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Copper slag as sand replacement for high performance concrete

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ABSTRACT

This paper reports on an experimental program to investigate the effect of using copper slag as a replacement of sand on the properties of high performance concrete (HPC). Eight concrete mixtures were prepared with different proportions of copper slag ranging from 0% (for the control mix) to 100%. Concrete mixes were evaluated for workability, density, compressive strength, tensile strength, flexural strength and durability. The results indicate that there is a slight increase in the HPC density of nearly 5% with the increase of copper slag content, whereas the workability increased rapidly with increases in copper slag percentage. Addition of up to 50% of copper slag as sand replacement yielded comparable strength with that of the control mix. However, further additions of copper slag caused reduction in the strength due to an increase of the free water content in the mix. Mixes with 80% and 100% copper slag replacement gave the lowest compressive strength value of approximately 80 MPa, which is almost 16% lower than the strength of the control mix. The results also demonstrated that the surface water absorption decreased as copper slag quantity increases up to 40% replacement; beyond that level of replacement, the absorption rate increases rapidly. Therefore, it is recommended that 40 wt% of copper slag can used as replacement of sand in order to obtain HPC with good strength and durability properties.

1. Introduction

Many countries are witnessing a rapid growth in the construction industry which involves the use of natural resources for the development of the infrastructure. This growth is jeopardized by the lack of natural resources that are available. Natural resources are depleting world wide while at the same time the generated wastes from the industry are increasing substantially. The sustainable development for construction involves the use of non-conventional and innovative materials, and recycling of waste materials in order to compensate the lack of natural resources and to find alternative ways for conserving the environment.

Aggregates are considered one of the main constituents of concrete since they occupy more than 70% of the concrete matrix. In many countries there is scarcity of natural aggregates that are suitable for construction while in other countries there is an increase in the consumption of aggregates due to the greater demand by the construction industry. In order to reduce dependence on natural aggregates as the main source of aggregate in concrete, artificially manufactured aggregates and artificial aggregates generated from industrial wastes provide an an alternative for the construction industry. Therefore, utilization of aggregates from industrial wastes can be alternative to the natural and artificial aggregates. Without proper alternative aggregates being utilized in the near future, the concrete industry globally will consume 8–12 billion tons annually of natural aggregates after the year 2010 [1]. Such large consumption of natural aggregates will cause destruction to the environment.

In the last few decades there has been rapid increase in the waste materials and by-products production due to the exponential growth rate of population, development of industry and technology and the growth of consumerism. The basic strategies to decrease solid waste disposal problems have been focused at the reduction of waste production and recovery of usable materials from waste as raw materials as well as utilization of waste as raw materials whenever possible [2]. The beneficial use of by-products in concrete technology has been well known for many years and significant research has been published with regard to the use of materials such as coal fly ash, pulverized fuel ash, blast furnace slag and silica fume as partial replacements for Portland cement. Such materials are widely used in the construction of industrial and chemical plants because of their enhanced durability compared with Portland cement. The other main advantage of using such materials is to reduce the cost of construction.

Copper slag is one of the materials that is considered as a waste material which could have a promising future in construction industry as partial or full substitute of either cement or aggregates. It is a by-product obtained during the matte smelting and refining of copper. To produce every ton of copper, approximately 2.2–3.0 tons copper slag is generated as a by-product material. In Oman approximately 60,000 tons of copper slag is produced every year.

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Also, the production of approximately 0.36, 0.244, 2.0, and 4.0 million tons of copper slag is reported in Iran, Brazil, Japan and the United States, respectively [3]. Utilization of copper slag in applications such as Portland cement substitution and/or as aggregates has threefold advantages of eliminating the costs of dumping, reducing the cost of concrete, and minimizing air pollution problems.

High performance concretes (HPC) can be designed to have the desired higher workability, higher mechanical properties and/or greater durability than those of conventional concretes. Production of HPC that possesses good properties may involve enhancements of the following: ease of placement without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, and life in severe environments. Therefore, HPC should have both high-strength and high-durability properties pertinent to an application. A HPC using cement alone as a binder requires high paste volume, which often leads to excessive shrinkage and large evolution of heat of hydration, besides increased cost. A partial replacement of cement by mineral admixtures, such as, fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash or fillers such as limestone powders in concrete mixes would help to overcome these problems and lead to improvement in the durability of concrete. This would also lead additional benefits in terms of reduction in cost, energy savings, promoting ecological balance and conservation of natural resources, etc. [4–7]. Although there are some studies that have been reported on the effect of copper slag as aggregates on the performance of normal strength concrete, there has been little research concerning the incorporation of copper slag as fine aggregates to produce high performance concrete (HPC). Thus this research was performed to evaluate the potential use of copper slag as sand replacement in the production of high performance concrete (HPC).

2. Materials

2.1. Cement

The cement used in this study was ordinary Portland cement (OPC) purchased from Oman Cement Company. This cement is the most widely used one in the construction industry in Oman.

2.2. Fine aggregates

Fine aggregates (i.e. 10 mm) and fine sand were purchased from a nearby crusher in Al-Khoudh area, which are typically the same materials used in normal concrete mixtures. The gradation test conducted on aggregates showed that they met specifications requirements.

2.3. Copper slag

Copper slag is a by-product material produced from the process of manufacturing copper. As the copper settles down in the smelter, it has a higher density, impurities stay in the top layer and then are transported to a water basin with a low temperature for solidification. The end product is a solid, hard material that goes to the crusher for further processing. Copper slag used in this work was brought from Oman Mining Company, which produces an annual average of 60,000 tons.

2.4. Silica fume

The silica fume used in the production of high-strength concrete was supplied and added to the mix in a powder form (Elkem Emsac 500s).

2.5. Superplasticizer

In order to improve the workability of high-strength concrete, superplasticizer in the form of a polynaphthalene sulphonate-based admixture (conplast SP430) was used. This had 40% active solids in solution.

3. Laboratory testing program

3.1. Mix design and sample preparation

The mix proportion chosen for this study is given in Table 1. Eight concrete mixtures with different proportions of copper slag ranging from 0% (for the control mix) to 100% were considered as shown in Table 2. The constituents were weighed in separate buckets. The materials were mixed in a rotating pan in accordance with ASTM C192-98 [8]. The overall mixing time was about 4 min. The mixes were compacted using vibrating table. The slump of the fresh concrete was determined to ensure that it would be within the design value and to study the effect of copper slag replacement on the workability of concrete. The specimens were demoulded after 24 h, cured in water and then tested at room temperature at the required age.

To determine the unconfined compressive strength, six cubes (150 mm × 150 mm × 150 mm) were cast for each mix and water-to-binder ratio, and three samples were tested after 7- and 28-days of curing. Three 150 mm diameter × 300 mm long cylinders were prepared for each mix in order to determine the 28-day tensile strength of concrete. Also, to determine the flexural strength (modulus of rupture) for each mix, three 100 mm × 100 mm × 500 mm prisms were cast and tested after 28-days of curing. Two more (150 mm × 150 mm × 150 mm) cubes were prepared and tested after 28-days in order to assess the durability of the HPC using the initial surface absorption test.

3.2. Testing procedure

After curing, the following tests were carried out on the concrete specimens:

- 7- and 28-day cube compressive strength test was conducted in accordance with BS 1881: Part 116 [9] using a loading rate of 2.5 kN/s;
- 28-day cylinder tensile (splitting) strength test was done in accordance with ASTM C496-96 [10] using a loading rate of 2 kN/s;
- 28-day flexural strength test was conducted in accordance with ASTM C78-94 [11] using a simple beam with third point loading at a loading rate of 0.2 kN/s; and
- the initial surface absorption test was conducted on two samples after 28-days of curing in accordance with BS 1881: Part 208 [12].

All strength tests were conducted using a DARTEC compression machine.

4. Results and discussion

4.1. Chemical analyses and physical properties

Chemical analyses of OPC and copper slag are presented in Table 3. It can be seen from Table 3 that free and combined limes contribute to nearly 63% of the chemical composition of OPC whereas copper slag has a very low lime content of approximately 6%. This indicates that copper slag is not chemically a very reactive material

Table 1
Mix proportion and water-to-cement (w/c) ratio for high performance concrete.

Mix proportions (kg/m^3)						w/c ratio	SP (l/m^3)
Cement	Silica fume	Sand	10 mm Agg.	20 mm Agg.	Water		
400	44	710	1190	–	140	0.35	7.9

Table 2
Properties of high-strength concrete at 7- and 28-days of curing.

Mix no.	Mix proportions	Density (kg/m^3)	Slump (mm)	Strength (MPa)			
				$(F_{cu})^a$	$(F_{cu})^b$	$(F_t)^b$	$(F_{cr})^b$
1	Control (100% S)	2568	28	76.9	93.9	5.4	14.6
2	10% CS + 90% S	2530	28	79.6	99.8	5.2	13.0
3	20% CS + 80% S	2588	50	74.5	95.3	6.2	12.4
4	40% CS + 60% S	2586	85	76.4	95.2	6.1	12.5
5	50% CS + 50% S	2625	115	77.8	96.8	6.1	12.9
6	60% CS + 40% S	2658	128	69.0	83.0	4.8	11.1
7	80% CS + 20% S	2673	143	63.8	83.6	4.7	10.3
8	100% CS	2700	150	63.4	82.0	4.4	10.1

F_{cu} = cube compressive strength, F_t = tensile strength, F_{cr} = flexural strength, S = sand, CS = copper slag.
[a] Cured at 7-days.
[b] Cured at 28-days.

Table 3
Chemical composition of ordinary Portland cement (OPC), copper slag (CS).

Component	OPC (%)	CS (%)
SiO_2	20.85	33.05
Al_2O_3	4.78	2.79
Fe_2O_3	3.51	53.45
CaO	63.06	6.06
MgO	2.32	1.56
SO_3	2.48	1.89
K_2O	0.55	0.61
Na_2O	0.24	0.28
TiO_2	0.25	0
Mn_2O_3	0.05	0.06
Cl	0.01	0.01
Loss on ignition	1.75	0
IR	0.21	0
CuO	0	0.46
$Al_2O_3 + SiO_2 + Fe_2O_3$	29.14	89.29

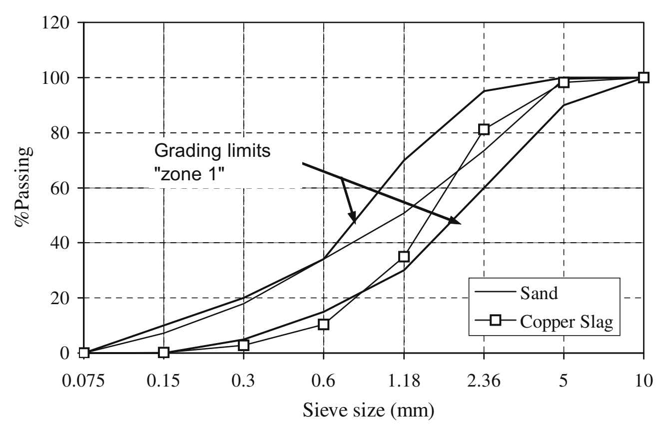

Fig. 1. Sieve analysis of sand and copper slag.

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, copper slag has high concentrations of SiO_2 and Fe_2O_3 compared with OPC. In comparison with the chemical composition of natural pozzolans of ASTM C618-99 [13], the summation of the three oxides (silica, alumina and iron oxide) in copper slag is nearly 89%, which exceeds the 70% percentile requirement for Class N raw and calcined natural pozzolans. Therefore, copper slag is expected to have good potential to produce high quality pozzolans.

Tests to determine specific gravity and water absorption for copper slag and sand were carried out in accordance with ASTM C128 [14]. Copper slag has a specific gravity of 3.4 which is higher than that for sand (2.77) and OPC (3.15) which may results in production of HPC with higher density when used as sand substitution. Also, the measured water absorption for copper slag was 0.17% compared with 1.36% for sand. This suggests that copper slag would demand less water than that required by sand in the concrete mix. Therefore, it is expected that the free water content in concrete matrix will increase as the copper slag content increases which consequently will lead to increase in the workability of the concrete.

Fig. 1 shows sieve analysis test results conducted to determine the gradation of copper slag and sand from which it may be seen that in general both materials met specification requirements of zone 1 grading limit [15]. However, it seems that sand has higher fines content than copper slag.

4.2. Effect of copper slag substitute on the workability and density of HPC

The effect of copper slag replacement as fine aggregates on the workability and density of high performance concrete is presented in Table 2 for different proportions of copper slag. The workability of concrete was assessed based on the measured slump of fresh concrete. It is clear from Table 2 that the workability of concrete increases significantly with the increase of copper slag content in concrete mixes. For the control mixture (i.e. Mix 1), the measured slump was 28 mm whereas for Mix 8, with 100% replacement of copper slag, the measured slump was 150 mm. This considerable increase in the workability with the increase of copper slag quantity is attributed to the low water absorption characteristics of copper slag and its glassy surface [16] compared with sand which caused surplus quantity of free water to remain after the absorption and hydration processes have completed. This increase in the workability may have beneficial effect on concrete in the sense that concrete mixes with low water-to-cement ratios, for the same amount of sand replaced, can be produced which may have good workability, greater strength and improved durability than the conventional HPC. However, it should be noted that mixes with high contents of copper slag (i.e. Mixes 7 and 8) showed signs of bleeding and segregation which can have detrimental effects on concrete performance.

Also Table 2 shows that there is general slight increase in the density of high performance concrete with the increase of copper slag quantity. The density of concrete was increased by almost 5%. This is mainly due to the higher specific gravity of copper slag which was 3.4 compared with sand which has a specific gravity of 2.77.

4.3. Effect of copper slag substitute on the strength of HPC

4.3.1. Unconfined compressive strength

The average 7- and 28-day unconfined compressive strengths for different HPC mixes are shown in Fig. 2. The results show that the compressive strength of concrete is slightly increased as copper slag quantity increases up to 50% addition of copper slag, beyond that the compressive strength was reduced significantly due to the significant increase in the free water remained in the mix in excess than that required for hydration of cement paste and for proper compaction of fresh concrete (Fig. 3). The excessive free water content in the mixes with high copper slag content causes the particles of the constituents to separate leaving pores in the hardened concrete which consequently causes reduction in the concrete strength.

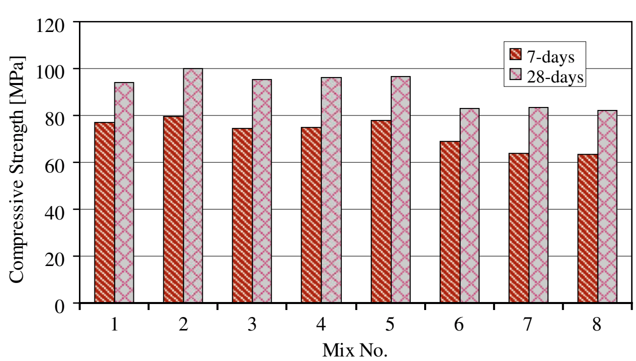

Fig. 2. Average cube compressive strength of high-strength concrete at 7- and 28-days of curing.

The highest compressive strength was achieved by Mix 2 (Table 2) with 10% replacement of copper slag, which was found about 100 MPa compared with 94 MPa for the control mixture. This means that there is an increase in the HPC strength of almost 6% compared to the control mix. However, mixtures with 80% and 100% replacement of copper slag (Mixes 7 and 8) gave the lowest compressive strength around 80 MPa which is almost 16% lower than the strength of the control mix.

The above observations are supported by the work of other researchers who studied the influence of copper slag as fine and coarse aggregates on the strength of both normal [17–24] and high-strength concrete [3]. The results indicated that the compressive and tensile strengths of concrete made with copper slag are almost the same as that of normal and high-strength concretes or even quite higher than the control mixtures. The compressive strength of mortars and concrete specimens containing copper slag as fine aggregate was investigated by Hwang and Laiw [20]. The study concluded that the mortars containing the larger amounts of copper slag sand had lower early strengths at w/c of 0.48 and that the strengths of mixtures with 20–80% substitution of copper slag were higher than that of the control specimens. Also the work conducted by Li [22] and Zong [23] showed that concrete containing copper slag as fine aggregate exhibited similar mechanical properties as that containing conventional sand and coarse aggregates. Recently the mechanical properties of high-strength concrete incorporating copper slag as coarse aggregates were investigated by Khanzadi and Behnood [3]. The results showed that the use of copper slag aggregate compared to limestone aggregated resulted in a 28-day compressive strength improvement of about 10–15%, and a splitting tensile strength increase of 10–18%.

4.3.2. Tensile and flexural strengths

Three cylinders were tested for splitting tensile strength in accordance with ASTM C496-96 [10]. The splitting tensile strength was determined using the following equation:

$$F_t = 2P/\pi Ld \tag{1}$$

where F_t is splitting tensile strength, P is the maximum applied load indicated by testing machine, L is the length of specimen, and d is diameter of specimen.

The results from the tensile test are presented in Table 2. It can be seen from Table 2 that the tensile strength of concrete showed similar behaviour to the compressive strength. The average tensile strength was within the permissible values in accordance with the design specifications. For design purposes, the tensile strength can be empirically taken as $0.45\sqrt{F_{cu}}$, where F_{cu} is the 28-day cube compressive strength [25].

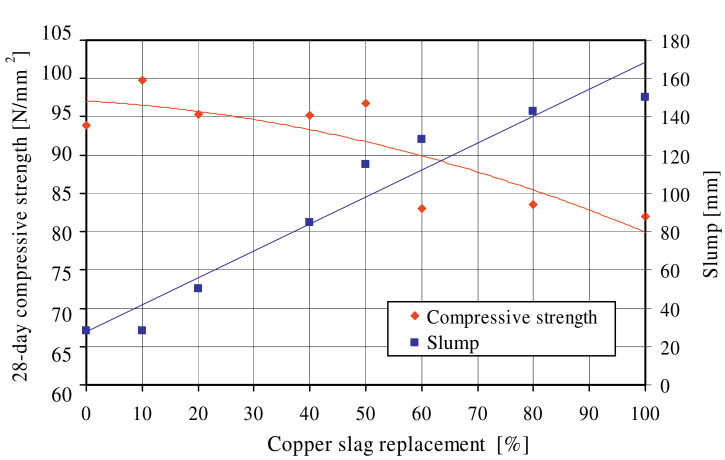

Fig. 3. Relationship between workability and strength of HPC.

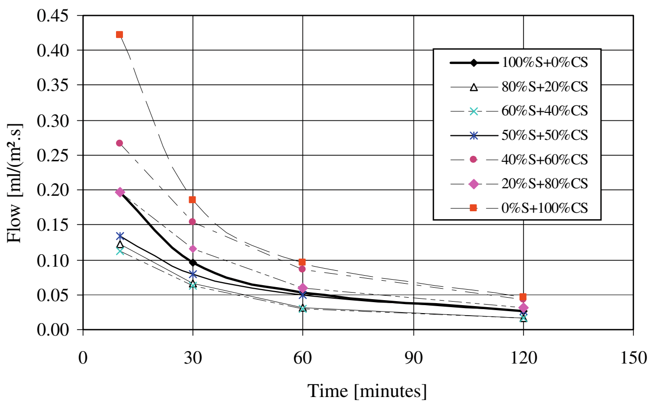

Fig. 4. Flow vs. time for different mixes.

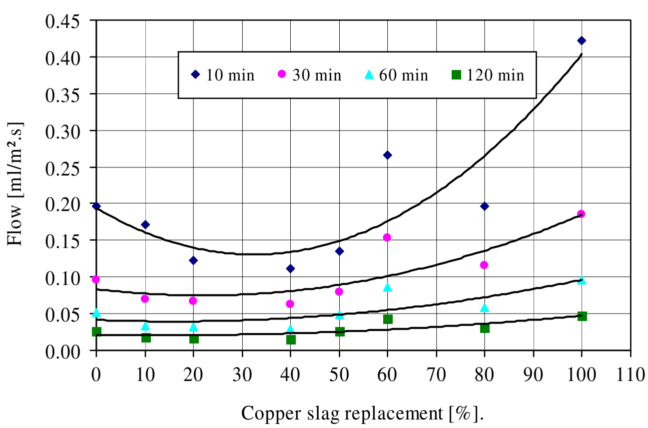

Fig. 5. Effect of copper slag addition on water absorption.

Three prisms (beams) were also tested for flexural strength [11] under third point loading conditions. The average modulus of rupture (flexural strength) was determined using the following expression:

$$F_{cr} = PL/bd^2 \tag{2}$$

where F_{cr} is the modulus of rupture, b is the average width of specimen, and d is the average depth of specimen.

Table 2 indicates that the modulus of rupture of all mixtures showed a similar behaviour to the compressive strength results.

4.4. Effect of copper slag substitution on the water absorption of HPC

The initial surface absorption test was used to assess the durability of HPC where the results are presented in Fig. 4. Fig. 4 shows the results from the initial surface absorption test for different mixes. All mixtures showed the same trend of decreasing surface absorption (the flow rate) with testing time. The decrease was generally sharp during the first 30 min, gradually decreased afterwards up to 120 min. Mix 8 (with 100% CS) showed the highest absorption rate compared to other mixes whereas mixes with 60% sand + 40% CS and 80% S + 20% CS showed the lowest absorption rate for the entire time duration. However, the control mix showed an intermediate absorption rate compared with other mixtures.

Fig. 5 shows that there is general decrease in the surface water absorption with the increase of copper slag content in the concrete mix up to 40% of copper slag substitution (i.e. Mix 4) beyond that the water absorption rapidly increases. This suggests that addition of 40% of copper slag in the concrete mix will have the lowest surface water absorption.

5. Conclusions

The following conclusions may be drawn from the present study:

1. Compared to the control mix, there was a slight increase in the HPC density of nearly 5% with the increase of copper slag content, whereas the workability increased rapidly with increases in copper slag percentage.
2. Addition of up to 50% of copper slag as sand replacement yielded comparable strength with that of the control mix. However, further additions of copper slag caused reduction in the strength due to an increase of the free water content in the mix.
3. Mixtures with 80% and 100% copper slag replacement gave the lowest compressive strength value of approximately 80 MPa, which was almost 16% lower than the strength of the control mix.
4. There was a decrease in the surface water absorption as copper slag quantity increased up to 40% replacement. Beyond that level of replacement, the absorption rate increases rapidly.
5. It is recommended that 40 wt% of copper slag can be used as replacement of sand in order to obtain HPC with good properties.
6. It should be noted that further research work is needed to explore the effect of copper slag as fine aggregates on the properties of concrete with different cement types, silica fume sources and the degree of fines.

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