CS content, which could lead to reduced ingress of chlorides, and other deleterious ions responsible for concrete deterioration. The improved chloride resistance may also be the result of refinement of the pore structure, such as occurs with silica fume concretes, or may be due to increased chloride binding by aluminate phases contained in the slag (Alexander et al., 2003).

4.0 CONCLUSIONS

Based on the experimental outcome, observations and trends determined from the results of the above experimentations, the following conclusions were made:

i. The results of the X-ray diffraction (XRD) pattern signifies quartz-(SiO_2) and augite-Ca(Mg, Fe)Si_2O_6 as the major mineralogical composition of the CS, similar to those found in literature, which contains mainly fayalite, magnetite and quartz (Gorai et al., 2002)

ii. The glass content of the CS was approximately 99.3%, comparable to Ground Granulated Blast Furnace Slag (GGBS), with glass content between 85 and 90% (Saddique et al., 2011). The high glassy content of the CS could be credited to the reduction of the overall compressive strength of the concrete.

Table 3.8: Results of Chloride Conductivity Test

Mix Design	Chloride Conductivity (mS/cm)
Control	2.42
2.5% Replacement	2.02
5% Replacement	1.82
10% Replacement	1.49
15% Replacement	1.30

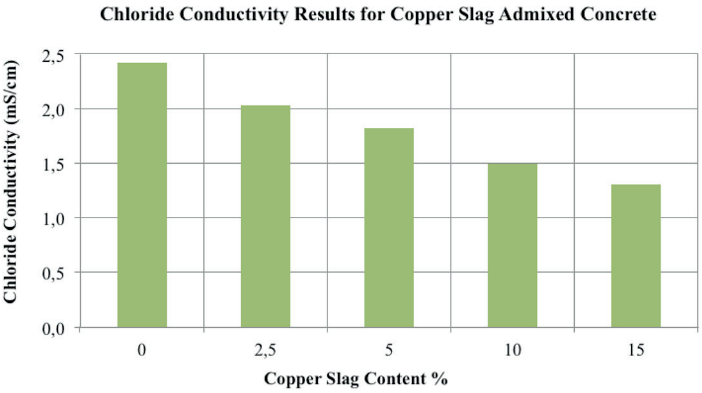

Figure 3.7: Chloride Conductivity Test Results

iii. In comparison with the chemical composition as per ASTM C618-99 natural pozzolans, the summation of the three oxides, namely, silica, alumina and iron oxides in the CS was approximately 72%, which satisfy the minimum 70% requirement for Class F pozzolans. Therefore, CS is expected to have potential to produce quality pozzolans.

iv. In assessment of the hydraulic properties of slag, The XRF chemical oxides composition result for CS was approximately 0.5% , which is less than 1, the recommended value required to be used as constituent for cement as per SANS 55167-1:2011.

v. The average Blaine air surface areas were 4000 m^2/kg and 3968 m^2/kg respectively for pulverised CS and Portland cement. The results confirmed CS used was about the same fineness as Portland cement and conforms to the requirements in accordance with SANS 55167-1:2011

vi. There was observed a delay in the setting time of the cement paste as the substitution level of pulverized CS increased. This observation could be due to delay pozzolanic action induced by the heavy ions contained in the CS

vii. The fresh concrete properties test results, show that, CS affects concrete workability; slumps of all samples increased as the proportion of the pulverized CS increases.it is therefore possible to reduce water to cement ratio and increased strength gained.

viii. For compressive strength results, there was a significant decrease as the CS content increases. The overall decrease in the ultimate strength for CS admixed concrete compared to control samples could be due to the low hydraulic activity index of the CS.

ix. The flexural strength generally shows a decreasing strength trend as more CS is added to replace cement, analogous to the trends of the compressive strength. At 90 days, the reduction in the flexural strength for 15% replacement is about 14%. However, the strength reduction is lower for the other samples.

x. The chloride conductivity and water sorptivity of the concrete sample decreases as the percentage of CS content increases. The reduction suggests an improvement in the durability performance of the slag samples compared to control, which could lead to reduce ingress of chlorides, sulphates, carbon-dioxide, moisture and other deleterious ions responsible for concrete deterioration.

xi. The results of the coefficient of oxygen permeability trends were irregular compared to those of chloride conductivity and water sorptivity. The observed trend could probably be due to the fact that, bleed voids and other macro-defects have a smaller effect on the rate of water absorption than on air permeability than. However, the oxygen permeability results indicate that, the CS could be effectively used in concrete to reduce the pore size of the concrete matrix.

This report is based on the study of the performances of concrete with partial replacement of Portland cement with pulverised CS up to 15%. For all percentage replacement of cement with CS resulted in significant reduction in both the compressive and flexural strength. The average reduction value for both compressive and flexural strength up to 90 days of water curing for 15% CS content was approximately 15%. However, the concrete disc samples generally performed better in all the three durability tests, namely oxygen permeability, water sorptivity and chloride conductivity.

A clear observation from this study was that, pulverised CS can be used remarkably up to 15% to replace OPC to improve concrete durability properties. Notwithstanding, for mechanical strength design, CS content should be restricted below 15%. ▲

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