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EFFECT OF COPPER SLAG ON WORKABILITY AND COMPRESSIVE STRENGTH OF CONCRETE

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Abstract

Reduction in cement used in concrete production is an important strategy to reduce non-renewable raw materials used in cement production, such as clay, limestone, and chalk. Reducing the use of cement in the production of clinker can result in a decrease in both energy consumption and CO_2 emissions. Furthermore, the process of calcining clay, limestone, and chalk emits carbon dioxide into the atmosphere, a problem that leads to global warming. Conversely, substantial amounts of industrial and agricultural wastes, which have limited alternative use, are being generated globally. Thus, copper slag, a byproduct of the industrial process of iron production, can cause environmental problems if not properly used. To benefit from it, it should be repurposed and used in other industries. Giad industrial company in Sudan provided the copper slag (CS). This study aims to investigate the effects of the substitution of Portland cement with copper slag at dosages of 10 and 15% by weight on the fresh and compressive strength of concrete. The findings indicate that copper slag incorporated into concrete slightly improved workability while reducing compressive strength.

Keywords: Giad, Copper Slag, Compaction Factor, Compressive Strength, Waste Material

1. INTRODUCTION

Currently, concrete is the dominant construction material worldwide. It is widely employed in many industries, including those dealing with water conservation, transportation, and the construction of buildings and bridges (Al-Saidy, et al., 2009; Zhang et al., 2022). The main reason for its popularity is its adaptability and flexibility, as well as its minimum maintenance needs throughout structures' service lives. As well, the raw materials required in the production of concrete are widely available and economical (Gursel & Ostertag, 2019). With an estimated annual usage of 25 million tons of concrete for infrastructure construction (Kashyap et al., 2023; Sharma & Khan, 2017; Siddique et al., 2020), it is considered the second most utilized material worldwide, trailing only water (Abdalla et al., 2022a; Rathanasalam et al., 2020).

Cement is considered a major constituent material in concrete production (Ahmad et al., 2022). Cement production has been rapidly increasing to meet the growing demand. As an illustration, the production of cement increased from 2.3 to 3.5 Gt between 2005 and 2020, which is equivalent to a 2.5 % yearly growth rate. Anticipatedly, cement production will increase to 3.7-4.4 Gt by 2050 (Abdalla et al., 2022b). In Portland cement production, raw materials are progressively milled, calcined, and cement clinker is milled with gypsum. As a result, its production poses numerous environmental concerns in addition to economic considerations

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(Shi et al., 2008). One ton of ordinary Portland cement (OPC) production is responsible for the release of one ton of carbon dioxide (Thomas et al., 2022). Therefore, it represents a significant contributor to greenhouse gas emissions resulting in the exacerbation of global warming (Ahmad et al., 2022). In order to minimize the emission of CO_2 and the utilization of cement, waste materials should be employed instead of cement during the production of concrete.

The recent advancements in technology and industrial growth, combined with population growth, have led to the unsustainable use of non-renewable resources, higher energy consumption, and a significant increase in waste production. At present, appropriately disposing of these by-products has become a significant environmental matter (Ali et al., 2022; Moura et al., 2007; Rajasekar et al., 2019). As a consequence, waste materials like fly ash, silica fume, and blast furnace slag can be used as supplementary cementing materials (SCMs) in the construction sector (Kubissa et al., 2019). The above-mentioned SCMs, copper slag (CS), are now uncommonly used in concrete as a cement or aggregate replacement. CS is a byproduct produced during the refining and smelting stages of copper manufacture (Lori et al., 2019; Singh et al., 2022). In 1900, less than 500,000 tons of copper were produced worldwide. However, by 2018, the production of copper mining had increased annually by 3.2%, reaching a total of 20.6 million tons. By 2023, the amount of copper mined is anticipated to increase to 28.9 million tons (Chaitanya & Kumar, 2022; Singh et al., 2022). As a byproduct of producing one ton of copper, on average, 2.2 to 3 tons of copper slag are produced.(Ambily et al., 2015; Bhoi et al., 2018; dos Anjos et al., 2017; Singh et al., 2022). Waste management, particularly copper slag, poses a major challenge for mining and processing industries, which are often disposed of in proximity to smelter sites (Gabasiane et al., 2021). Therefore, copper slag can be used for various applications including the replacement of cement and/or as aggregates, which can result in three major advantages: the dumping costs are eliminated, concrete costs are reduced, and problems related to air pollution are mitigated (Al-Oraimi, et al., 2009; N. Gupta & Siddique, 2020).

The type of furnace, the metallurgical procedure used and the makeup of the extracted ore all play a role in determining the composition of a given slag (Shi et al., 2008). Copper slag contains high amounts of iron oxide (Fe_2O_3) and small amounts of several other oxides, including such as Al_2O_3, SiO_2, CaO, MgO…so on (Sharma & Khan, 2017). Given its chemical and physical characteristics, this substance could be employed as possibly even a cement substitute as well as an aggregate in concrete production (Mavroulidou, 2017). Table 1 summarizes the copper slag chemical compositions from various research.

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Table 1: The chemical compositions of copper slag carried out by different authors

							Oxide				
Reference	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**K_2O**	**MgO**	**Na_2O**	**Mn_2O_3**	**SO_3**	**CI**	**∑P**
Al-Saidy, et al. (2009)	33.05	2.79	53.45	6.06	0.61	1.56	0.28	0.06	-	0.01	89.29
Gupta & Siddique (2020)	33.62	3.65	55.6	3.31	0.82	1.51	0.37	-	1.12	-	92.87
Bhoi et al. (2018)	33.85	2.79	53.45	6.06		1.61	0.28	0.02	1.89	0.01	90.09
Panda et al. (2022)	20.49	5.73	64.27	1.05	0.56	1.89	1.4	-	1.45	-	90.49
Gu et al. (2023)	22.57	5.13	48.33	15.5	1.39	2.05	0.07	-	0.41	-	76.03
Wu et al. (2010)	31.92	2.52	59.11	1.25	0.81	1.65	1.4	-	1.34	-	93.55
$\sum P = SiO_2 + Al_2O_3 + Fe_2O_3$											

Previous research has examined the effect of the use of copper slag instead of cement and aggregates while producing concrete. For instance, Gupta & Siddique (2020), investigated the effects of replacing the sand in self-compacting concrete (SCC) with 0–60% copper slag, in increments of 10%. Various characteristics, including sorptivity, penetration of chloride ion, permeability, compressive strength, and water absorption were evaluated. The authors reported that the use of SCC mixes with a maximum of 30 % copper slag greatly increased compressive strength and durability; however, any further replacement produced results similar to the control concrete mix. A study by Moura et al. (2007), examined the feasibility of substituting copper slag for cement in the production of concrete and the results indicated that copper slag may be used instead of cement material. Also, research by Wu et al. (2010), suggested that the replacement of a portion of the sand with copper slag, up to 40%, during the evaluation of high-strength concrete leads to comparable or improved mechanical properties compared to the control mixture. Nevertheless, the concrete performance is considerably reduced when the substitute exceeds 40%. Moreover, Panda et al. (2022) studied the interfacial transition zone (ITZ) of concrete using copper slag instead of sand and concluded that copper slag has greater pozzolanic reactivity than natural sand and improves the ITZ properties of hardened concrete.

In the literature review, copper slag used in concrete can provide numerous environmental benefits such as recycling waste material, the reduction of the use of natural resources, the reduction of greenhouse gas emissions, the reduction of water pollution, and the promotion of sustainability. This research aimed to investigate copper slag from the Giad industrial company, Sudan as a replacement for cement in ratios of 10 and 15% and to evaluate its effect on the workability and compressive strength of concrete.

The remaining sections are as follows: section 2 gives an extensive description of the methods and materials, including data on mix design, sample preparation, and sample testing, section 3 discusses the results of the study, and section 4 presents the conclusions.

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2. MATERIALS AND METHODS

2.1 Raw materials

In this context, the cement used was ordinary Portland cement (OPC) CEM I/42.5N, which was produced locally and complied with EN 197-1. This type of cement is most commonly used in the construction sector in Sudan. The Giad industrial city in the Gazira state of Sudan provided copper slag, and x-ray fluorescence (XRF) was used to determine the chemical compositions of cement and copper slag. Table 2 lists the physical characteristics of cement and copper slag. Figure. 1 (a and b) depict the image of the copper slag and coarse aggregate, respectively.

Coarse aggregate (CA) is constituted of natural aggregates with a maximum size of 20 mm. In this study, the CA was collected from the Kinana region and then subjected to a washing and sun-drying process. The natural sand used as the fine aggregate (FA) was taken from the Al-Damazin region and washed before drying in an oven for 24 h at 105°C. The physical characteristics of the aggregates are shown in Table 3 and also, the grading curves for both fine and coarse aggregates were plotted on a semi-logarithmic graph indicating the cumulative percentage passing as shown in Figure. 2.

Table 2: The physical properties of cement and copper slag

Material	Cement	Copper slag
Water absorption	28%	-
Initial sitting time	60 minutes	-
Final sitting time	4 hours	-
Specific gravity	3.1	3.6

(a) (b)

Figure 1: (a) image of copper slag and (b) image of coarse aggregate

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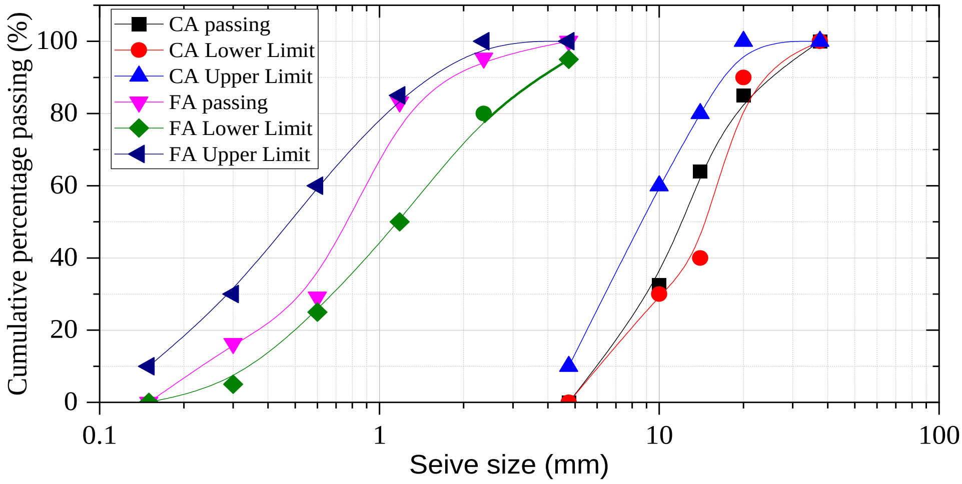

Figure 2: Particle size distribution of the aggregates

Table 1: The physical properties of the aggregates

Type of aggregates	Fineness modulus	Specific gravity	Silt Content (%)	Density (kg/m^3)
Coarse aggregates	-	2.64	-	1,550
Fine aggregates	2.76	2.60	2	1,675

2.2 Mix design

Three concrete mixes were made according to the DoE method procedure. The first mix, labelled as the control mix, did not contain any copper slag. The remaining two mixes had copper slag, with cement partially replaced at rates of 10 and 15% respectively. The details of all three mixes are listed in Table 4.

Table 4: The concrete mix proportions (kg/m^3)

Mix	Copper slag (%)	Cement	Copper slag	Water	Fine aggregates	Coarse aggregate
Mix 1	0	415	0	195	587	1193
Mix 2	10	373.5	41.5	195	587	1193
Mix 3	15	352.75	62.25	195	587	1193

2.3 Experimental

2.3.1 Research execution

To conduct the research, the materials were collected, processed, analyzed, and subsequently utilized for the preparation of the test samples according to the flowchart depicted in Figure 3.

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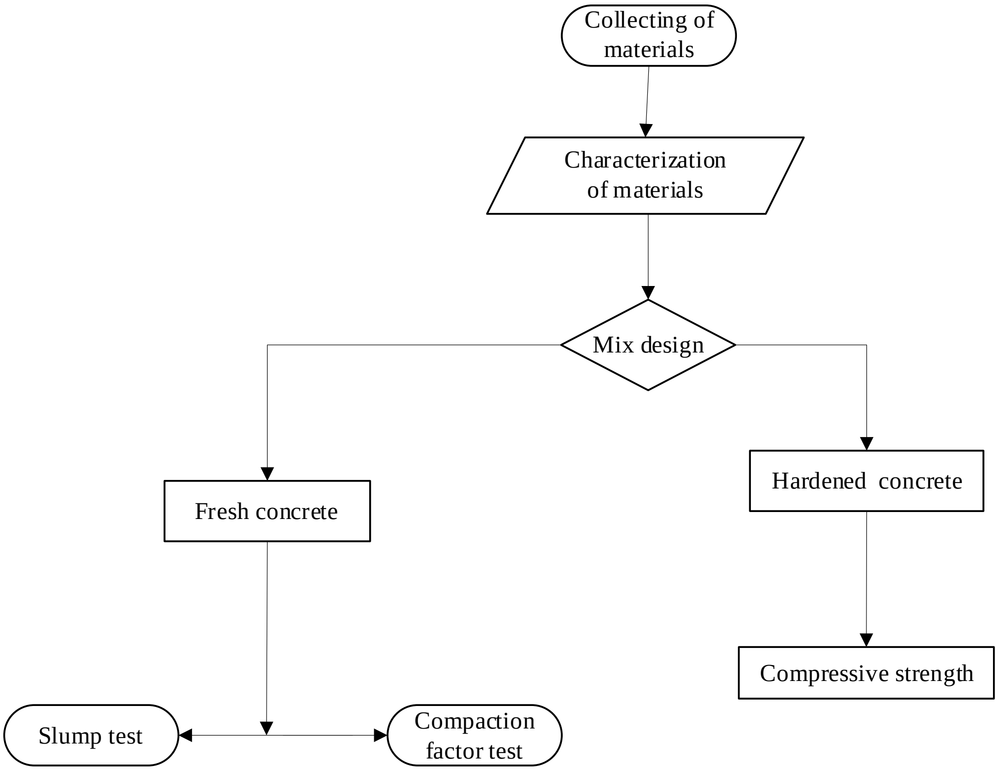

Figure 3: Flow chart of research execution

2.3.2 Fresh concrete properties

In the assessment of the workability of freshly mixed concrete, according to BS 1881-104, the slump test was employed as part of the mix design process. In addition, in accordance with BS 1881-103, the compaction factor test was conducted to evaluate the workability level of the freshly mixed concrete.

2.3.3 Concrete compressive strengths

Concrete cubes measuring 150 mm in size were produced, subjected to curing, and subsequently tested at the 7-day and 28-day. The compressive strength was determined following the guidelines outlined in BS EN 12390-03. The test was conducted using a universal testing machine (UTM) on three cube specimens, with the average value serving as the measure of compressive strength.

2.3.4 Split tensile strength

in order to assess split tensile strength at 7 and 28 days, concrete cylinders measuring 150 mm in diameter and 300 mm in height were employed in accordance with BS 1881-117. The test was performed using a universal testing machine (UTM) by averaging the results from three samples.

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3. RESULTS AND DISCUSSIONS

3.1 Chemical compositions

The XRF technique determined the chemical compositions. Table 5 is a list of chemical compositions of cement and copper slag. Iron (III) oxide (Fe_2O_3) comprises the majority of the oxides in copper slag, constituting 57.56 %, followed by silicon dioxide (SiO_2), which was 28.38%. Furthermore, silicon oxide (SiO_2), iron (III) oxide ((Fe_2O_3), and aluminium oxide (Al_2O_3) resulted in 90.71% of the total, as a result, the copper slag was categorized as Class F pozzolan according to ASTM C618. Previous researchers reached a comparable conclusion (Al-Saidy et al., 2009; Bhoi et al., 2023; Gupta et al., 2021; Panda et al., 2022).

Table 5: The chemical compositions of copper slag and cement

Oxide (%)	Copper slag	Cement
SiO_2	28.38	24.619
Al_2O_3	4.77	5.454
Fe_2O_3	57.56	2.741
CaO	1.05	62.741
K_2O	0.47	0.607
MgO	1.25	0
P_2O_5	0	0.439
TiO_2	0	0.193
MnO	0	0.025
SO_3	0.97	2.964
Na_2O	0.98	-
$\sum(SiO_2+Al_2O_3+Fe_2O_3)$	90.71	-

3.2 Fresh properties of concrete

Concrete workability refers to its capacity for effortless placement, compaction, and finishing without experiencing issues such as separation or bleeding. Factors such as the ratio of water to cement, the quantity and nature of the aggregate, and the incorporation of chemical admixtures influence this attribute. The slump test (also known as the “slump cone test”) is a commonly employed method for evaluating the workability of recently mixed concrete. It can be conducted either on-site during construction or in a laboratory environment (Razeman et al., 2023). The combination of copper slag in freshly placed concrete results in a slight improvement in workability, as evidenced by the slump value (measured in millimetres) presented in Figure 4. The limited water absorption capabilities of copper slag bring about this enhancement by maintaining free water in the concrete matrix during hydration. As a result, there is a significant increase in workability. Many researchers (Al-Jabri et al., 2011; Al-Oraimi, et al., 2009; dos Anjos et al., 2017) have reported a similar observation.

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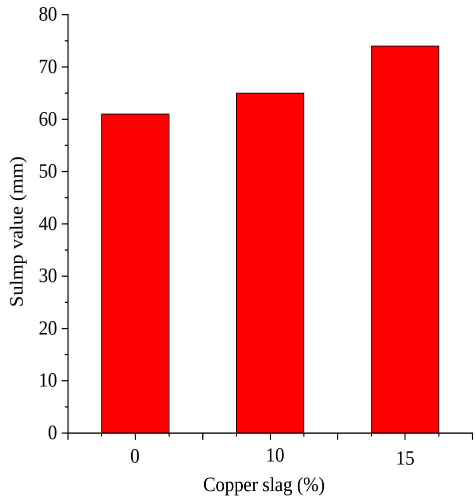

Figure 4: Sulmp value of copper slag concrete

The concrete compaction factor is a gauge for the workability of concrete and its ease of compacting and consolidating fresh concrete. It quantifies the relationship between the weight of partially compacted concrete and the weight of fully compacted concrete indicating its compaction characteristics. Figure 5 shows the results of the compaction factor for the concrete with copper slag; the compaction factor of a mixed concrete (e.g., 0% copper slag) was 0.93, whereas, for a mix of 10% and 15% copper slag, the compaction factor was 0.9 and 0.92, respectively.

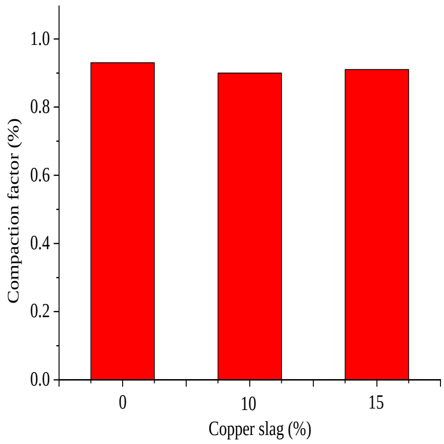

Figure 5: Compaction factor of copper slag concrete

3.3 Compressive strength of concrete

Notably, the compressive strength of concrete serves as a crucial engineering characteristic that allows the indirect evaluation of numerous mechanical and durability properties. The assessment of compressive strength provides valuable insights into other essential mechanical and durability properties of concrete, allowing meaningful inferences to be drawn (Abdalla et al., 2022a; Faraj et al., 2022). Figure 6 presented the compressive strength of the concrete after

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curing for 7 and 28 days under normal water conditions The results indicated that the addition of 10% and 15% dosages did not significantly impact the compressive strength at the 7-day. Meanwhile, at a curing age of 28 days, the results reveal that all mixes containing copper slag perform less well than control concrete for instance, the strength of mixes containing 10% and 15% copper slag decreased by 13% and 18%, respectively, in comparison to the control mix. According to the results, the strength of copper slag concrete is generally lower than that of control concrete. Shi et al. (Shi et al., 2008) using copper slag as a replacement for cement in mortar, made a similar observation by varying its content from 0% to 10%. The decrease in compressive strength can be attributed to the relatively low absorption rate of copper slag, resulting in an increased presence of free water within the mixture. Consequently, this promotes the formation of pores in the hardened concrete, leading to a reduction in its overall strength (Al-Oraimi, et al., 2009; Gu et al., 2023; Rajasekar et al., 2019). The inclusion of heavy metals within copper slag, which has the potential to hinder the hydration process in concrete mixtures, may provide insights into the observed reduction, as reported by Sharma & Khan (Sharma & Khan, 2017).

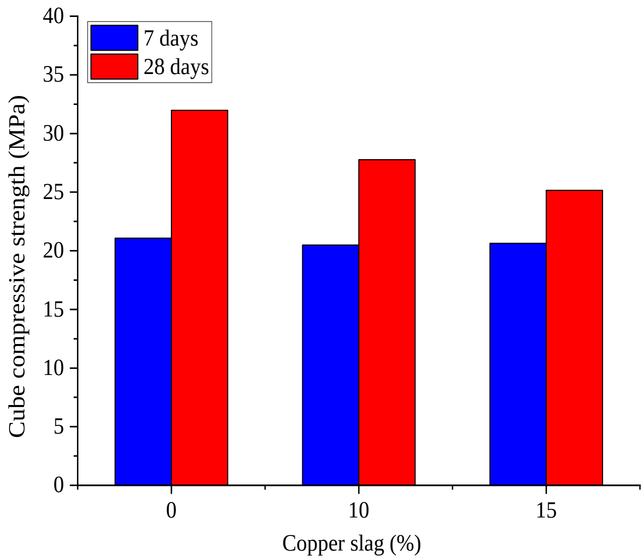

Figure 6: Compressive strength of copper slag concrete

3.4 Split tensile strength

The results of indirect tensile strength testing at 7 and 28 days, particularly the splitting cylinder results, are depicted in Figure 7. Although concrete is generally not designed for tensile strength, assessing this property is valuable as it correlates with the occurrence of concrete cracking. At 7 days the split tensile values are similar, meanwhile at 28 days with 0% copper slag (reference mix) the tensile strength was 2.8 MPa and with 10%, and 15% it reduced to 2.71 MPa and 2.69 MPa of reduction of 3.3% and 4.1%, respectively. It can be observed that as the dosage of copper slag increases tensile strength is reduced. Moreover, it is noteworthy that the splitting tensile strength results align with expectations for ordinary concrete, as the trend of tensile strength follows a similar pattern as that observed in compressive strength. The

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reduction of tensile strength can be attributed to the relatively low absorption rate of copper slag, resulting in a higher concentration of free water within the concrete mixes. Similar results were observed by Mavroulidou (2017) who also stated that tensile strength reduced with the increased copper slag dosages.

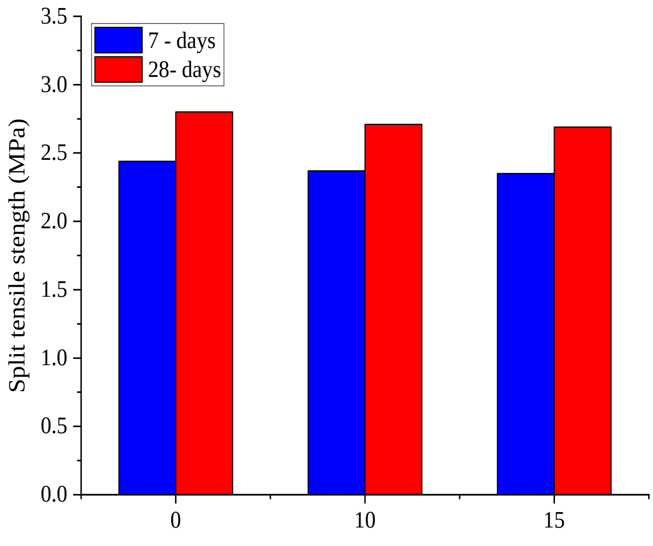

Figure 7: Effect of copper slag on the split tensile strength

4. CONCLUSIONS

In order to reduce waste material and cement usage, this study aims to replace cement in concrete productions with copper slag obtained from the Giad industrial company in Sudan. Consequently, it is possible to draw the following conclusions.

a) The reduced water absorption of copper slag and the smooth texture of its particles probably contribute to the notable enhancement of workability in fresh concrete when copper slag is incorporated.

b) The concrete mixtures containing copper slag demonstrate a slightly reduced compressive strength compared to the control mix after 28 days of curing.

c) A similar trend of split tensile strength and compressive strength was observed, demonstrating a consistent relationship between these two properties.

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Conflict of interest

The authors express no conflicting interests regarding this work.

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