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Study on Mechanical and Durability Properties of M30 and M40 Sustainable Concrete Containing Copper Slag and Eggshell Powder

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HIGHLIGHTS

- Copper slag improved concrete workability due to its smooth surface and low water absorption
- Replacing 30% fine aggregate with copper slag and 5% cement with eggshell powder produced optimum mechanical performance.
- Copper slag and eggshell powder offer sustainable alternatives for producing durable structural concrete.

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ABSTRACT

In recent years the growing consumption of sand from a natural river and Portland cement in concrete manufacturing, there are environmental problems such as resource depletion and emission of carbon. Using industrial and agricultural waste as alternative building material can be a sustainable way to overcome environmental impacts along with maintaining concrete performance. In this research, the durability and mechanical characteristics of M30 and M40 grade concrete with copper slag (CS) partially replacing fine aggregate and partial substitution of cement by eggshell powder (ESP) have been experimentally investigated. CS was used in percentages of 0%, 10%, 20%, 30%, and 40%, and ESP was kept constant at 5% cement replacement ratio. The slump test was used to analyse the qualities of fresh concrete, while the compressive strength, split tensile strength, and flexural strength tests were used to analyse the properties of hardened concrete. The experimental findings indicate that the greater the proportion of copper slag utilized, the better workability because of the poor absorption of water capacity and smoother particle surface of the copper slag. The optimum concrete mix with 30% of copper slag and 5% eggshell powder showed excellent compressive, tensile, and flexural strength without compromising on the durability features. The results prove that the copper slag and eggshell powder can be efficiently used as sustainable materials for structural concrete.

1. INTRODUCTION

Concrete is one of the most widely used construction materials worldwide because of its versatility, durability, and relatively economical production. Growing infrastructure development has resulted in the extensive consumption of natural resources, particularly ordinary Portland cement (OPC) as a binder and river sand as a fine aggregate. However, the excessive extraction of river sand has

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caused serious environmental problems, including riverbank erosion, groundwater depletion, habitat destruction, and deterioration of aquatic ecosystems. At the same time, cement production contributes substantially to global carbon dioxide emissions, making the concrete industry an important source of greenhouse gases. Therefore, the development of sustainable concrete through the utilization of industrial and agricultural by-products as alternatives to conventional construction materials has become increasingly important (Nandhini & Karthikeyan, 2022; Shi et al., 2008; Yang et al., 2022).

Among the industrial by-products available, copper slag (CS) has emerged as a promising substitute for natural fine aggregate. Copper slag is produced during the smelting and refining of copper ore, with approximately 2.2–3.0 tonnes of slag generated for every tonne of copper produced (Shi et al., 2008). It possesses several desirable physical characteristics, including high density, angular particle shape, low water absorption, abrasion resistance, and relatively smooth surface texture. These characteristics make copper slag suitable for use as a partial replacement for natural river sand in concrete (Al-Jabri et al., 2009; Brindha & Nagan, 2010; Wu et al., 2010). Its use in concrete can also reduce the demand for natural aggregates while addressing the environmental problems associated with the disposal of industrial waste.

Several studies have demonstrated that copper slag can improve concrete density through enhanced particle packing and aggregate–paste interaction. Al-Jabri et al. (2009) found that copper slag could be used as a fine aggregate in high-strength concrete and that its inclusion could improve compressive strength because of the dense physical characteristics of the slag particles. In a subsequent investigation, Al-Jabri et al. (2011) reported that copper slag influenced the mechanical and physical properties of cement mortar and concrete when used as a fine aggregate.

Brindha and Nagan (2010) demonstrated that copper slag could partially replace natural fine aggregate without adversely affecting concrete performance when used at an appropriate replacement level. Their later durability investigation indicated that copper slag-admixed concrete could achieve satisfactory resistance to environmental deterioration (Brindha & Nagan, 2011). Similarly, copper slag has been reported to improve the mechanical properties of high-strength concrete when incorporated as an aggregate because of its favourable strength, density, and particle characteristics (Khanzadi & Behnood, 2009).

The amount of copper slag incorporated into concrete is an important factor determining its performance. Wu et al. (2010) reported that the strength of high-strength concrete improved up to an optimum copper slag replacement level. Beyond the optimum level, excessive copper slag may result in increased free water within the concrete mixture because of its low water-absorption capacity. This condition can cause bleeding, segregation, and weakening of the interfacial transition zone, ultimately reducing concrete strength. Therefore, the water-to-binder ratio must be carefully controlled when copper slag is used as a fine aggregate.

Copper slag has also shown considerable potential for improving concrete durability. Sharma and Khan (2017) found that incorporating copper slag as a fine aggregate influenced the mechanical and durability characteristics of self-compacting concrete. Improvements in durability were primarily associated with better particle packing and the resulting reduction in permeable voids. Maharishi et al. (2021) similarly reported favourable strength and durability performance in slag cement concrete containing copper slag as a fine aggregate. More recent research has further supported the suitability of copper slag waste as an alternative fine aggregate, provided that an appropriate replacement percentage and mixture design are adopted (Pushpakumara & Bandara, 2025).

Agricultural wastes have also been extensively investigated as alternative materials for sustainable concrete production. Among these materials, eggshell powder (ESP) has attracted considerable attention as a partial cement-replacement material because of its high calcium carbonate content. Eggshell waste is generated in large quantities by poultry farms, food-processing industries, restaurants, and households. Its disposal in landfills can create environmental, odour, and hygiene-related problems. Converting waste eggshells into a construction material may therefore reduce waste-disposal problems and decrease the consumption of Portland cement (Nandhini & Karthikeyan, 2022; Yang et al., 2022).

When eggshell waste is properly cleaned, dried, ground, and sieved into a fine powder, it can exhibit a micro-filler effect within the cementitious matrix. Fine ESP particles can fill small voids between cement grains and provide additional nucleation sites for the formation of hydration products, thereby contributing to matrix densification (Amin et al., 2022; Yang et al., 2022). However, ESP consists predominantly of calcium carbonate and generally exhibits limited pozzolanic activity compared with conventional supplementary cementitious materials such as fly ash and silica fume. Its contribution to concrete performance is therefore primarily associated with its filler, nucleation, and calcium-carbonate effects rather than substantial pozzolanic reactions (Nandhini & Karthikeyan, 2022; Yang et al., 2022).

The effects of ESP on concrete depend substantially on its processing method, particle fineness, replacement percentage, and the characteristics of the concrete mixture. Nandhini and

Karthikeyan (2022) concluded that relatively low ESP replacement levels could maintain or improve concrete strength through filler and nucleation effects. However, excessive replacement can reduce strength because it decreases the proportion of reactive cementitious material available for hydration. Yang et al. (2022) similarly observed that the engineering performance of ESP-containing cement-based materials is strongly affected by eggshell processing, particle size, chemical composition, and replacement level.

Al Abri et al. (2022) experimentally investigated the partial replacement of cement with ESP and demonstrated its potential for producing more sustainable concrete. However, the benefits were dependent on selecting an appropriate replacement percentage. Amin et al. (2022) also reported that nano-sized eggshell powder, particularly when combined with sugarcane bagasse ash, could influence the mechanical and durability properties of high-strength concrete. The finer ESP particles served as nucleation sites and filled microscopic voids in the cement matrix, contributing to a denser internal structure.

Although a considerable number of studies have separately investigated copper slag and eggshell powder, relatively few have examined their simultaneous incorporation into structural concrete. Reddy et al. (2022) evaluated concrete containing both ESP and copper slag and demonstrated that the combined utilization of these wastes could influence its strength and durability properties. Their study provides evidence that agricultural and industrial wastes can be incorporated together, although the proportions of both materials must be optimized to prevent reductions in concrete performance.

Most previous studies have concentrated primarily on compressive strength, while comparatively limited attention has been given to the combined effects of copper slag and ESP on workability, split tensile strength, flexural strength, and durability. In addition, several studies have examined only one replacement material or a restricted range of concrete grades (Al-Jabri et al., 2011; Brindha & Nagan, 2011; Reddy et al., 2022; Sharma & Khan, 2017). Consequently, further investigation is required to determine the optimum combined replacement levels of copper slag and ESP for structural concrete. Such research should evaluate both fresh and hardened concrete properties and identify mixture proportions that achieve environmental benefits without compromising mechanical strength, serviceability, or long-term durability.

1.1. SIGNIFICANCE AND OBJECTIVES OF THE PRESENT STUDY

Sustainability concerns for construction material have resulted in the increased use of industrial and agricultural waste products in concrete manufacturing. Whereas many investigations have individually studied the incorporation of copper slag (CS) as a fine aggregate substitute and eggshell powder (ESP) as a partial cement substitute, fewer studies have explored the use of both together in structural grade concrete. Moreover, few evaluations exist that address the combined effect of both materials on the performance of M30 and M40 concrete. Thus, the current study analyzes the joint use of copper slag and eggshell powder in M30 and M40 grade concrete in order to analyze their effect on workability, compressive strength, split tensile strength, flexural strength, and durability. The goal of the current study is to identify the optimal proportioning of such material to obtain the best engineering characteristics, which would make it possible to use these materials for sustainable construction purposes. In particular, the study considers the effect of partial substitution of fine aggregate by copper slag and cement by eggshell powder on the properties of concrete in fresh and hardened states. Moreover, mechanical properties are studied by means of compressive strength, split tensile strength, and flexural strength tests, and durability is tested by means of water absorption and sorptivity tests. Based on the experimental data, the study determines the optimal ratio of copper slag and eggshell powder providing sustainable structural concrete.

2. MATERIALS AND METHODS

2.1 Materials

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Concrete mixes were prepared using Ordinary Portland Cement (OPC) of 43 Grade as per IS 8112:2013, natural river sand (Zone II) as per IS 383:2016, crushed coarse aggregate of 20 mm nominal size, copper slag (CS), eggshell powder (ESP), and potable water (Figure 1) . OPC was used as the main binding material, whereas natural river sand and crushed coarse aggregate were used as the conventional aggregates after checking their physical properties in compliance with the respective Indian Standards. Copper slag, collected from an industry in Odisha, was employed as the partial replacement of fine aggregate due to its high specific gravity, angular particle shape, and low water absorption capacity. Eggshell powder was manufactured by washing, drying, grinding, and sieving waste eggshells through a 90 μm sieve, which was used as a partial replacement of cement due to its high $CaCO_3$ content and micro-filler properties. Water conforming to IS 456:2000 was used for both mixing and curing purposes of concrete specimens. The chosen materials were used for conducting this research to explore the possibility of producing sustainable concrete with better mechanical and durability properties using the wastes of industry and agriculture sector.

Figure 1. Materials used in the present investigation: (a) Ordinary Portland Cement (43 Grade), (b) Natural River sand, (c) Crushed coarse aggregate, (d) Copper slag, and (e) Eggshell powder

2.2 Mix Design

The concrete mixes for M30 and M40 grades were designed considering IS 10262:2019 and IS 456:2000. The control mixes made with normal ingredients were prepared first. After that, copper slag was used as a replacement material for natural fine aggregates at various levels of substitution, and eggshell powder was used as a replacement material for cement at the same percentage level. The ratio of water and cement was chosen based on the strength and durability considerations.

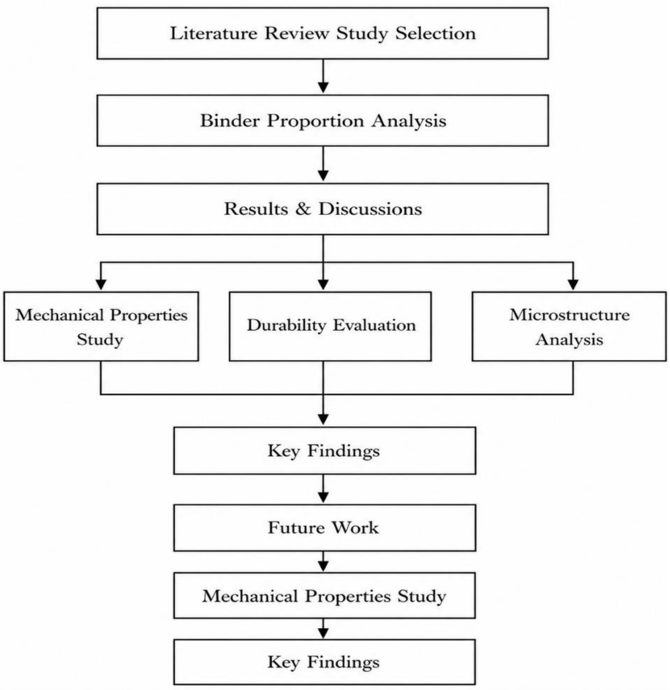

Figure 2. Flow chart of the Experimental Methodology

Table 1: Concrete Mix Matrix

Mix	Concrete Grade	Copper Slag (%)	Eggshell Powder (%)
CM	M30 / M40	0	0
CS10	M30 / M40	10	5
CS20	M30 / M40	20	5
CS30	M30 / M40	30	5
CS40	M30 / M40	40	5

2.3 Specimen Preparation and Curing

Mixing of concrete was done using tilting drum mixer to have homogenous mixing of all materials used in the process. At first, cement, sand, gravel, copper slag, and eggshell powder were mixed dry until uniformity was attained. Water was slowly added, and mixing was continued until a suitable mix of concrete was achieved. The fresh concrete was subjected to slump test before casting. Standard steel moulds were used in preparation of samples for various mechanical tests. Concrete samples of 150mm × 150mm × 150mm were prepared for compressive strength testing, cylindrical samples of 150mm diameter × 300mm height were prepared for split tensile strength testing, and prismatic samples of 100mm × 100mm × 500mm were prepared for flexural strength testing. Concrete samples were vibrated using table vibrator, demoulded after 24h, and cured in clean water at room temperature up to testing age.

3. RESULT AND DISCUSSION

3.1. Workability Test of Concrete

Workability of concrete mixes was assessed using slump cone test in accordance with IS 1199:1959 in order to study the effect of partial replacement of fine aggregates with copper slag (CS) and cement with eggshell powder (ESP) on fresh properties of concrete. Slump results for the control mix (CM) and different concrete mixes are shown in Figure 8. It is noted that control concrete had a slump value of 75 mm, while the use of copper slag and eggshell powder increased the slump value to 80 mm for CS10, 85 mm for CS20, 92 mm for CS30, and 100 mm for CS40. As compared to control mix, the slump value increased by 6.7%, 13.3%, 22.7%, and 33.3% for CS10, CS20, CS30, and CS40, respectively. The improvement in workability is mainly due to the properties of the copper slag itself. In contrast to natural river sand, copper slag has a smooth, dense, and glassy texture that absorbs little water, leaving much more free water for mixing in the concrete matrix. As a result, the availability of extra free water improves particle lubrication and reduces the inner friction, allowing the easier movement of the aggregate particles in the mixing process, thus increasing the slump of concrete. While eggshell powder has smaller particles that increase the specific surface area of concrete mixtures, its small amount did not affect the positive effect of copper slag significantly. The combination of copper slag and eggshell powder led to the production of concrete mixtures with adequate cohesion and good workability.

It is very evident from Figure 3 that there is a rise in the slump value from 75 mm for the control concrete to 100 mm for the concrete with maximum replacement of copper slag, which proves that the use of copper slag greatly improves the workability of sustainable concrete.

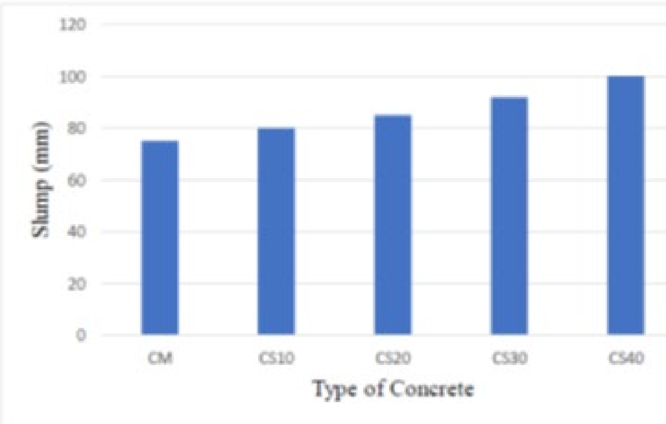

Figure 3. Workability test of concrete at different replacements of copper slag

3.2 Compressive Strength

One of the most important mechanical characteristics employed for determining the load bearing ability and performance of concrete structures is the compressive strength of concrete. In the present study, the compressive strength tests were carried out for the concrete cubes of 150×150×150 mm size that were cured in water for 7 and 28 days according to the IS 516:1959 specification. Three specimens for each mix were tested at both ages of curing and average compressive strength values were analyzed. Figure 9 shows the 28-day compressive strength of the control concrete (CM) and concrete mixes with different ratios of copper slag (CS) and eggshell powder (ESP). As can be seen from the figure, there is a considerable increase in compressive strength for increasing amounts of copper slag addition up to an optimal ratio, and then, there is a slight drop. The compressive strength for the control concrete (CM) was found to be 32 MPa; however, it was increased to 34 MPa, 36 MPa, and 38 MPa for CS10, CS20, and CS30, respectively. Nevertheless, an increase in the ratio of copper slag to CS40 gave a compressive strength value of 35 MPa, which, while being higher than the control mix of about 9.4%, was lower than the optimized CS30 mixture. From this analysis, it is obvious that the optimized ratio for the current experiment was 30% of copper slag with eggshell powder since this gave the highest compressive strength.

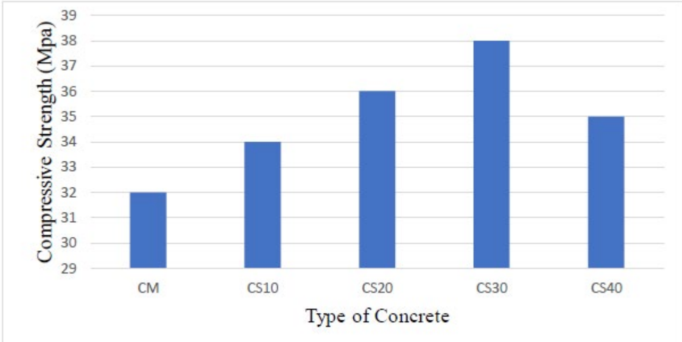

Figure 4. Compressive strength of Concrete at different percentage of copper slag

3.3 Split Tensile Strength

The split tensile strength of concrete is a significant criterion in assessing the tensile resistance and crack propagation behaviour of concrete in indirect loading condition. In the current study, the tests of split tensile strength were carried out on 150 mm x 300 mm concrete cylinders at 7 and 28 days of curing period as per IS 5816:1999. The average result of three cylinders for each concrete mix was considered. The 28-day split tensile strengths of concrete mixes are shown in Figure 10 where it becomes evident that the inclusion of copper slag (CS) and eggshell powder (ESP) effectively enhanced the tensile strength of concrete up to optimum replacement level. For control concrete (CM), the split tensile strength is 3.2 MPa while it is 3.4 MPa, 3.6 MPa, and 3.9 MPa for CS10, CS20, and CS30, respectively. These values indicate an increase by about 6.3%, 12.5%, and 21.9%, respectively, relative to the control concrete. Nevertheless, a decrease was noted at the maximum replacement percentage (CS40), when the value of split tensile strength became 3.7 MPa, which was still about 15.6% higher than the one for the control concrete. In conclusion, the best concrete mix proved to be CS30, with the highest split tensile strength among all the tested mixes.

In the split tensile test, all specimens of cylindrical geometry broke in the form of a crack that almost ran parallel to the vertical axis of the specimen, which is the normal way of breaking during an indirect tensile test. The control concrete specimen broke through a wider crack opening and brittle breaking while the modified concrete specimens, especially CS20 and CS30, showed a relatively smaller crack width before splitting, suggesting better crack resistance. The normal testing setup for a cylinder and the mode of failure are shown in Figure 5.

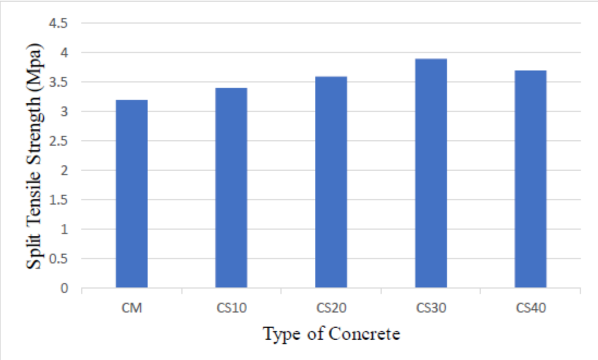

Figure 5. Split Tensile strength of Concrete at different percentage of copper slag.

3.4. Flexural Strength

The flexural strength of concrete is an important parameter to assess its resistance to bending and is quite crucial for pavements, slabs, bridge decks, and other flexural members. Flexural strength tests have been carried out in the current investigation on 100 × 100 × 500 mm concrete prism specimens using two-point loading method according to the standards set out in IS 516:1959 at 7 and 28 days of water curing. The average of three specimens per concrete mix has been considered. The flexural strength at 28 days is shown in Figure 12 and the use of copper slag and eggshell powder significantly improved the flexural strength of concrete up to an optimum replacement level. The control concrete shows the flexural strength of 4.8 MPa, while the strength increases to 5.1 MPa, 5.4 MPa, and 5.8 MPa for CS10, CS20, and CS30, respectively, with a percentage increase of approximately 6.3%, 12.5%, and 20.8%, respectively, compared to control concrete. In the case of CS40, the flexural strength was reduced marginally to 5.6 MPa but still maintained about 16.7% increase over the conventional concrete mix. It is very clear from the above analysis that the CS30 concrete mix gave the highest flexural strength compared to all other mixes tested.

The test for the flexural strength of concrete was done on prism samples that exhibited typical behaviour with regards to flexural failure. Failure occurred after initiation of the crack along the tension side at the midspan of the prism, with the crack propagating to the compression side until failure took place. The cracks formed were wider in the case of control concrete, but CS20 and CS30 concrete prism samples exhibited delayed crack propagation and improved crack resistance before failure occurred. The typical prism failure in flexural tests is illustrated in Figure 6.

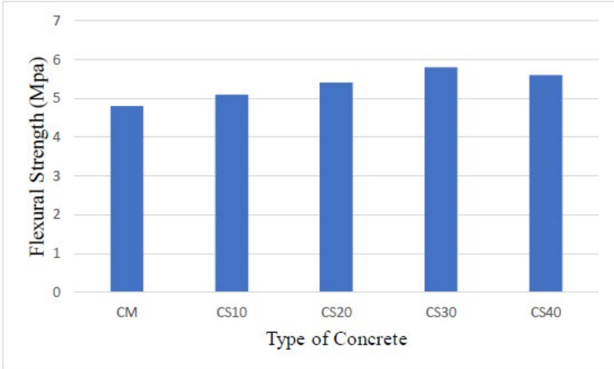

Figure 6. Flexural strength of Concrete at different percentage of copper slag

3.5. Water Absorption

Water absorption is one of the most significant durability properties in order to investigate the permeability and pores structure of the concrete because it affects the absorption of the water and aggressive ions which can cause deterioration of reinforced concrete structures. The concrete having low water absorption shows dense microstructure, low porosity, and higher durability in the long run. In the current research, the water absorption test was conducted on 28 days water cured concrete cubes according to ASTM C642 standard or its equivalent IS standard, whichever may be followed. The specimens were first subjected to drying in the oven to achieve the constant mass at 105 ± 5 °C and then they were cooled to room temperature and weighted in order to get the dry mass of the specimens. After that, the specimens were kept in water for 24 hours to attain complete saturation and again weighted. The percentage water absorption was found by taking the difference between the masses of saturated and dry specimen.

Among all the tested mixes, the concrete mix CS30 showed the lowest amount of water absorption, which confirmed that the concrete at this replacement ratio had the densest internal microstructure. Yet, it was noticed that water absorption increased slightly in the concrete mix CS40. This behaviour could be explained by the fact that copper slag is excessively used to replace natural sand, thus causing an increase in the water-to-cement ratio due to the non-water absorbing nature of copper slag. Thus, the presence of extra water during hydration would cause the formation of isolated capillaries, causing the marginal increase in water absorption compared to that of optimal concrete. Nonetheless, the water absorption in the mix CS40 remained low compared to the control concrete.

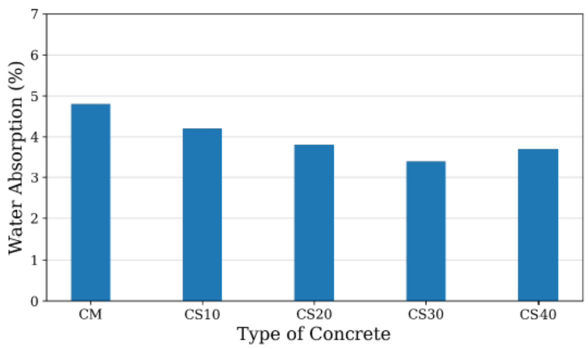

Figure 7. Water Absorption of Concrete at different percentage of copper slag

4. CONCLUSIONS

This study has experimented with the effect of partial substitution of natural fine aggregate by copper slag (CS) and cement by eggshell powder (ESP) on fresh, mechanical, and durability properties of M30 and M40 grade concrete. Experimental data have revealed that the use of both copper slag and eggshell powder has substantially improved the engineering properties of concrete up to the optimum percentage substitution. Enhanced workability, compressive strength, split tensile strength, flexural strength, and durability properties were achieved because of the denser packing of particles, fill effect of eggshell powder, and excellent physical properties of copper slag. In all the mix proportions studied, CS30 has been identified as the most optimal concrete, suggesting that industrial and agricultural waste materials can be used sustainably to produce structural concrete without affecting its engineering properties. The findings indicate that both copper slag and eggshell powder can be used as eco-friendly alternative construction material, which can save the consumption of natural resources and eliminate waste problems.

- Copper slag and eggshell powder were able to develop sustainable concrete with improved properties both in fresh and hardened state.
- Workability improved with an increase in copper slag, where the slump value increased from 75 mm (CM) to 100 mm (CS40), attributed to the lesser water absorbance and smoother surface finish of copper slag.
- The highest compressive strength of 38 MPa was achieved with the CS30 concrete mix, which is an improvement by about 18.8% relative to the control concrete at 32 MPa.
- The split tensile strength increased from 3.2 MPa to 3.9 MPa, implying an improvement of about 21.9%, with CS30 concrete mix showing the best performance.
- The highest flexural strength of 5.8 MPa was obtained with CS30 concrete mix, which implies that there was a 20.8% improvement with CS30 mix relative to the control concrete mix.
- The excessive replacement of copper slag (CS40) resulted in a slight drop in the mechanical strength compared to the optimum mix, but still, it had better properties than the conventional concrete.
- From the results obtained from this study, the use of copper slag and eggshell powder together makes a suitable material for sustainable structural concrete, resulting in the conservation of natural sand and cement, as well as the industrial and agricultural wastes.
- Therefore, from the overall results, the CS30 mix is the optimum mix for sustainable structural concrete.

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AI Disclosure: The authors declare that artificial intelligence (AI) tools were used solely to assist in language refinement, organization, and editing of the manuscript. AI was not used to generate original research data, conduct analyses, or draw scientific conclusions. All technical content, interpretations, and final decisions were developed and verified by the authors, who take full responsibility for the accuracy, integrity, and originality of the work.

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