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Effects of Copper Slag as a Replacement for Fine Aggregate on the Behavior and Ultimate Strength of Reinforced Concrete Slender Columns

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Abstract: Use of copper slag (CS) as a replacement for fine aggregate (FA) in RC slender columns was experimentally investigated in this study. Twenty columns measuring 150 mm x150 mm x 2500 mm were tested for monotonic axial compression load until failure. The concrete mixture included ordinary Portland cement (OPC) cement, fine aggregate, 10 mm coarse aggregate, and CS. The cpercentage of cement, water and coarse aggregate were kept constant within the mixture, while the percentage of CS as a replacement for fine aggregate varied from 0 to 100%. Four 8 mm diameter high yield steel and 6 mm mild steel bars were used as longitudinal and transverse reinforcement, respectively. Five cubes measuring 100 mm x100 mm x100 mm, eight cylinders measuring 150 mm x 300 mm and five prisms measuring 100 mm x 100 mm x 500 mm were cast and tested for each mixture to determine the compressive and tensile strengths of the concrete. The results showed that the replacement of up to 40% of the fine aggregate with CS caused no major changes in concrete strength, column failure load, or measured flexural stiffness (EI). Further increasing the percentage reduced the concrete strength, column failure load, and flexural stiffness (EI), and increased concrete slump and lateral and vertical deflections of the column. The maximum difference in concrete strength between the mixes of 0% CS and 100% CS was 29%, with the difference between the measured/control failure loads between the columns with 0 and 100% CS was 20% the maximum difference in the measured EI between the columns with 0 and 100% CS was 25%. The measured to calculated failure loads of all specimen varied between 91 and -100.02%. The measured steel strains were proportional to the failure loads. It was noted that columns with high percentages of CS (≥ 60%) experienced buckling at earlier stages of loading than those with lower percentages of CS.

Keywords: Copper slag, Fine aggregate, Column, Axial load, Slender column

تأثير استخدام خبث النحاس كبديل عن الركام الناعم على السلوك والأحمال القصوى للأعمدة الرفيعة

أس النعيمي

الخلاصة: تمت دراسة استخدام خبث النحاس بديلا عن الركام الناعم في الأعمدة الخرسانية المسلحة. تم اختيار عشرين عموداً بأبعاد ١٥٠×١٥٠×٢٥٠٠ ملم تحت تأثير حمل انضغاط متزايد حتى انهيار العمود. احتوت الخلطة الخرسانية على إسمنت بورتلاندي عادي وركاماً ناعماً خشن ١٠ ملم زائدا خبث النحاس. وقد ثبتت نسب الإسمنت والماء والركام الخشن في حين تم تغيير نسبة خبث النحاس كبديل للركام الناعم من صفر٪ الى ١٠٠ ٪. تم استخدام أربعة قضبان بقطر ٨ ملم للتسليح الطولي واستخدام قضبان ٦ ملم للتسليح العرضي في العمود. كما تم استخدام خمسة مكعبات (١٠٠×١٠٠×١٠٠ملم) كعينات لاختبار قوة الانضغاط وقوة الشد في الخرسانة. أثبتت النتائج أن استخدام كميات أقل من ٤٠٪ من الخبث كبديل للركام الناعم لايؤثر تأثيرا كبيرا على قوة العمود لمقاومة الانحناء. أما إذا زادت كمية الخبث عن ٤٠٪ بدلا عن الركام الناعم فإن ذلك يؤدي إلى نقصان قوة الخرسانة وانخفاض الحمل الأقصى للعمود وانخفاض القدرة على الانحناء وزيادة هبوط الخرسانة، وزيادة التشوهات الرأسية والأفقية في العمود. وقد بلغ أقصى انخفاض في قوة الخرسانة حين استخدام ١٠٠٪ خبث حوالي ٢٩٪ بينما انخفضت النسبة بين الأحمال القصوى في حالتي ٥٠٪ و١٠٠٪ إلى حوالي ٢٠٪ وانخفضت نسبة القدرة على الانحناء بين تلك النسب إلى ٢٥٪. وقد تراوحت النسبة بين الأحمال المقاسة في المعمل إلى الأحمال الحسابية ما بين ٩١٪ الى ١٠٠٪ وكانت الإجهادات المقاسة متناسبة طرديا مع الأحمال القصوى. كما لوحظ أن الأعمدة التي احتوت نسبا أعلى من ٦٠٪ من خبث النحاس انهارت بانبعاج أكثر من تلك التي احتوت كميات أقل من الخبث.

الكلمات المفتاحية: خبث النحاس، الركام الناعم، عمود ، حمل محوري، عمود نحيف

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1. Introduction

Aggregate is the main constituent of concrete, occupying more than 70% of the concrete matrix. In many countries, there is a scarcity of natural aggregate that is suitable for construction, whereas in other countries the consumption of aggregate has increased in recent years, due to increases in the construction industry. In order to reduce depletion of natural aggregate due to construction, artificially manufactured aggregate and some industrial waste materials can be used as alternatives. Copper slag (CS), the glassy material, produced during matte smelting and copper conversion was previously considered waste and disposed as landfill. It has been estimated that for every ton of copper production about 2.2-3 tons of slag are generated. Slags containing < 0.8% copper are either discarded as waste or sold cheaply (Shi *et al.* 2008; Gorai *et al.* 2003).

Processed, air-cooled, and granulated CS has a number of favorable mechanical properties for aggregate use, including excellent soundness characteristics and good abrasion resistance (Queneau *et al.* 1991). Alter (2005) studied the effect of CS on the environment on the basis of basel convention and characterized it as non-hazardous. Shanmuganathan *et al.* (2008) carried out toxicity characterization and long-term stability studies on CS and reported that the slag samples are non-toxic and pose no environmental hazard additionally poor leachability of the slag metals assure long-term stability, even in extreme climates. The tests indicate that the heavy metals present in the slag are stable and are not likely to dissolve significantly even through repetitive leaching under acid rain.

Utilization of CS for applications such as replacement for fine aggregate (FA) in concrete has the dual benefit of eliminating the costs of disposal and lowering the cost of the concrete in some countries. Slight variations in prosperities of the slag may be anticipated depending on source. Taha *et al.* 2007 explored the use of CS as a replacement in cement in controlled low-strength concrete and reported that mixes which were designed using waste material (*i.e.*, CS), cement, and fine aggregate yielded higher strength values than those mixes where the waste material was used as a full replacement for cement. Shoya *et al.* (1999) found no major differences in concrete compressive strength due to the use of CS as a replacement for FA. Resende *et al.* (2008) reported a small reduction in concrete compressive and flexural strengths due to substitution of CS. Khanzadi and Behnood (2009) also explored the possibility of using CS as a replacement for coarse aggregate and reported an improvement in the mechanical properties of the high strength concrete mixture. Al-Jabri *et al.* (2009a) investigated the use of CS as a replacement for sand in high performance concrete (HPC) with a constant water content. They reported that an addition of up to 50% CS for sand yielded comparable strength to that of a control mixture with no CS. Further addition of CS caused a reduction in strength. Al-Jabri *et al.* (2009b) studied the use of CS as a replacement for sand in high-strength concrete (HSC) with almost constant workability. The water content was adjusted in each mixture in order to achieve the similar workability as for the control mixture. They noted a remarkable 22% reduction in water demand when they replaced 100% of the sand with CS compared to a control mixture of 0% CS. They reported an increase in the concrete strength due to the increased content of CS as replacement of FA, while super-plasticizer was found to be a very important ingredient in HSC made with CS in order to provide good workability and better consistency. Recently (Wu *et al.* 2010) recommended that less than 40% CS as sand replacement can achieve a high strength concrete that is comparable or better than a control mix.

No test results were found in the literature on the use of CS as a replacement for FA in structural members. In this research, the CS was used as a replacement for FA in twenty reinforced concrete (RC) slender columns. The objective was to investigate the effect of partial and full replacement of FA with CS on the strength and behavior of columns. The column cross section was 150 mm x150 mm and its length was 2500 mm. The columns were divided into six groups based on the percentage of CS used as a replacement for FA as follows: 0% CS, 20% CS, 40% CS, 60% CS, 80% CS and 100% CS. The water and cement contents as well as the coarse aggregate (10 mm) were kept constant for all specimens. At least three columns were tested from the same group. The results were judged based on the failure load, lateral and vertical deflections, steel strain, concrete compressive and tensile strengths, effects on EI and slump values.

2. Materials Used

OPC produced by Oman Cement Company, natural fine and 10 mm coarse aggregates from a nearby crusher, and fresh tap water were used in the concrete mixture. The CS was brought from Oman Mining Company, which produces an average of 60,000 tons annually (Taha *et al.* 2007). Table 1 shows the chemical and physical properties of the CS and cement used, and Figure 1 shows sieve analysis of the FA and CS. It is clear that both fit within the grading limits of zone 1 of the (Omani standard for fine aggregate (OS-2, 1982). However, many more particles of fine aggregate than CS passed through sieves from 0.1 to 1 mm. Figure 2 shows a picture of the glassy surface CS

Table 1. Chemical composition and physical properties of copper slag and cement produced in Oman

Composition	Copper Slag %	OPC Cement %
SiO_2	33.05	20.85
Al_2O_3	2.79	4.78
Fe_2O_3	53.45	3.51
CaO	6.06	63.06
MgO	1.56	2.32
SO_3	1.89	2.48
K_2O	0.61	0.55
Na_2O	0.28	0.24
TiO_2	0	0.25
Mn_2O_3	0.06	0.05
Cl^-	0.01	0.01
Property	**Value**	**Value**
Loss on ignition	0	1.75
Density (ton/m^3)	2.8-3.5	1.42
Fineness (cm^2/kg)	1261	3.357
Specific gravity	3.45	3.15
Initial setting time (min)	250	110

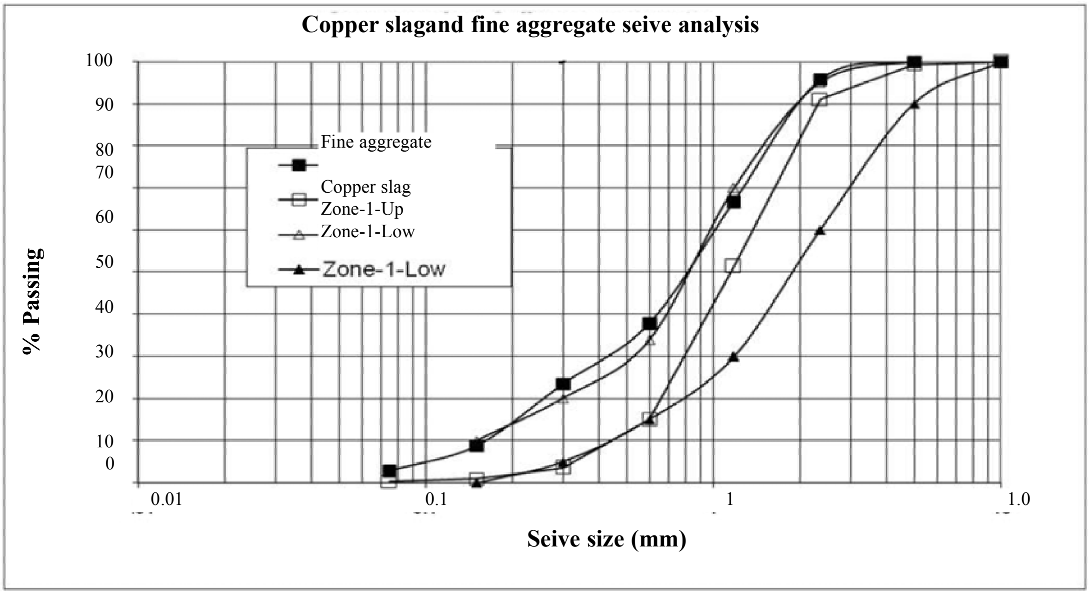

Figure 1. Fine aggregate and copper slag sieve analysis

used. Table 2 shows the mix design quantities. The mix constituents were weighed in separate buckets and mixed in a rotating drum in accordance with the American Society for Testing and Materials (ASTM C192, 1998) for about 4 minutes before casting. A vibration table was used for the compaction of the samples, while the column specimen was compacted using a special concrete vibrator. For each mix five cubes measuring 100 mm x100 mm x 100 mm (compression), eight cylinders measuring 150 mm x 300 mm (3 for compression and 5 for splitting), and five prisms measuring 100 mm x 100 mm x 500 mm (flexural) were cast. A slump value for the fresh concrete of each mixture was taken as the average of three samples in accordance with British Standards Institute (BS1) 881: part 102 (1983). Curing of the columns and samples was carried out for one week using wet Hessian cloth and then the samples were placed under room temperature. In addition, three cubes of 150 mm x150 mm x150 mm, three cylinders of 150 mm x 300 mm and three prisms of 100 mm x 100 mm x 500 mm

Figure 2. Sample of the copper slag used

Table 2. Concrete mix design quantities (kg/m²)

Component	0% CS	20% CS	40% CS	60% CS	80% CS	100% CS
Water	226.7	226.7	226.7	226.7	226.7	226.7
Cement	384.3	384.3	384.3	384.3	384.3	384.3
10mm Agg.	1136	1136	1136	1136	1136	1136
Fine Agg.	712.6	570.1	427.56	285.04	142.52	0
Copper slag	0	142.5	285.04	427.56	570.1	712.6

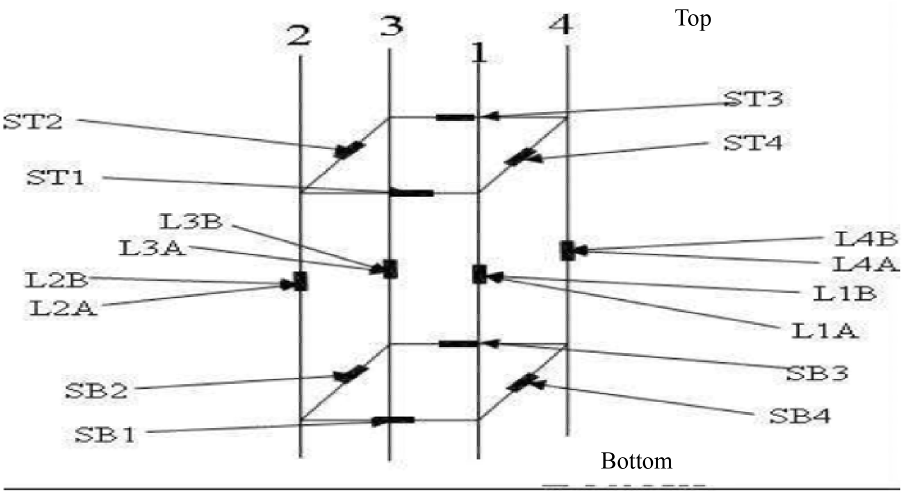

Figure 3. System of labeling the strain guages

samples were cast from three mixes and reported in (Alnuaimi 2009). Four 8 mm diameter high yield bars were used as longitudinal reinforcement. For stirrups, 6 mm diameter mild steel bars with a spacing of 150 mm in the middle 1.5 meters and a spacing of 75 mm in the 500 mm ends were used to ensure failure occured in the middle region of the column. The tensile strength of the steel bars was tested according to BS4449, 2005.

3. Specimen Construction and Preparation for Testing

Figure 3 shows the steel strain gauges' labelling method. For each longitudinal bar, two strain gauges (A, B) were stuck opposite one another at the mid-span of the column. The letter L identifies the location of the strain gauge, (*i.e.*, L2A means the number of the strain gauge which is stuck on longitudinal bar number 2 at location A). Two stirrups, one 75 mm below and

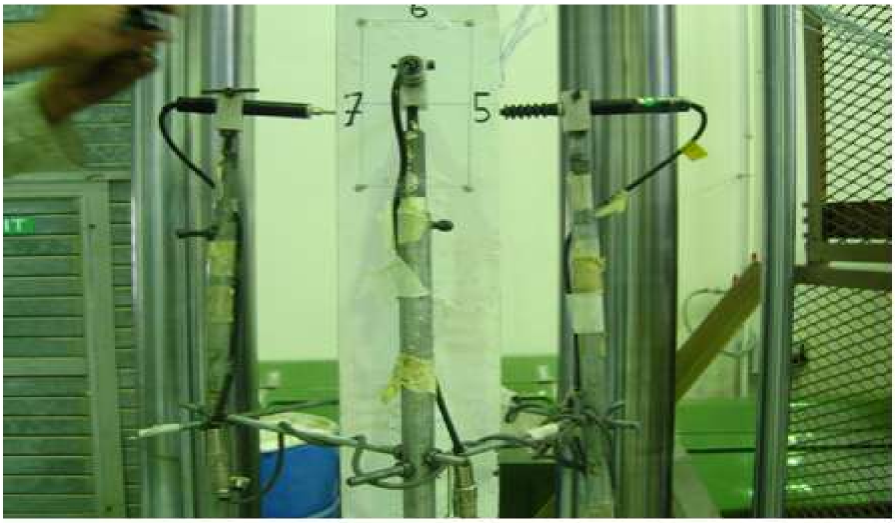

Figure 4. LVDT on each face at mid-span of the column

Figure 5. Base plate, ball and cap used at the bottom and top ends of the column

one 75 mm above the mid-span of the column were strain gauged. Four strain gauges were stuck on each stirrup with one in each face of the column. The letters S and B/T were used to differentiate between the strain gauges (*i.e.*, ST1 means the strain gauge in the upper stirrup on face 1 of the column and SB4 means the strain gauge which is in the lower stirrup at face 4 of the column). For measuring lateral deflection of the beam, a linear variable differential transducer (LVDT) was installed on each face at the mid-span of the column as shown in Figure 4. The concrete surface strains were measured using 100 mm horizontal and 200 mm vertical Demec gauges at mid-span.

After installing the steel strain gauges, the steel cage was erected and inserted into a wooden mould. The mould was laid horizontal on a levelled surface and its walls were perfectly vertical to ensure straightness of the specimen and minimize the imperfection. Strain gauges were numbered and casting of the specimen and the samples was carried out. After curing under wet Hessian cloths for one week, the specimen and the samples were left under room temperature for about four weeks before testing.

The column was painted white and the Demec pins were fixed. The column was installed on a 5000 kN Dartec universal testing machine using steel plate caps and a steel ball at the center of the plate at each end to ensure the application of a compressive axial load. Figure 5 shows the cap and ball system used, while Figure 6 shows a typical column installed on a testing machine. The strain gauges and LVDTs were connected to a data logger while the Demec readings were taken manually.

4. Testing Procedures

The compressive axial load on the column was applied in increments of 50 kN for the first three increments followed by reduced increments of 20 kN till the load reached 210 kN, and then by 10 kN increments until failure. The rate of loading was 1 kN/second. To allow for stable deformation to take place after each load increment, an interval of about one minute was used before recording the readings. The applied load, the steel strain, and the defection readings were directly recorded by a data acquisition system while the DEMEC readings were taken manually. The cube, cylinder, and prism samples were tested in the same day that the column was tested. The cube unconfined compressive strength was tested in accordance with

Figure 6. Typical column installed on teh 5000 kN DARTEC testing machine

Table 3. Average physical properties of concrete and steel used

Mix	0% CS	20% CS	40% CS	60% CS	80% CS	100% CS
Slump (mm)	43.33	44.00	58.33	85.00	Collapsed	Collapsed
Density (kg/m^3)	2416.00	2432.00	2480.00	2516.00	2550.00	2604.00
f_{cu} (N/mm^2)	36.56	35.04	33.44	31.98	30.62	28.44
f'_c (N/mm^2)	31.13	29.33	24.33	25.97	23.77	22.53
f_t (N/mm^2)	2.94	3.08	2.68	2.88	2.72	2.72
f_r (N/mm^2)	3.89	4.04	4.45	4.58	4.43	4.48
f_y (N/mm2)	580	580	580	580	580	580
f_{yv} (N/mm2)	250	250	250	250	250	250

f_{cu} = 100x100x100 mm cube compressive strength
f'_c = 150x300 mm cylinder compressive strength
f_t = 150x300 mm cylinder splitting tensile strength
f_r = 100x100x500 mm prism flexural tensile strength
f_y = yield strength of the longitudinal steel
f_{yv}= yield strength of the stirrups

BS1881 part 116 (1983), with a rate of loading of 2.5 kN/seconds while the cylinder compressive strength was obtained using the ASTM C39 (1986) with a rate of loading of 2 kN/second. For testing the tensile strength, the average strength of the five prisms from each mixture was considered using BS1881 part 118 (1983) with a rate of loading of 0.2 kN/second while the average of splitting strengths of five cylinders was recorded using BS 1881 part 117 (1983) with a rate of loading of 4.4 kN/second.

5. Test Results and Discussion

The slender column behavior is controlled by material strength, support conditions, type of loading, and

Table 4. Measured failure loads of the tested column (kN)

Column	1	2	3	4	Average
0% CS	552.1	594.9	521	561.7	557.43
20% CS	521.5	590.1	552.6	-	554.73
40% CS	629.4	531.5	526.0	535.4	555.58
60% CS	510.0	503	490.0	-	501.00
80% CS	472.1	480.0	482.3	-	478.13
100% CS	465	432.9	442.7	-	446.87

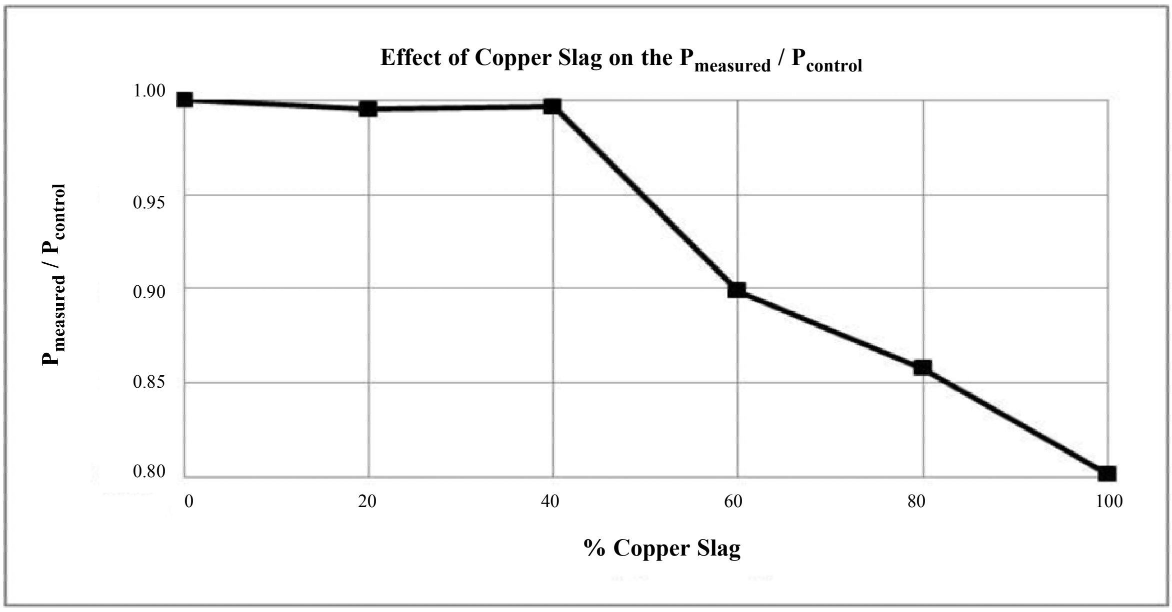

Figure 7. Effect of % of copper slag on $P_{measured}$ / $P_{control}$

the slenderness ratio. The material effect in this research was evaluated by CS as a replacement for FA. The percentage of replacement varied from 0 to 100%. The reinforcement type, strength, and arrangement were kept the same for all specimens. The cement, coarse aggregate, water types, and quantities were kept constant in all specimen tested. The support condition was maintained to be pinned by introducing steel balls at both ends in all tested columns. The loading was maintained to be concentrically axial as the steel balls guaranteed that no applied moment or shear force were introduced. The slenderness ratio, kl/r, was kept constant as the column length, square cross-section, supporting condition, and load arrangement were maintained to be the same in all specimen. Unlike short columns, the slender columns' failure was usually controlled by buckling. The buckling load decreased as the slenderness ratio increased. Since, in our case, the column is hinged, the k value is equal to one and the effective length is equal to the actual length of the column.

5.1 Strength of Materials

Table 3 shows the average slump values, density of concrete, cube and cylinder compressive strengths, the cylinder splitting and prism flexural tensile strengths. It also gives the average tensile yield strength of the reinforcement used. It is clear that minor reduction in the concrete compressive and tensile strengths were reported due to the increase of CS as replacement for FA. The increase in CS also led to higher slump and the mixture reached collapse in the 80 and 100% lavels of CS. This is due to the fact that the glassy surface of CS absorbs less water (0.17%) than FA. This excess water formed internal voids, which led to concrete bleeding and contributed to the increase of porosity that weakened the concrete strength. A microscopic study made by Wu *et al*. (2010) showed that with the increase of CS content in the concrete mixture the voids increased. It is also possible that the porosity resulted from the reduction in the content of fine particles, which led to a reduction in the interlocking effect in the concrete matrix. The sieve analysis of CS and FA presented in Figure 1 proves that many more 0.1 to 1 mm particles of FA than CS passed through the sieves. The result is a matrix with a higher percentage of voids than the control mixture (0% CS) and weaker bounds between the coarse aggregate particles. This problem cannot be detected by only studying the values of concrete density recorded in Table 3, due to the fact that CS possess a much higher density (about 3.5 ton/m^3) and specific gravity (3.45) than the density (1.4 - 1.5 ton/m3) and specific gravity (2.77) of the FA. In other words, although the concrete density increases due to the increase in CS content, the porosity also increases, which adversely effects the concrete strength.

5.2 Failure Load of Specimen

Table 4 shows the measured failure loads. The column was considered collapsed when it could resist no more loads. This was preceded by buckling of the column at mid-height into a half-sine wave shape in all cases. The measured failure load is the maximum load recorded before the column fails. It is clear from Figure 7 that the presence of up to 40% of CS as a replacement for FA resulted in no major change in the load carrying capacity of the column compared to the measured failure load of the control specimen (0% CS). Gradual drops in the load carrying capacity were observed for the columns having 60% CS and more. The maximum difference in the measured/control failure load between the group with ≥ 40% CS and that of the larger CS was recorded in the columns with 100% CS as 20%. It was noticed during testing that a large presence of CS resulted in earlier buckling of the column, which led to an earlier failure load than when the percentage of CS was low. The failure of the 0% CS column was more sudden with less time between the start of buckling and failure load than columns with a high percentage of CS.

5.3 Steel Strain

The effect of replacing FA with CS on the measured to calculated failure load ratios of each column is shown in Table 5. Euler equation, (Gere, Timoshenko 1995), $P_c = \frac{\pi^2 E1}{kl^2}$, with k =1, was used for calculating the theoretical failure load of a cracked section with the flexural stiffness E_c I is also for a cracked section. The Young Modulus for concrete, $E_c = 5.5\sqrt{\frac{f_{cu}}{Y_m}}$ kN/mm^2, Y_m = 1.5, (BS8110 1997) and the Moment of Inertia for a cracked reinforced concrete section, $I = I_{cr} + \alpha_e A_{sc} (x - d')^2 + \alpha_e A_{sc} (d - x)^2$ with $I_{cr} = \frac{bx^3}{12} + \frac{bx^3}{4}$ as shown in Figure 8 using the equivalent area of concrete with modular ratio, $\alpha_e = \frac{E_s}{E_c}$ = 15 and A_{sc} = 2T8 = 100.5 mm^2, Mosley *et al.* 1999. It is clear that there is little effect of replacing FA with CS on the measured failure load compared with calculated failure load for each specimen. The measured loads varied between 91 – 100.02% of the calculated loads with small decrease in measured loads with the increase in the percentage of CS.

The effect of replacing the FA with CS on the measured EI of the column is shown in the Figure 9. The Euler equation, $P_m = \frac{\pi^2 EI}{kl^2}$ was used for the judgment, with P_m being the measured failure load and EI is calculated accordingly with k = 1. It is clear that there was almost no effect on the EI due to the addition of CS as a replacement for FA for the values of 0 – 40%, but after that the values of the EI decrease as the CS values increase.

Table 6 shows the measured to yield strain ratios $\varepsilon/\varepsilon_y$ in the longitudinal steel versus the ratios of measured to control loads. The measured strain reported in this table is the strain recorded for the load increment just before failure. In general, more strains were recorded in the columns with a CS content ≤ 40% than those of higher CS contents. This is due to the fact that columns with a CS content ≤ 40% have resisted more loads and therefore the steel was subjected to higher stresses than the columns with higher CS. The measured to yield longitudinal steel strain $\varepsilon/\varepsilon_y$ versus the measured to control load ratios of the members of each group behaved almost in a similar fashion. Figure 10 shows the effect of CS content on the longitudinal steel strains for a typical member of each group. It is clear that as the percentage of copper slag increases the column stiffness decreases (more strain for same load).

As to be expected, the strain in the stirrups was negligible and no trend could be observed, therefore, it was not reported.

5.4 Lateral Deflection

Table 7 shows the maximum measured displacement values in the front and rear faces of the twenty columns tested with different percentages of CS as replacement for FA. The positive values indicate extension. The front face is the face of the column that was on the convex side (negative values) while the rear face is on the concave side (positive values). It should be mentioned that, for the purpose of safety, the LVDT readers were removed immediately after the signs of buckling, which means few final readings were recorded. It was noted that all columns' buckling occurred at the columns' midpoints, as can be seen in Figure 11. The measured lateral displacement versus the measured load to control load ratios of the members of each group behaved almost in a similar fashion. Figure 12 shows typical measured/control load ratios versus lateral displacement in the tested columns. In general, there was a gradual increase in displacement with the increase of CS, which indicates gradual loss in stiffness due to increased CS. The drops were more pronounced in the columns with a large percentage of CS (≥ 60%). This indicates that a high percentage of CS as a replacement for fine aggregate leads to more

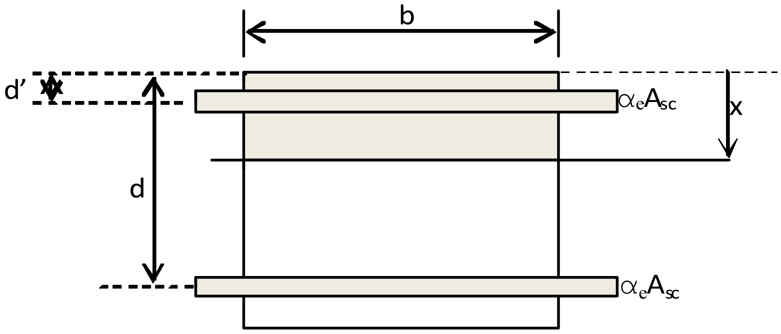

Figure 8. Cracked section for calculation of moment of inertia

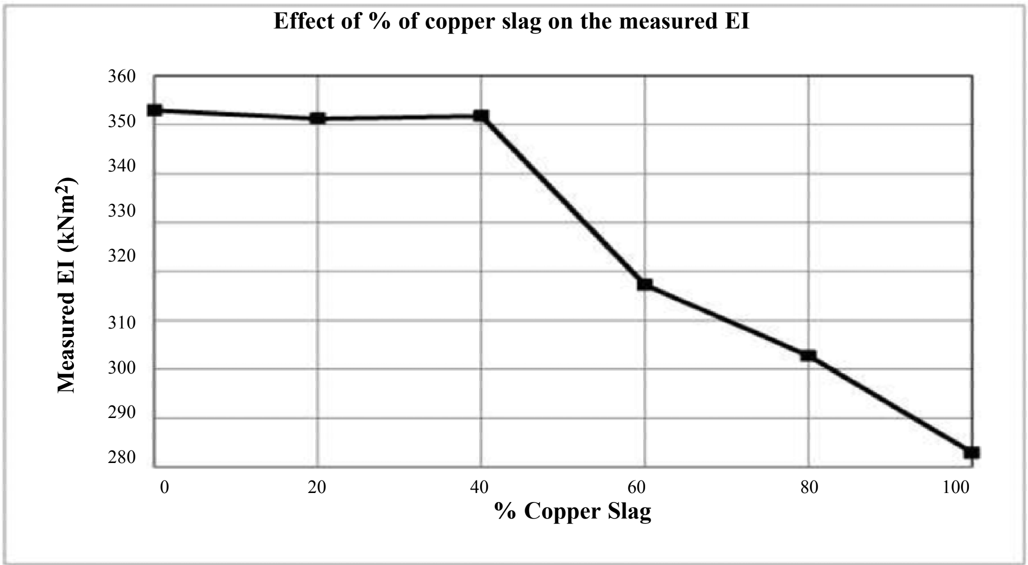

Figure 9. Effect of % copper slag on the measured flexural stiffness EI

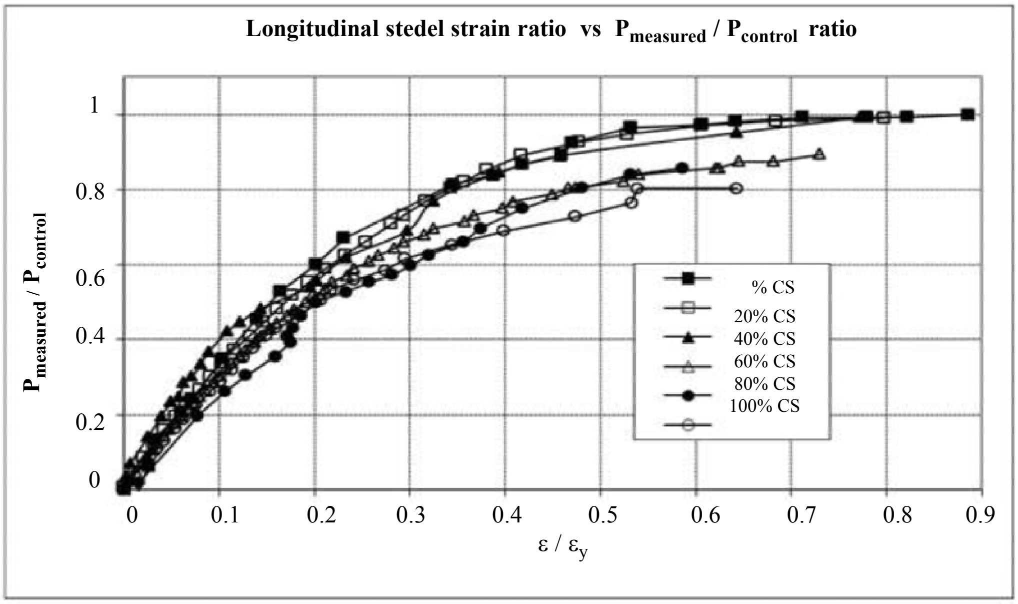

Figure 10. Effect of CS% on longitudinal steel strain

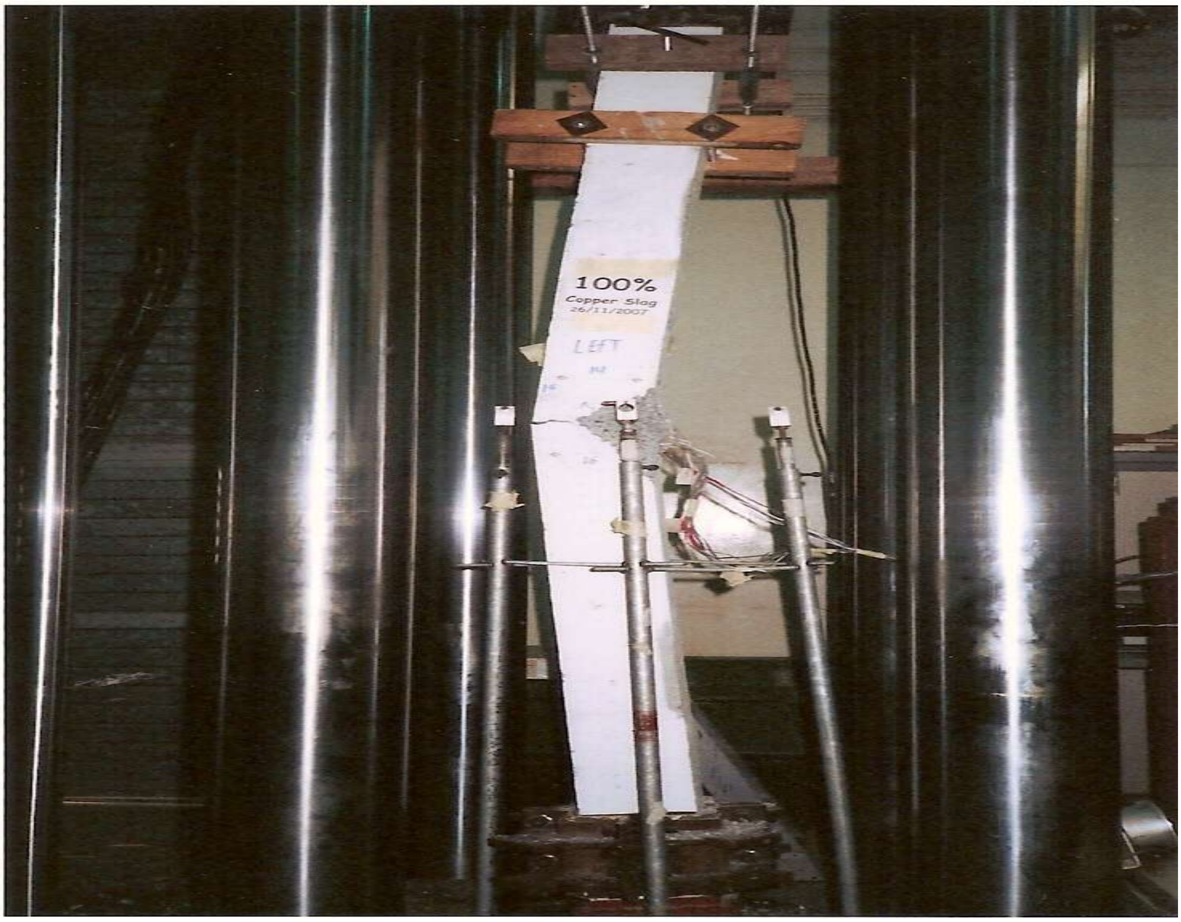

Figure 11. Typical failure mode and location of buckling of a column

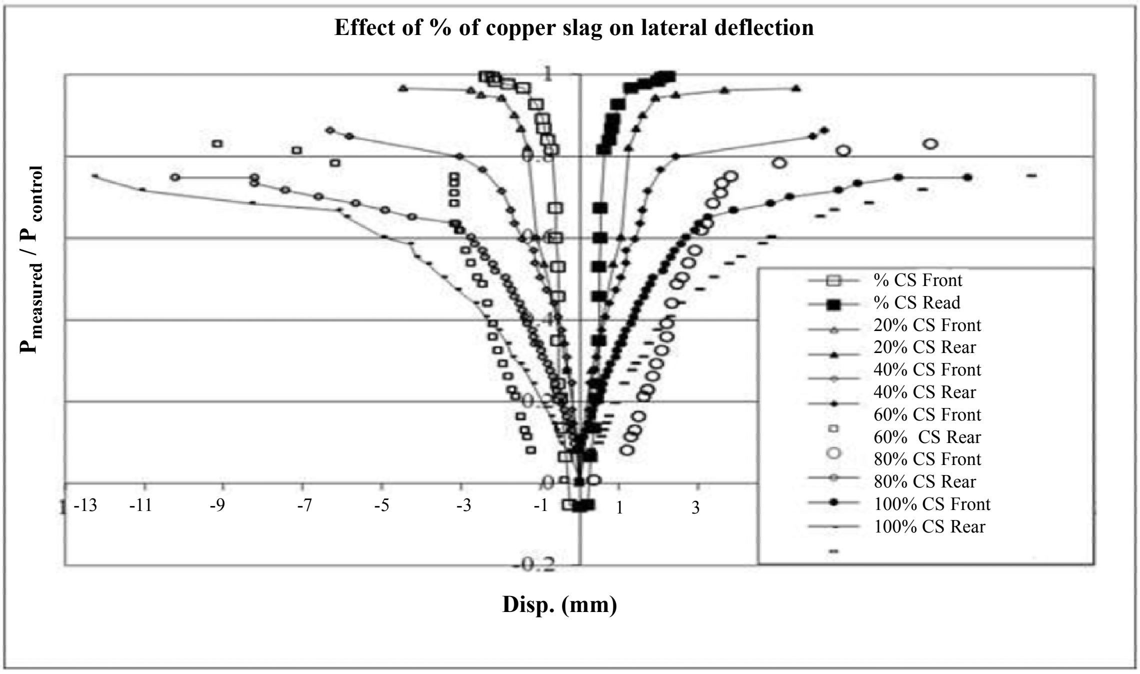

Figure 12. Typical lateral deflection of tested columns

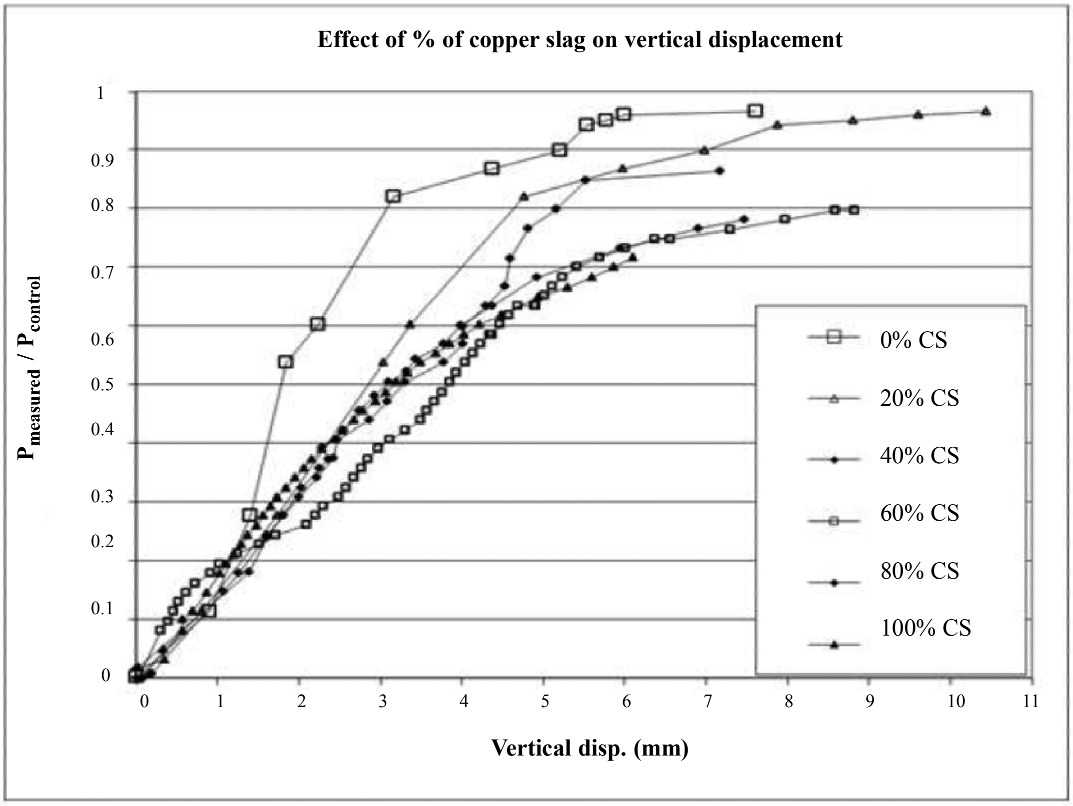

Figure 13. Typical vertical deflection of the tested columns

Table 5. Effect of copper slag on $P_{measured}$ / $P_{calculated}$

Column	f_{cu}	I	l	k	E_c	E_cI	P_c	P_m	P_m/P_c
No	N/mm^2	mm^4	mm	-	N/mm^2	Nmm^2	kN	kN	Ratio
0% CS	36.56	12978395	2500	1	27153.15	352404253237.74	556.49	557.4	1.002
20% CS	35.04	12978395	2500	1	26582.70	345000795586.63	544.80	554.7	1.018
40% CS	33.44	12978395	2500	1	25968.70	337032034652.65	532.22	555.6	1.044
60% CS	31.98	12978395	2500	1	25395.47	329592467312.23	520.47	501.0	0.963
80% CS	30.62	12978395	2500	1	24849.61	322508110629.25	509.28	478.1	0.939
100% CS	28.44	12978395	2500	1	23948.70	310815625557.21	490.82	446.9	0.910

P_c = Calculated failure load, P_m = Measured failure load

Table 6. Average ratios of measured to yield strains $\varepsilon / \varepsilon_y$ in the longitudinal steel

Column	1	2	3	4	Average
0% CS	0.483*	0.886	0.910	0.88	0.89
20% CS	0.776	0.708	0.797	-	0.76
40% CS	0.654	0.951	0.772	0.85	0.81
60% CS	0.697	0.730	0.707	-	0.71
80% CS	0.503	0.586	0.637	-	0.58
100% CS	0.700	0.643	0.704	-	0.68

*Ignored

ductile behavior. The deflections in the right and left faces were very small, as to be expected.

5.5 Vertical Deflection

Table 8 shows the maximum measured vertical deflection values one increment before collapse in the twenty columns tested with different CS percentages. Although the columns with a CS percentage ≤ 40% resisted higher loads, they experienced smaller values of vertical deflections than CS = 60%. The comparatively small values of deflections recorded in the CS = 80% and CS = 100% groups are due to the fact that these columns experienced premature buckling and loss of strength due to the large CS content. The measured to vertical displacement versus the measured load to control the load-ratios of the members of each group behaved almost in a similar fashion. Figure 13 shows a typical load to control load ratios versus vertical displacement in the tested columns. These results emphasize the findings recorded in the lateral deflection of gradual loss in stiffness with the increase of CS content.

Table 7. Average measured lateral displacement in the front and rear faces (mm)

Column	1F	1R	2F	2R	3F	3R	4F	4R	Average Front	Average Rear
0% CS	-2.32	2.19	-3.95	4.10	-3.34	4.38	-3.80	4.11	-3.35	3.69
20% CS	-8.06	7.11	-4.46	5.47	-6.93	6.78	-		-6.49	6.45
40% CS	-2.70	2.71	-3.22	6.12	-2.13	1.66	-6.29	6.20	-3.58	4.17
60% CS	-9.15	8.90	-9.09	12.23	-8.57	9.59	-	-	-8.94	10.24
80% CS	-10.22	9.81	-6.56	8.29	-10.29	11.75	-	-	-9.03	9.95
100% CS	-12.30	11.44	-10.74	13.91	-10.27	9.07	-	-	-11.10	11.47

Table 8. Average measured vertical displacements (mm)

Column	1	2	3	4	Average Vertical Displacement (mm)
0% CS	7.68	7.61	9.64	9.37	8.57
20% CS	7.22	10.44	9.77	-	9.14
40% CS	11.44	10.13	3.96	7.16	8.17
60% CS	12.68	13.25	8.83	-	11.58
80% CS	8.23	7.46	5.74	-	7.14
100% CS	5.87	7.70	6.10	-	6.55

6. Conclusion and Recommendation

The use of CS as a replacement for FA is environmentally helpful due to the reduction in the waste produced from the copper manufacturing process. It also contributes to conservation of natural FA. Twenty RC slender columns measuring 150 mm x 150 mm x 2500 mm with different percentages of CS as a replacement for FA were tested in this research. The contents of cement, water, and coarse aggregate were kept constant while the percentages of CS as a replacement for FA varied from 0 to 100%. Results showed that replacement of up to 40% of FA with CS caused no major changes in column failure load, EI or concrete strength. Further increasing the ratio of CS ro FA reduced the concrete strength and column failure load, and increased concrete slump and lateral and vertical deflections. The maximum difference in measured to control failure load between the group with a CS ≤ 40% and that of the larger CS was recorded in the columns 100% CS as 20%. The measured steel strains were proportional to the failure loads. It was noticed that columns with high percentages of CS (≥ 60%) experienced buckling at earlier stages of loading than those of low percentages of CS.

It is possible that the reduction in strength resulting from increasing CS is due to increased voids due to the fact that CS possesses fewer fine particles than FA . It could also be due to the increase of the free water because the CS absorbs less water than the FA.

It is recommended that the effect of CS change on total void volume and amount of free water content be studied separately.

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