Effect of Water-Cement Ratio on Mix Design and Mechanical Strength of Copper Slag Aggregate Concrete

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Abstract. In concrete, the distinct influence on most or the entirety of the properties is the measure of water utilised in the matrix. In concrete mix design, the water-cement ratio is responsible for binding all constituents of concrete together. If the water-cement proportion is higher, it brings about wider spacing between the cement aggregates and thus, influences the compaction. Correspondingly, concrete’s durability and compressive strength are decreased due to increased dampness levels. Especially with added fine aggregates the water demand increases because of the increased surface area of concrete which prompts a higher water-cement ratio. Wider spaces are formed between the aggregate materials with the addition of extra water and when the moisture vaporises, voids are filled up with air. The subsequent insufficient compaction lessens the concrete’s strength. Sets of basic experimental investigations were conducted to examine the impact of various water-cement proportion on mix design and mechanical strength of concrete incorporated with fine aggregate in terms of copper slag. Natural sand replaced with copper slag with four different percentage and correlation coefficients between mechanical properties of copper slag concrete were also evaluated.

1. Introduction
Concrete is now the biggest used composite structural material in today’s era of the construction world. The concrete matrix comprises of hard and chemically inert substances usually fine and coarse aggregates and binder typically cement when added with water works as adhesive, which hold the concrete matrix together. These ingredients of concrete making, influence the properties of concrete largely. The wish for the structure to be strong and durable exclusively depends on the mix design of the structural concrete at the rudimentary stage. The design mix of concrete is the method of choosing and arranging all constituents of concrete and deciding their relative quantities to produce concrete of desired strength, durability and workability under the circumstances as economic as possible [1,2]. There are some common factors that affects not only the mix design but also the strength and durability of structural concrete to a great degree such as (i) water/cement ratio, (ii) compaction (iii) ingredients of concrete (v) shape and size of aggregate (vi) weather condition and casting temperature [3-6]. The potential for immense strength overly indicates the quality and grade of concrete, which is related to the long-term performance of the concrete structure. The evaluation of ability of the concrete structure to withstand various external loads can be done through different laboratory tests for compression, tension and flexure, void content measurement test etc.
Apart from this, curing of concrete and the age of concrete are also influential in achieving strength and durability [7,8]. Out of all stated factors, utilization of water is significant on the grounds that the proportion of water to cement is the most basic factor for producing "perfect" concrete. The working mechanism of water in the concrete mix is a two-stage process, one is bonding and the second one is workability. Water establishes and increases the bond between all constituents of a concrete mix by behaving as a lubricant. At a perfect water-cement ratio, the perfect fluidity of the mix can be achieved [9-12]. If the percentage of water is increased in the concrete mix, the mass concrete becomes permeable and penetrable and in the event that it is less, concrete gets dry and inefficient to achieve full strength due to poor binding quality. At the same time, the type and quality of aggregates used in concrete production are also very important [13,14]. An aggregate provides body i.e. volume or mass to the concrete but ultimately does contribute significantly to the final properties of concrete. Research and development of new materials are continuously going on to replace the conventional concrete not only in order to achieve the requisite properties for application on the different situations but also to set back ecological and environmental inconsistency. Many types of industrial by-products and waste materials are now being used in concrete production [15-18]. These waste materials are being incorporated in concrete by replacing cement, coarse aggregates or fine aggregates. This incorporation of industrial waste in concrete making, not only boost better strength but also imparts better imperviousness and durability by making dense and homogeneous concrete.

Copper slag is one such trash material generated at the time of refining and smelting process of copper ore. Naked disposal of copper slag is very hazardous for the environment as it contains highly toxic elements like arsenic, barium, cadmium, copper, lead, and zinc [19]. Some of the researchers have examined copper slag as binder material where many have used as filler material by replacing conventional sand. Recent studies revealed usages of copper slag in concrete as partial or full replacement of fine aggregate, because it has definite positive impacts on enhancements in the strength of structural concrete leading to sustainability in the construction industry [20-23]. But, because of deficiency in appropriate concrete mix design utilizing copper slag as fine aggregate, in the field for structural concrete is very little. Though the outward form of copper slag is very similar to natural sand its physico-chemical parameters are much different from conventional sand [24]. So, its impact on mix design of concrete incorporating copper slag as fine aggregates cannot be ignored. For the present investigation, Ordinary Portland Cement (OPC) is taken as a binder, both copper slag and natural sand used as fine aggregate and coarse aggregates are collected from the nearby crusher. Copper slag is collected from Hindustan Copper Pvt. Ltd., Jharkhand, India and natural sand is collected from basin of Brahmani river, Rourkela, Odisha, India.

### 2. Characterization of copper slag

Characterization of material is the practice of quantifying and defining the mechanical, chemical, physical and micro structural properties of materials. The material characterization provides the essential constituents, its chemical and structural composition with material defects that are substantial for research, utilization or a particular preparation, and study of properties. Table 1 describes the important materialistic aspects of fine aggregate and their significant usability in the concrete mix design.

| SL# | Characteristics                      | Significance                              |
|-----|--------------------------------------|------------------------------------------|
| 1.  | Grain structure of particles         | Affects workability of fresh concrete     |
| 2.  | Relative density                     | Optimise a mixer, unit weight of concrete, yield of concrete |
| 3.  | Bulk density                         | Useful for checking uniformity of aggregate |
| 4.  | Absorption and surface moisture      | Affects the mix design, fixing water/cement ratio |
| 5.  | Deleterious substance                | Affects hydration of cement               |
| 6.  | Grading                              | Economises cement content and improves workability |
2.1. Physical characterization
The physical characteristics such as shape/texture and particle size distribution of copper slag, natural sand, and coarse aggregates were examined and evaluated by following the code, IS 2386-Part-III 1963 [25]. In the process of smelting of copper slag, slag is formed from the impurities that float on the molten state of metal and after dampen down with water, waste is then disposed in the form of angular granules. Copper slag is black in colour, glassy in texture and has angular sandy grains in nature and has almost similar/higher particle size range like conventional sand. Figure 1 shows the physical appearance of copper slag both at the raw and microscopic level.

(a) Copper slag, (b) Copper slag under microscope.

Relative density and water absorption of copper slag and natural sand were obtained by following the procedure as per IS Code: 2386-Part-III 1963 [25]. Similarly, the particle size distribution curve and corresponding fineness index of both copper slag and natural sand were evaluated by IS 2386-Part-I 1963 [26]. All materialistic properties of both copper slag and natural sand are given in table 2. Gradation curve and bulking of both copper slag and natural aggregate are shown in figure 2 and figure 3.

| Properties       | Copper slag | Natural sand |
|------------------|-------------|--------------|
| Relative density | 3.89        | 2.60         |
| Water absorption | 0.37%       | 0.80%        |
| Fineness modulus | 3.68        | 2.89         |

Figure 2 shows the grading limits for both the fine aggregates which are similar to zone III sand and the grading of copper slag can be termed as continuous grading. Figure 3 indicate that copper slag is a coarser aggregate, its increment in volume due to the presence of free water is insignificant as the thickness of the dampness layer is very small when compared with its particle size, whereas natural sand is medium grade sand. The mix design of concrete with copper slag will slightly differ from conventional concrete design because its relative density is high and water absorption capacity is low.

2.2. Chemical characterization
Chemical characterization and X-ray Fluorescence (XRF) tests for both copper slag and natural sand and X-ray Diffraction (XRD) test was conducted only for copper slag. The XRF was conducted through Zetium PAN Analytical XRF spectrometer with WROXI as a quantitative archive and XRD was conducted through Rigaku XRD Ultima IV with cross beam optics (CBO) technology and automatic alignment capability. XRD test of copper slag is conducted to identify the presence of minerals with phase angel, and XRD plot of copper slag is shown in figure 4. Copper slag mainly contains the oxides of iron and silica. The results of the XRF test data of both copper slag and natural sand are presented in table 3.
Figure 2. Gradation of Copper slag and Natural sand.

Figure 3. Effect of moisture content on the bulking of Copper slag and Natural sand.

Figure 4. XRD plot of Copper Slag.

As per the given data in table 3 copper slag contains natural pozzolanas of class ‘N’ in accordance with ASTM C 618-2019 [27] as the summation of oxides of silicon, aluminium and iron exceed 70%.

Table 3. Chemical composition of Copper slag and Natural sand (%).

|        | SiO₂ | Al₂O₃ | Fe₂O₃ | TiO₂ | MgO | CaO | K₂O | SO₃ | Na₂O | CuO |
|--------|------|-------|-------|------|-----|-----|-----|-----|------|-----|
| Copper slag | 24.87 | 3.09 | 64.27 | 0.21 | 0.89 | 1.05 | 0.56 | 1.45 | 1.4 | 0.04 |
| Natural sand | 98.3 | - | - | - | - | - | - | - | - | - |

3. Mix design with copper slag and specimen preparation
The mix design of copper slag concrete is slightly complex than conventional concrete as more design parameters such as low water absorption capacity of the material, high relative density, higher fineness modulus and wide range of particle size, etc. are needed to be considered. At present as a result of a deficiency in suitable mix design procedures, the developed concrete blended with copper slag shows relatively low performance. For the current study, M₄₀ grade of concrete, OPC of 53 grade, 20mm and 10mm graded angular coarse aggregate of nominal size and natural sand confirming to Zone III were used. Three different water-cement ratios were taken for the design mix with copper slag as fine aggregate. As per IS 456-2000 [28], the maximum water-cement ratio of M₄₀ grade of the concrete is obtained as 0.45. So, for the present investigation, three water-cement ratios were taken such as 0.55, 0.45, and 0.35 in a reducing manner for respective exposure conditions as per IS 10262-2000 [29]. Four different percentage of copper slag were considered along with control specimens from 0% to 80% (MCS0, MCS40, MCSS60, and MCS80). The schematic diagram for design mix concrete with copper slag is shown in figure 5.
To study the effects of reduced water-cement ratios on the fresh concrete properties and hardened concrete properties of copper slag blended concrete, all the basic tests have been conducted by following the Indian Standard code. The workability of copper slag blended concrete was studied through a slump test for each mix with four selected water-cement ratios by following IS 1199-1959 [30]. Similarly, compressive, split tensile and flexure strengths were evaluated experimentally following the guidelines of IS 516-1959 [31], ASTM C496-2017 [32] and ASTM C293-2016 [33] respectively. Concrete cubes of 150 mm, cylinders of 150 mm diameter × 300mm height and prisms of 100mm × 100mm × 700mm were cast respectively for compressive, split tensile and flexure strength test. After completing one day of casting all specimens were removed from the mould and kept in water tank for conventional curing of 28 days. For M_{40} grade of concrete a mix proportion 1: 1.35: 2.7 was determined as per IS 10262-2000 [29]. Cement of 450 kg/m^3, fine aggregate of 608 kg/m^3, coarse aggregate of 1215 kg/m^3 with three selected water-cement ratios 0.55, 0.45, and 0.35 were taken for preparing the mix.

4. Experimental results
The initial ability of the concrete mix to adopt virtually any shape can be evaluated from its slump test. Figure 6 shows the graphical presentation of all respective slump values for each copper slag blended concrete with three selected water-cement ratios. With 0.55 and 0.45 water-cement ratio, the copper slag blended concrete was found to have high to medium workabilities. For a water-cement ratio of 0.35, the degree of workability is medium and perfectly plastic for copper slag concrete mixes (MCS40, MCS60 and MCS80). For each selected water-cement ratio the workability of copper slag blended concrete is increasing with the increase in the percentage of copper slag on concrete. For water-cement ratios of 0.55 and 0.45, some segregation and bleeding were observed for the mix MCS60 and MCS80. For water-cement ratio of 0.35, segregation was not observed for MCS60 and MCS80 because of properly proportioned cohesive concrete mix with copper slag.

Figure 5. Schematic diagram for mix design with copper slag.

Figure 6. Slump value of copper slag concrete mix with selected water-cement ratio.

Figure 7. Compressive strength of copper slag concrete mix versus water-cement ratio.
Figure 7 shows compressive strength of all copper slag blended concrete mix for all three selected water-cement ratios. Compressive increases as the copper slag percentage increases and it is inversely proportional to water-cement ratios. As the water-cement ratio increases, the compressive strength of copper slag blended concrete also decreases.

\[
0.35 \text{ 0.45  0.55}
\]

\[
\begin{align*}
\text{Mix ID} & \quad \text{MCS0} & \quad \text{MCS40} & \quad \text{MCS60} & \quad \text{MCS80} \\
\text{Flexural strength (MPa)} & \quad 6 & \quad 4 & \quad 3 & \quad 2 & \quad 1 & \quad 0
\end{align*}
\]

Figure 8. Flexural strength of copper concrete mix with selected water-cement ratio.

Figures 8 and 10 show strength of copper slag blended concrete for flexure test and split tensile test cured at 28 days for all three selected water-cement percentages. In figure 9, a second order polynomial correlation is established between the compressive strength and flexural strength for all selected water-cement ratios. Similarly, another second order polynomial correlation is established between compressive strength and split tensile strength shown in figure 11. Figure 9 and 11 indicates a good correlation between compressive, split tensile and flexural strength of copper slag blended concrete mixes for all selected water-cement ratios.

\[
\begin{align*}
\text{Mix ID} & \quad \text{MCS0} & \quad \text{MCS40} & \quad \text{MCS60} & \quad \text{MCS80} \\
\text{Split Tensile strength (MPa)} & \quad 6 & \quad 5 & \quad 4 & \quad 3 & \quad 2 & \quad 1 & \quad 0
\end{align*}
\]

Figure 10. Split tensile strength of copper slag concrete mix with selected water-cement ratio.

5. Conclusions
The following conclusions are drawn concerning mix design with copper slag as fine aggregate in concrete making.

1. The addition of copper slag as fine aggregate improves mechanical strength of resulting concrete in comparison with the control concrete specimens.
2. Due to low water absorption capacity, copper slag incorporated concrete performs better with low water-cement ratio.

3. The bending strength and split tensile strength of copper slag incorporated concrete can be calculated from the compressive strength using the proposed relationships.

6. References
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