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Assessment of Cement Mortar Strength Mixed with Waste Copper Mine Tailings (CT) by Applying Gradient Boosting Regressor and Grid Search Optimization Machine Learning Approach

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Abstract: Growing environmental concerns and resource scarcity, the construction industry must investigate sustainable materials that reduce waste while improving building material properties. This study investigates the viability of using waste copper mine tailings (CT) as a partial replacement for river sand in cement mortar, assessing the impact on mechanical strength and developing a predictive model using a Gradient Boosting Regressor (GBR) and Grid Search Optimization (GSO). Copper tailings mix designs ranging from 0% to 50% replacement by volume (river sand) were developed, with a constant cement quantity while varying the proportions of sand and tailings. The experiments were carried out at Poornima University in Jaipur, using standard protocols to prepare specimens and measure their compressive strength for 0% CT to 50% CT as volume percent in the mixture. The results showed that the addition of copper tailings up to 20% (3CT2) had highly increased the mortar strength, while mix design 6CT3 showed the best strength at 30% CT. Beyond this threshold, strength declined, thus indicating an optimal replacement level. In the final step of the research, the GBR-GSO-based machine learning approach was employed for developing the predictive model for compressive strength in mortar with different contents of copper tailing for mix types 3CT and 6CT. The predictions obtained by the developed model were in very good agreement with empirical data, thus supporting the potential of machine learning to predict material performance for guiding the use of unconventional additives in construction. It could be said that this work not only represents the material properties of copper-tailing-infused mortar but also showcases state-of-the-art machine learning techniques in the building materials science domain while opening new paths for more innovative and sustainable building practices.

Introduction

Copper is a highly critical metal for industrial and technological purposes. This electric and thermal amazing conductive material finds application in the majority of industrial sectors. Hence, this has initiated more intense mining activities to meet the increasing demand that results from population growth and increased need for copper products. Such activities have focused on extracting copper from low-grade ores, and thus, they significantly increased copper mine tailings (CT) (Khyaliya et al., 2017; Schipper et al., 2018). They thus leave behind significant environmental challenges. (Elshkaki et al., 2016) predicted from their model that copper consumption would rise by 270%-355% by 2050, strongly underlining the urgent timing of addressing environmental implications due to the disposal of CTs.

The demand for better building materials by the construction industry is enormous; this demand accelerates the depletion of natural fine aggregates used in concrete and mortar. Increased mining activities over the past decade related to these aggregates, have had impacts on the environment, such as alterations to water

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channels, contamination of water sources, and damage to local ecosystems. Governments across the world have regulated fine aggregate mining due to such concerns (Kossoff et al., 2014; Gautam et al., 2018). These restrictions could be mere short-term solutions and would still not meet the fundamental need for fine aggregates in construction. Sustainability seekers have been demanding sustainable alternatives to show the possibility of substituting industrial by products like CT. This is, therefore, a strategy that solves environmental problems while meeting construction industry standards. This study investigates the possibility of using waste copper mine tailings as an additive in cement mortar, using machine learning techniques to predict and improve the strength of these materials, thereby providing a sustainable solution that combines environmental conservation and technological innovation (Bonavetti and Irassar, 1994; Huntzinger and Eatmon, 2009).

The worldwide construction sector consumes billions of tonnes of cement each year, a trend that is expected to continue due to the ongoing need for new and renovated infrastructure (Narayana Rao et al., 2024). Cement manufacture, while necessary, is a major source of CO_2 emissions, accounting for 5% to 7% of global emissions, according to many studies. Incorporating additional cementitious materials obtained from industrial waste represents a possible alternative in the pursuit of sustainability. This method is ecologically sound because it reduces the carbon print of cement production by putting waste materials to beneficial use. A few more have been combined successfully into cement-based materials, such as silica fume, fly ash, ground granulated blast furnace slag, diatomite, natural pozzolans, and metakaolin. These materials have given low-cost options to regular cement and also increased the strength and durability of cement composites. It is believed that there are favorable benefits of such SCMs, particularly with high SiO_2 content in materials, through both pozzolanic and filler effects. Such developments open the possibility to further innovate in cement composites that let sustainable construction ways get established in the path without compromising material performance (Mehta, 1973; Prakash et al., 2021; Bernard et al., 2022; Arunachalam et al., 2023; Joseph et al., 2023). The use of industrial by-products as supplementary cementitious materials (SCMs) in cement composites is a new way to fulfill the continuous growth in cement demand in an environmentally friendly way. This is not only a cost-beneficial practice but, additionally, the pozzolanic reaction and filler effect considerably improve the mechanical properties and durability of cement composites, especially for the high SiO_2 materials (Özsoy, 2023; Aruntaş et al., 2024; Zhang et al., 2024). Conversely, cement mortar from tailings showed minimal adverse effects on the environment and was, therefore, sustainable (Krishna et al., 2024; Perumal et al., 2024; Narciso et al., 2023).

In order to create a holistic and transparent approach to data collection and analysis, we used the PRISMA way while conducting a systematic literature review for the current study (Boland, 2021). This clearly set a path to the discovery, screening, and inclusion of studies, making it much easier to examine a wide variety of sources systematically. By using the PRISMA criteria, we had maintained rigor and reproducibility in making sure our review process was really in-depth and scientifically sound. Such technique allowed us to extract relevant insights and trends that are descriptively feeble in the existing body of literature, setting the groundwork for our research on using waste copper mine tailings as cement mortar additives.

In fact, research into pozzolans, primarily made up of aluminosilicates or fine-grained silicates, has shown that they are of first importance to cement hydration mechanisms. Pozzolans react with water and calcium hydroxide to form C-S-H and other cementitious products. On the other side, the effectiveness of the mentioned SCMs is basically affected by their physical, mineral, and chemical properties. A good understanding of the qualities of mine tailings is synchronous in developing efficient and long-lasting SCMs. Research in copper mine tailings has been carried out with a view to their potential application in construction, mainly production, with better properties of construction materials. For instance, Marghussian and Maghsoodipoor (Marghussian and Maghsoodipoor, 1999) reported that 40% CMT unglazed tiles had better acid resistance and mechanical strength when burned at 1025°C for one hour. This result indicates that the necessity and benefit of CMT towards making a sustainable building material becomes more critical, coupled with the need for additional research investigations into the values of industrial by-products in construction.

Gupta and Vyas (Gupta and Vyas, 2018) demonstrate the utility of waste granite powder, showing significant improvements in mortar properties like compressive strength and water absorption when substituted for fine aggregate. It was observed that the water mixing requirement was reduced by using these waste materials. Chouhan et al. (2019) explore the potential of dimensional limestone waste, presenting its beneficial impact on mortar's mechanical strengths and suggesting a path towards reducing the construction industry's environmental footprint. Together, these investigations underscore the viability of repurposing industrial by-products in construction, aligning with sustainable development goals by enhancing material properties and conserving natural resources (Chouhan et al., 2019).

Some research works have been reported that the utilization of industrial byproducts, such as waste granite powder, enhances the characteristics of cement mortar, while some have indicated that the utilization of recycled fine aggregates and fly ash as replacement materials reduces strength (Kou and Poon, 2013; Bilir et al., 2015). This might be due to the various changed physical properties in relation to the classical sand. Furthermore, more and more research and studies on using recycled aggregates and crushed glass indicate that these materials show poorer performance in regard to the strength characteristics as compared to natural sand, presumably because of changed morphology, fineness, and interaction with cement paste. Similarly, experiments of the ferrochrome slag and stabilized soil used as partial replacements for natural sand have produced some promising results, which need further evaluation and application so as to obtain a series of potential environmental benefits (Poon and La, 2008; Priyadharshini et al., 2018; Dash and Patro, 2021). However, complete usage of these alternatives in place of natural fine aggregates is far from a well-researched site, underlining the need for much further study in such sustainable materials in concrete production.

The present study has focused on two major challenges: shortage of river sand and emission of CO_2 from cement production. In the present study, iron ore tailings and sugarcane bagasse ash have been used as partial replacements for sand and cement, respectively. The by-products from iron ore processing and sugarcane juice extraction might have potentially reduced the impacts on the environment while improving concrete performance. Thirteen concrete mixes were designed in this research, testing workability, strength, and durability; optimal performance was found at some replacement levels. The ingenuity of this approach is that it answers both material deficiencies and supports sustainable construction (Onuaguluchi and Eren, 2012; Külekçi, 2022; Yang et al., 2023).

Other researchers have also pointed to the new, innovative use of some mine tailings—low sulfide base metal, copper, phosphate, and gold-mine tailings—on Blazers, along with tungsten mine waste mud for new sustainable construction materials. These studies investigate the suitability of these materials as aggregates in mortars, the production of supplementary cementitious materials, as well as their mechanical and durability properties in concretes and mortars. They have shown the possibility of activating these wastes for environmental good, touting strength increases, durability, and socio-economic impacts of reusing mine tailings in construction, which would be a huge step toward sustainable building practices and material recycling (Qasrawi, 2000; Onuaguluchi and Eren, 2012; Kuranchie et al., 2013; Thomas et al., 2013; Ince, 2019).

In the research (Arunachalam et al., 2023), copper mine tailings were studied for potential development as a cement mortar filler and the possibilities for enhancing their mechanical and durable qualities. It was found that up to 30 wt% CMT incorporation increased the compactness, pore densification, compressive, and flexural strength and showed resistance toward attacks from acids and sulfates. These results indicate that CMT has enormous potential in carrying out sustainable construction with an aim to recycle waste and enhance the sustainability of mining and construction industries.

Onuaguluchi and Eren (Onuaguluchi and Eren, 2013) investigated the possibility of using copper tailings as a green cement replacement. They obtained that copper tailings decrease the yield stress, efficiently maintain the flow loss and increase in mechanical and durability attributes in cement mortars with respect to compressive strength, flexural strength, abrasion resistance, resistance to action from acid and chloride penetration. Mortars containing pre-wetted tailings at 5% cement replacement showed the best results. This study highlights the potential environmental and sustainability benefits of using copper tailings in mortar, indicating a promising avenue for lowering greenhouse gas emissions and encouraging resource recycling in the building industry.

The current study intends to assess the possibility of waste copper mine tailings as a sustainable alternative to river sand in cement mortar, with a focus on mechanical strength like compressive strength, flexural strength, tensile bond strength etc. It investigates appropriate replacement ratios, uses the GBR-GSO Algorithm to estimate strength, and confirms results using experiment results, all of which contribute to environmentally friendly construction practices (Sekhar et al., 2024).

Materials and Methods

Fine aggregate and Cement

In present research, local manufacturers Portland cement (IS-1489, 1991), procured from Jaipur, Rajasthan, characterized by its fine grain size, forms the binding matrix. The chemical analysis of cement was shown in table 1. Local river Banas sand, selected for its compatibility with industry standards, serves as the fine aggregate, ensuring cohesion and workability. Both materials underwent rigorous quality checks, aligning with ASTM C566 (ASTM C566-97) for dry sand conditions and selected the sand as per IS: 2116-1980 standards (IS-2116, 1980) for optimal particle size distribution (ASTM, 2014; 6913–04, 2009), a critical factor in achieving the desired strength and durability in cement mortar composites. The integration of these locally sourced materials underpins the study's commitment to sustainable and regionally tailored construction practices. The particle distribution of sand is shown in figure 1 for both CT and sand particles.

Table 1. Chemical Composition of River Sand, Cement and CT (Cooper Tailings) in wt%.

Composition	Short Description	Cement	CT	Banas River Sand
Alumina	Al_2O_3	6	7.24	-
Barium oxide	BaO	-	0.17	-
Lime	CaO	64	16.50	0.64
chlorine	Cl	-	0.11	-
Copper Oxide	CuO	-	1.53	-
Dicalcium silicate	C_2S	1.5	-	-
Iron oxide	Fe_2O_3	2.5	43.25	1.05
magnesia	MgO	1.5	2.02	-
manganese monoxide	MnO	-	0.24	-
Potassium oxide	K_2O	0.5	0.62	-
Silica	SiO_2	20	25.36	97.80
Sodium oxide	Na_2O	0.15	0.54	-
Sulphur trioxide	SO_3	0.45	1.32	-
Tricalcium aluminate	C_3A	2.5	-	-
Tricalcium silicate	C_3S	0.9	-	-
Loss of ignition	LOI	-	1.1	0.51

Table 1 explains the chemical composition of the binding and aggregate materials in wt. percentages, with river sand from Banas, Rajasthan, Portland cement sourced locally from Jaipur, and copper tailings (CT) sourced from Khetri, Jhunjhunu (Rajasthan). Alumina and iron oxide are more prevalent in CT, indicating potential pozzolanic activity, while the high silica content in Banas River Sand aligns with standard fine aggregate properties. Lime, predominantly in cement, is essential for the mortar's strength, setting the stage for a nuanced analysis of how these components' interactions could influence the final mortar's properties.

Figure 1 illustrates the particle size distribution for river sand and copper tailings (CT), key components in the study's mortar mix. The graph reveals that sand has a broader gradation range, with a higher percentage passing through the mid-sized sieves. In contrast, CT shows a sharper distribution, with the majority of particles concentrated in the finer sizes. This comparison is crucial for understanding how the differences in particle size distribution can affect the workability and strength of the cement mortar when river sand is partially replaced with CT. The particle size distribution of sand and copper tailings is present in table 2.

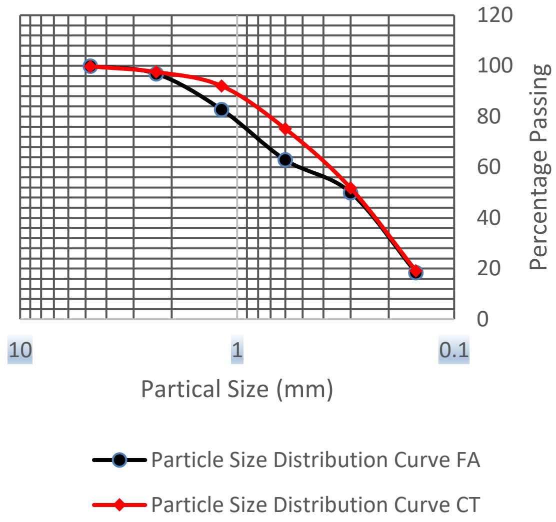

Figure 1. Particle Size Distribution of River Sand and Copper Tailings (CT).

Copper tailings (CT)

In the present study, the copper tailings were collected from a mining site located at Khetri, Jhunjhunu (Rajasthan). This site is one of the largest sites for copper production in Rajasthan (India). Granular copper tailings collected from the mining site, exemplifying their physical state before processing for use in cement mortar mixtures, as shown in figure 3, showcases a homogenous mixture of fine, naturally occurring river sand blended with cement, highlighting the initial stages of preparing the mortar mix for construction applications. The collected copper tailings were first dried at a desired temperature range of 100~110 C (Arunachalam et al., 2023) for 48h using the industrial oven. This dried CT material was then crushed by using a ball mining machine to make the fine particles, as shown in figure 2.

The chemical composition of the CT is present in Table 1, which shows the high concentration of Iron oxide, lime, and silica. Some percentages of heavy metals were also found in the CT procured from Khetri mining site.

Scanning Electron Micrograph (SEM)images of river sand and fine powder of copper tailings are shown in Figure 4. It was observed that there were wide texture differences present in both sand and CT particles. Copper tailings SEM images reveal the smoothness of the particles then river sand particles in these SEM images. Two different samples were used to capture the SEM images for sand and copper tailings for more understanding of the texture quality of these aggerates mixed with cement.

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Figure 2. River Sand and Copper Tailing were used in Present Study.

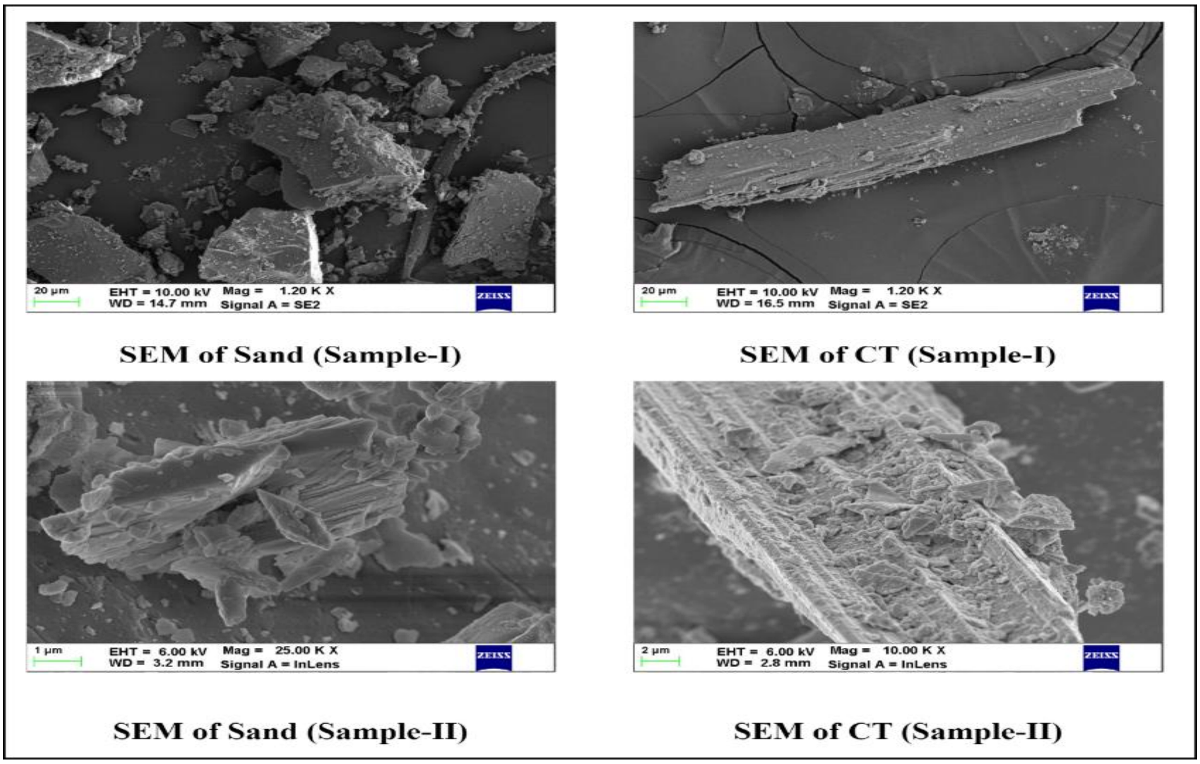

Figure 3. SEM Images for Different Samples of Sand and Copper Tailings (CT).

Table 2. Particle Size Distribution of Sand and CT.

Sieve Size (mm)	Sand (%)	CT (%)
4.75	99.9	99.8
2.36	96.9	97.6
1.18	82.8	92.1
0.6	62.9	75.2
0.3	50	51.8
0.15	18.4	19.1
0.01	0	0

Mixing compositions for cement mortar

The research outlines a series of mix compositions for cement mortar, integrating varying proportions of river sand and copper tailings (CT) to assess performance. The mix designs, identified as 3CT0 through 3CT5, systematically reduce the percentage of sand while increasing the CT content and maintaining a constant cement weight, as shown in Table 4.

Table 3. Physical Properties of Sand and Copper Tailings (CT).

Properties	River Sand	Copper Tilling
Specific Gravity	2.6	3.2
Moisture Content %	10	16
Fineness Modulus	1.94	1.64
Bulk Density (kg/m^3)	1628	1467

Water-to-cement (W/C) ratios are adjusted accordingly to achieve workable consistencies across the spectrum. The variations range from a traditional mix with 100% sand to an innovative mix containing equal parts sand and CT, providing a comprehensive study on the influence of CT on the mechanical properties and

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sustainability of mortar. Like 3CT compositions, in present study 6CT compositions (1: 6:: cement: sand) by volume percentage were also fabricated for 0% CT to 50% CT replacement with sand. The physical properties of the sand and copper tailings (table 3) differed from each other, so only cement was kept constant and all remaining mixing components varied as per the standard required for mortar making in India.

Table 4. Sand, CT Cement and Water Mixing as per Replacement of Copper Tailings (CT).

Mix Id	% of Sand	% of CT	Cement (kg)	W/C Ratio	Water (kg)	Sand (kg)	CT (kg)
3CT0	100	0	350	0.87	305	1494	0
3CT1	90	10	350	0.92	322	1345	129
3CT2	80	20	350	0.98	343	1195	259
3CT3	70	30	350	1	350	1046	389
3CT4	60	40	350	1.1	385	896	519
3CT5	50	50	350	1.15	403	747	648
6CT0	100	0	200	1.01	202	1707	0
6CT1	90	10	200	1.79	358	1536	148
6CT2	80	20	200	1.82	364	1366	296
6CT3	70	30	200	1.86	372	1195	444
6CT4	60	40	200	1.88	376	1024	593
6CT5	50	50	200	2.12	424	854	741

3CT (1:3:: cement: sand); 6CT (1:6:: cement: sand)

For proper mixing of the compositions for making the mortar, the vibration instruments were used during the Molding process. The fabrication steps during making the mortar are shown in figure 4. The proper plastic sheet was used to wrap the mortar to reduce the immediate evaporation (Arunachalam et al., 2023) from the mortar and take it for 48h during the fabrication phase.

After 48h, the mold was removed and mortars were kept in the water. In the present study all results were measured for 28 days after the fabrication of the mortar. The water absorption capacity of the copper tailing was more than river sand, so by replacing the sand with CT, the water quantity was also increased as seen in Table 4.

The present study has meticulously selected various testing standards to ensure rigorous assessment of the cement mortar's properties. These standards encompass a wide range of tests, including compressive strength (IS 2116: 1980, 1999) and flexural strength (both ASTM C348, 1998), which are fundamental for evaluating the structural integrity of the cementitious mix. Water absorption, density, and percentage air voids are gauged using ASTM C642, 2008, to determine the porosity and durability aspects of the mortar. Adhesive strength adheres to EN 1015-12, 2000 standards, while the resilience of the material against environmental degradation is tested through acid attack (ASTM C952, 2003) and sulphate attack (ASTM C 267, 2001) assessments. Together, these standards provide a comprehensive framework for analysing the multifaceted performance of the mortar mixes in the study. A detailed description of the testing standards is presented in Table 5.

Table 5. Testing Standards Used for Present Study.

Testing Parameter	Standard	Sample size
Water absorption	70 mm cube	ASTM C642, 2008
Bulk Density	70 mm cube	ASTM C642, 2008
Air Voids	70 mm cube	ASTM C642, 2008
Tensile bond strength	NA	ASTM C952, 2003
Compressive strength	50 mm cube	IS 2116: 1980, 1999
Flexural strength	40x40x160 mm beam	ASTM C348, 1998
Use of Copper tailing (CT)	NA	ASTM C 618-02

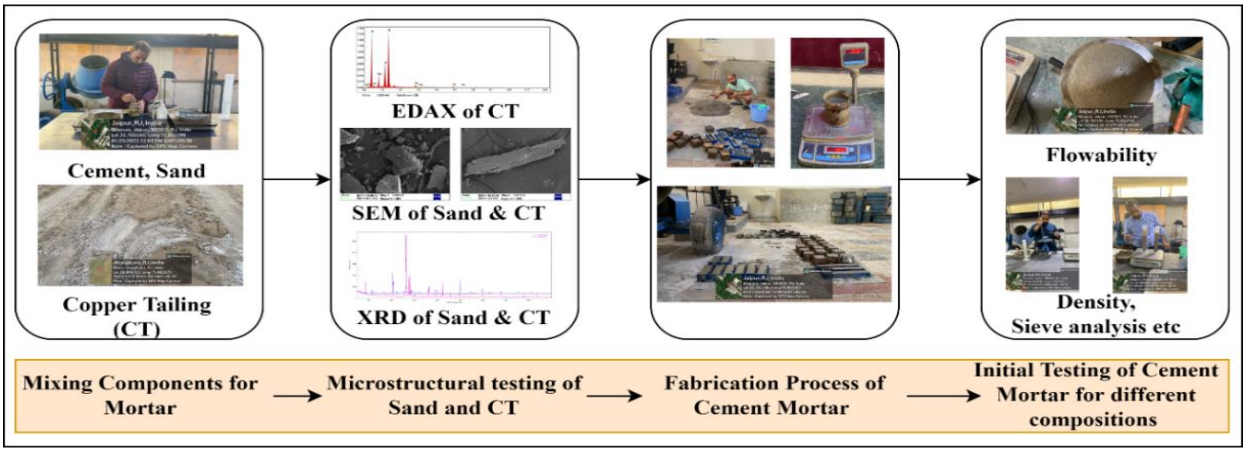

Figure 4. Fabrication and Initial Testing During Making the Cement Mortar.

The testing for different parameters was conducted at Poornima University, Jaipur, which is shown in figure 5.

mineral phases, indicating a complex composition that may contribute to subsequent pozzolanic reactions,

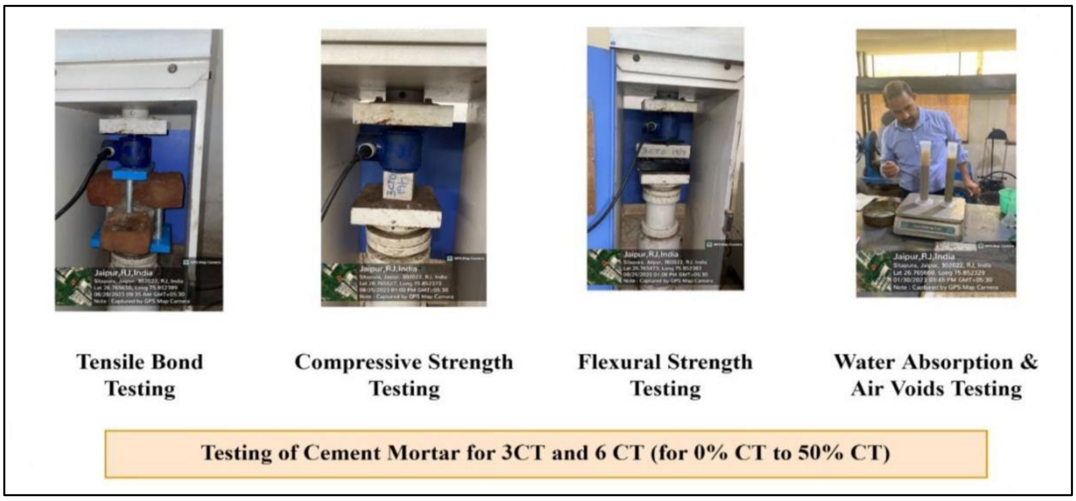

Figure 5. Various testing conducted during study at Poornima University, Jaipur (India).

Result and Discussion

The characterization of copper tailings (CT) demonstrates that they have finer granularity than typical river sand, as evidenced by the cumulative particle size distribution analysis. The specific surface area of CT is significantly larger, implying a higher reactivity potential in cementitious mixes. CT's oxide level exceeds the ASTM C618 standard's 80% threshold (ASTM C 618), showing its significant pozzolanic potential despite failing to meet traditional fly ash or natural pozzolans parameters. CT has a lower density than river sand and cement, which suggests that adding it could result in lighter construction materials (Arunachalam K. P. et al., 2023).

The mineralogical study of CT, as demonstrated by XRD patterns as seen in figure 6, identifies various confirming CT's viability as a long-term alternative additive in specialised cementitious applications.

Water absorption and Air Voids

The present study's analysis of water absorption characteristics for cement mortars with varying percentages of copper tailings (CT) indicates a clear trend: as the CT content increases, so does the water absorption rate as seen in figure 7. Specifically, the mortar mix with a 1:3 cement to sand ratio (3CT) exhibits an increase in water absorption from approximately 9% with no CT to around 15% at 50% CT inclusion. This increment is consistent and gradual, illustrating a predictable relationship between CT content and porosity.

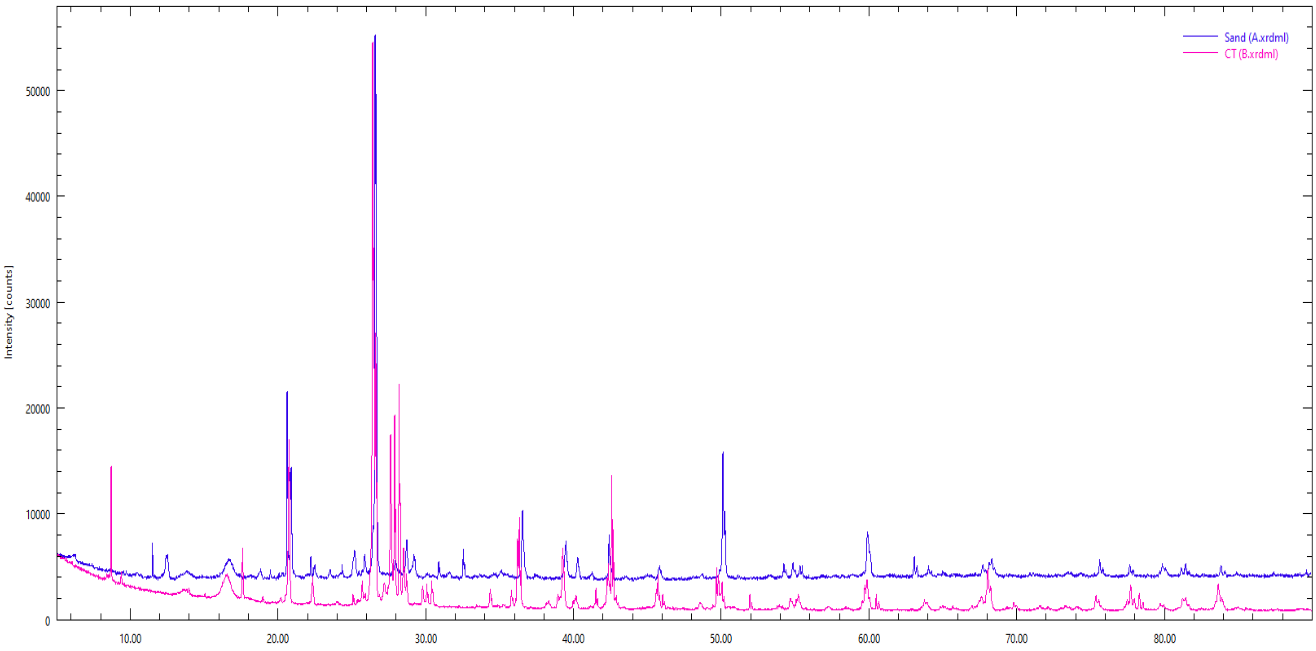

Figure 5. XRD Pattern for Both Sand and Copper Tailings.

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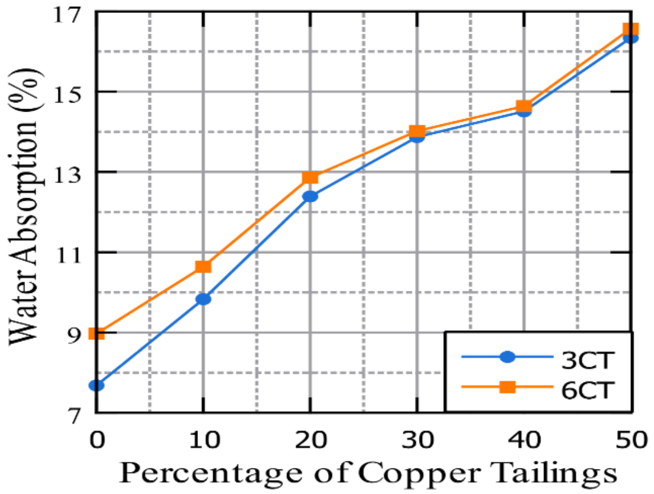

Figure 6. Water Absorption (%) of Cement Mortar for 3CT and 6CT Compositions.

Similarly, the 1:6 cement-to-sand ratio mix (6CT) also shows a rise in water absorption, albeit starting slightly higher at around 11% with no CT and reaching just above 15% with 50% CT. The parallelism in the curves of both mix compositions suggests that the intrinsic properties of CT—finer particle size and potentially higher porosity—are influential regardless of the mix's cement content.

These findings are important because these results indicate that CT (copper tailings) can improve the mechanical properties of cement mortar. It also increases water absorption, which may impair the casted structure's longevity and moisture susceptibility. Increased CT percentages result in increased absorption rates, which must be carefully considered when designing mortar compositions, especially in situations where water exposure is crucial. It is a research that underlines the attention toward striking a balance between improved sustainability and prospective strength improvements in CT and their consequences for its long-term performance under varying environmental circumstances.

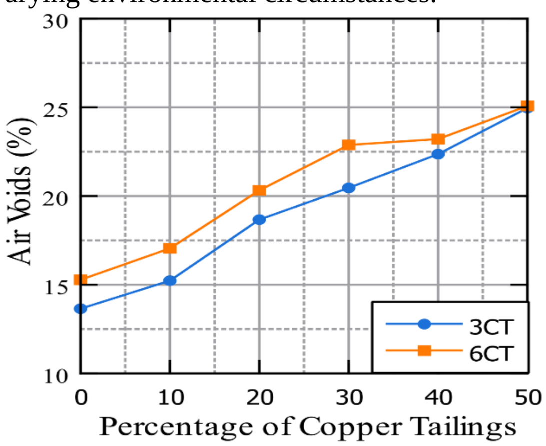

Figure 7. Air Voids (%) of Cement Mortar for 3CT and 6CT Compositions.

Figure 8 shows the relation between CT content and air voids in cement mortar, and some interesting trends can be noticed in the case of both mixes: 1:3 and 1:6 cement-to-sand ratio. The air voids in mortar will increase with an increased proportion of CT in the mix. More precisely, the 3CT mix started at about 15% air voids with no CT and increased to nearly 25% when 50% CT was added. This pattern is paralleled in the 6CT mix, which starts off around 17% air voids without CT and approaches 25% with 50% CT addition. The progressive increase in air-voids with increasing CT content could be due to fineness and, at times irregular forms of the CT particles that may not pack as tightly as would be the case with normal sand, thereby leaving more void spaces within the mortar matrix. This feature could impact the thermal and acoustic qualities of the mortar, making it more of an insulating material while impacting its structural integrity. According to this research, a fine line must be tread when incorporating CT into mortar mixes between pursuing sustainability and waste material usage and the implications for structural and physical qualities. The understanding of the role of air gaps in predicting and controlling the behavior of CT-enriched mortars in real-world settings will be very critical. These findings will, therefore, be useful to the research community and industry practitioners who are trying to improve the use of CT in construction materials.

E) Fresh Bulk density

The fresh bulk density results of the present study provide clear explanations for the influences of mixing copper tailings into cement mortar. Figure 9 data indicate that fresh bulk density decreases with increasing CT for both 3CT and 6CT mortar mixes. The fresh bulk density of the 3CT mix reduces from about 1.95 gm/cc without CT to approximately 1.75 gm/cc with 50% CT. Similarly, the density of the 6CT mix decreases from about 1.90 gm/cc down to 1.77 gm/cc at the same CT inclusion rate. Density reduction can be important for structural applications where lighter materials are preferred to reduce stresses on foundations and buildings. Lower density might also mean that the matrix is less compact and hence will affect its mechanical strength and durability for mortar. It should be noted that while a lighter mortar may be very useful, care needs to be exercised regarding the ramifications towards strength and durability.

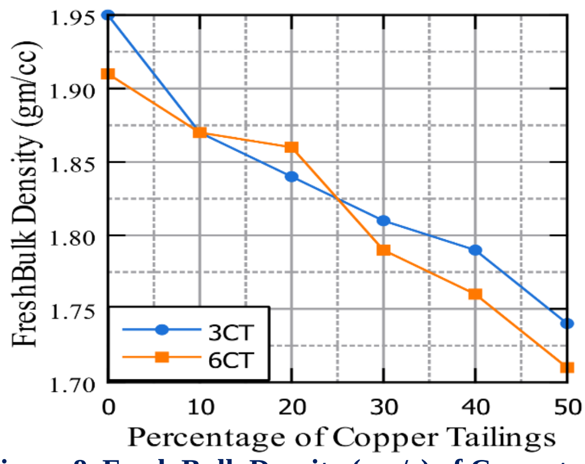

Figure 8. Fresh Bulk Density (gm/c) of Cement Mortar for 3CT and 6CT Compositions.

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Compressive and flexural strength

The relationship between the increasing CT content and reduced fresh bulk density underlines that finding the right balance is imperative when designing CT-enriched mortar mixes. The findings encourage the use of CT as a viable alternative in sustainable construction materials but were tempered by a nuanced understanding of how changes in material composition come to bear on the overall performance of mortar.

The compressive strength results from the present study specify details about how CT, or copper tailings, affect cement mortar. The addition of CT increases the strength of the 3CT mix until it peaks at 13.1 MPa at a 20% replacement level and then drops with a further increase in CT. This peak is higher than the baseline compressive strength without CT, which was 10.3 MPa, thus showing the optimum CT content with respect to strength improvement. In contrast, the 6CT mix reveals a different pattern. Compressive strength without CT is 4.3 MPa, increasing slightly to 6.2 MPa at 30% CT. Any further CT results in a fall in strength, with a huge slump to 4.0 MPa at 50% replacement.

The initial increase in strength observed for both mixtures may be due to the filling action of the fine CT particles, which could offer a denser microstructure. At high percentages of CT, however, it becomes too dense, and particle packing may get disrupted, leading to reduced compressive strength. This drop in strength at higher CT percentages could be due to the fact that CT interferes with the hydration process as a result of its different chemical and physical properties in comparison with normal aggregates.

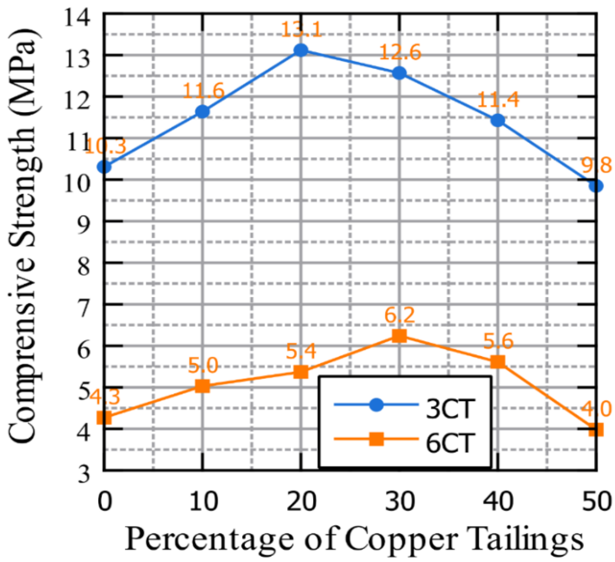

Figure 9. Compressive Strength (MPa) of Cement Mortar for 3CT and 6CT Compositions.

These findings underline the need for the proportion of CT in mortar to be adjusted with a view to improving mechanical qualities. The results show that there is a threshold value of CT content beyond which compressive strength starts declining, thus underlining the balanced approach that needs to be adopted while using such sustainable materials in construction. It thus provides valuable insight into developing green construction materials, indicating that copper tailings can improve compressive strength up to some degree beyond which the benefits fade.

Flexural strength data from this study provides a full overview of the effects when copper tailings are incorporated into mortar. The flexural strength in the mix 3CT starts with 3.9 MPa when there is no CT and reaches a peak of 4.9 MPa at the replacement of 20% CT, thus marking an appropriate point for flexural performance augmentation. Beyond this, the decrease reaches a strength of 3.7 MPa at 50% replacement.

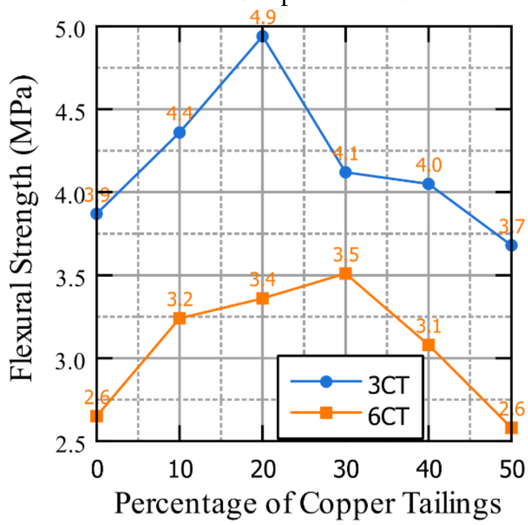

Figure 10. Flexural Strength (MPa) of Cement Mortar for 3CT and 6CT Compositions.

The 6CT mix performs quite differently, starting from a lower baseline of 2.6 MPa, reaching a moderate peak of 3.5 MPa when CT inclusion is at 30%, and then steeply drops off to a mere 2.6 MPa at 50% replacement. This peak is not as high compared to that for the 3CT mix, showing that the ratio of cement-to-sand and CT is important in flexural strength. The first increase in strength due to CT addition can be attributed to an increase in interparticle bonding and densification of the mortar matrix at an optimal CT concentration. However, while the CT fraction grows, workability may be reduced, then, microstructure faults such as larger voids or incomplete hydration reduce flexural strength.

These data thus suggest that there could be a threshold in CT content beyond which the highest flexural strength is achieved, and afterward, the material qualities start degrading. This, from a practical point of view, underlines the proper percentage of CT addition to enhance mortar sustainability without loss of structural integrity. In this paper, the partial replacement of sand by CT will be based on experimental results, which clearly reveal that mix proportions need to be fine-tuned for optimum exploitation of CT's potentials in enhancing flexural strength.

Tensile Bond strength

Figure 12 gives an informative analysis of the tensile bond strength in cement mortars with varying content of copper tailing. For the 3CT mortar mix, the tensile bond strength appears relatively stable across the range of CT

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percentages. It starts at 0.168 MPa with no CT, slightly increases to a peak of 0.179 MPa at 20% CT, and then gradually decreases to 0.158 MPa at 50% CT inclusion. The minimal decrease after the peak suggests that the inclusion of CT up to 20% could be beneficial for tensile bond strength, but beyond this point, the benefits may diminish. In contrast, the 6CT mortar mix experiences a significant reduction in tensile bond strength with increased CT content.

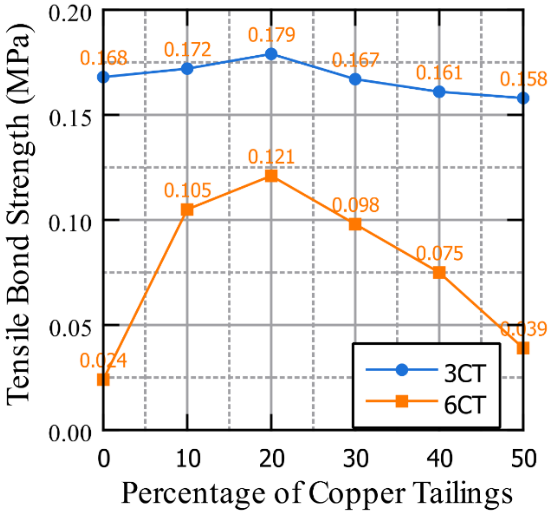


Figure 11. Tensile Bond Strength (MPa) of Cement Mortar for 3CT and 6CT Compositions.

It begins at 0.105 MPa with no CT and reaches a maximum of 0.121 MPa at 10% CT, followed by a sharp decline to 0.039 MPa at 50% CT. This steep drop-off highlights a critical threshold beyond which the CT content negatively affects the tensile bond strength of the mortar. This implied general trends that, while it may enhance tensile bonding strength at small doses, at least on account of finer grain size or even as a filler, its addition at higher doses could turn out to be detrimental to the general bonding characteristics of the cementitious matrix. It could be a consequence of a different interfacial transition in the cement paste/CT grains at higher doses. The findings of this research will portray practical knowledge of the optimum use of CT for increased tensile bond strength in cement mortars. Keeping this in mind, one of the most important roles is to maintain the integrity of the construction materials.

Machine Learning method for the strength prediction model

GBR-GSO strategy is a supervised machine learning method tailored for regression analysis. It inherits the strong properties of Gradient Boosting Regressor and Grid Search Optimization fine-tuning procedure in one approach (Dadhich et al., 2023). This collaboration is focused on solving the complex problems of complex systems, such as material properties, that often involve nonlinear dynamics, optimal determination of the parameters, and a high-accuracy forecast in variable environments. There are many major advantages to the application of the GBR-GSO framework:

Iterative Improvement Mechanism: In GBR-GSO, what is taken is a sequence of decision trees, where every subsequent tree is aimed at rectifying residual mistakes left behind by its immediate predecessor. This iterative refinement takes advantage of the gradient of the loss function in relation to the output of the ensemble at any given time, reducing mistakes across the model ensemble (Jain and Thada, 2024).

Robustness to Noise and Anomalies: The unique structure of GBR algorithms lends this agent to capture the complex nonlinear trends while simultaneously giving a very sparse response to noises and outliers in data. That said, due to this robustness, one does need to be very careful about overfitting, especially with a very complicated model or very noisy data (Kadam and Jadhav, 2020).

Hyperparameter Optimization: The dataset will be divided into a training and testing part before deployment. Fine-tuning the hyperparameters—like learning rate and the number of trees-utilizing grid search optimization increases model effectiveness.

Offshoots of GBR-GSO Correct the Inaccuracies: By using foundational principles of Gradient Boosted Trees, with the CART model as its basic learner, the method ensures that each iteration corrects the inaccuracies of its predecessors, hence placing it very strongly in regression tasks in the analysis of complex systems (Thai, D. K. et al., 2020).

The composite predictive framework operates on an iterative construction principle, engaging a sequence of M distinct predictive elements, each denoted as an individual decision tree T_m. Initially, T_1 is calibrated employing the feature dataset F and the corresponding target vector τ. Upon completion, the first approximation $\hat{\tau}_1$ is utilized to determine the initial discrepancy, Δ_1, from the actual target values. Sequentially, the following decision tree, T_2 is tailored not to the original targets but to these residuals. The process advances such that each tree T_m hones in on the residuals Δ_{m-1}, iteratively refining the predictions.

A pivotal parameter within this ensemble strategy is the 'contraction' factor, symbolized as λ effectively scaling down each individual tree's output by this factor before amalgamation into the final model prediction. This rate of contraction λ is judiciously selected within the range of (0,1) to modulate the convergence rate and complexity of the model. The equilibrium between λ and the quantity of trees, M, embodies a balancing act to achieve the desired fidelity in predictive capability—typically, a diminutive λ entails a requirement for a greater M, to maintain model accuracy. After the education of each tree T_m an interim predictive inference can be assembled. The cumulative predictive result for a given instance x after M trees have been cultivated is furnished by the aggregated correction of each tree to the preceding outcome, formalized as follows:

$$\hat{\tau}(x) = \tau_0 + \lambda \sum_{m=1}^{M} \Delta_m(x) \qquad (1)$$

In this expression, τ0 designates the initial prediction and Δ_m signifies the m_{th} tree's contribution to the rectification process. This sum essentially encapsulates the progressive refinement characteristic of the ensemble learning method.

To optimize hyperparameters in machine learning models, a reliable method known as K-fold cross-validation is used (Dadhich et al., 2023). This approach divides the dataset into k equal-sized parts. During each validation iteration, a single distinct segment is reserved

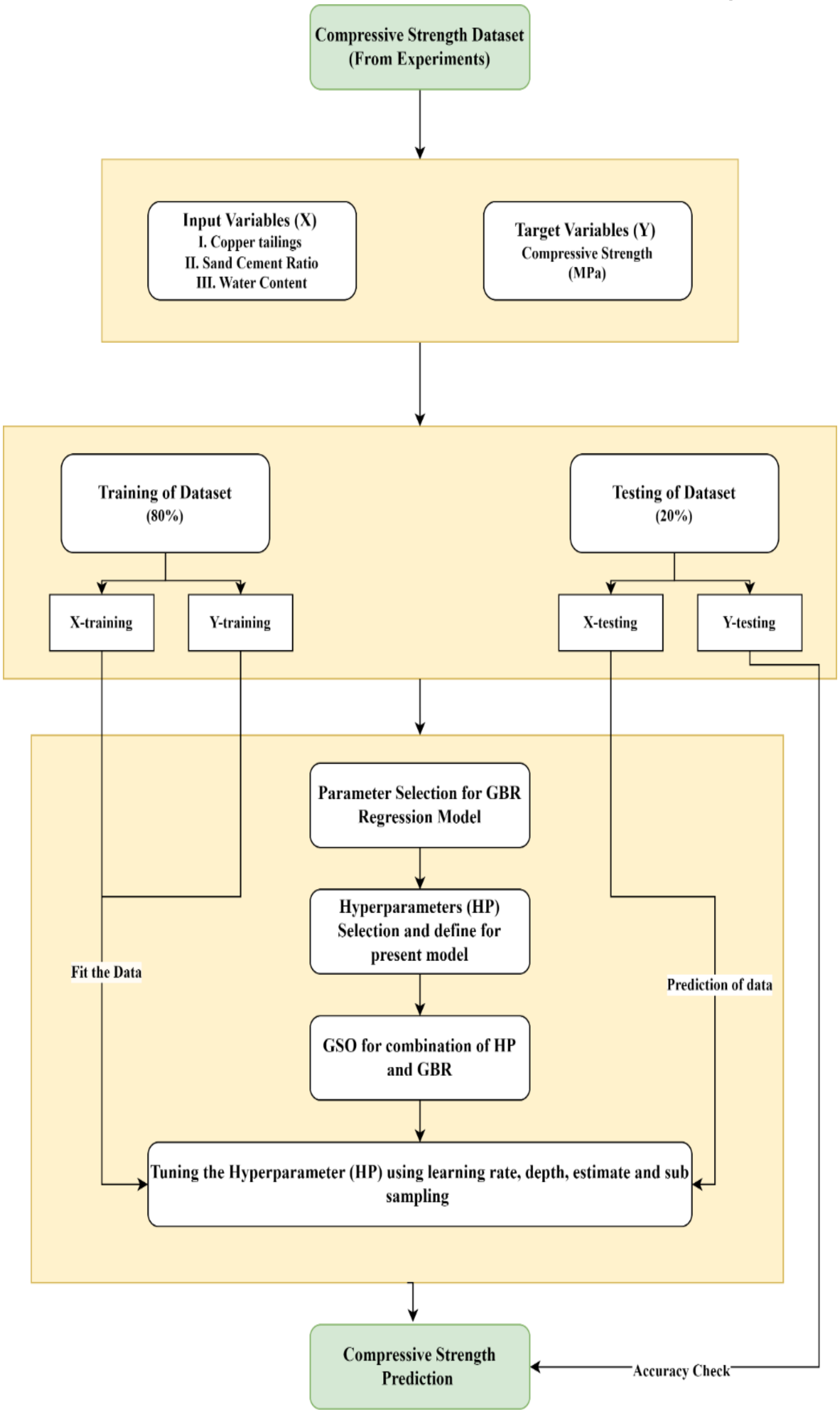


Figure 12. GBR-GSO Flow Diagram for Current Study.

for model validation, with the remaining k-1 segments combined for training. The process will be repeated k times, and in each of these k iterations, every segment will alternatively act as the validation set. This is solely instrumental in practice to tune a model according to differences in hyperparameters, wherein an attempt is made to minimize the average error from all k iterations for an excellent model. This strategy is very effective because data in the full data set involve both training and validation at least k-1 times and only precisely once in the validation, thus making full use of all the data available to the estimation model (Pal et al., 2023).

GBR-GSO for Strength Prediction of Cement Mortar

Such methodology combines the high predictive power of GBR—a machine learning technique that constructs an ensemble of decision trees in a sequential error-correcting process—with the refinement capabilities of GSO in searching for one optimal set of hyperparameters. During its working process, the GBR-GSO technique is initiated by training a large number of decision trees in a sequential manner, where each tree learns from the mistakes of the previous one. The compounded model allows one to compensate for deficiencies in any one learner through collective intelligence. Second, GSO thoroughly explores a space of predefined hyperparameters to settle on the one producing the best prediction accuracy. This is a synergistic technique where GBR models complex, nonlinear interactions in data and GSO tunes it to peak performance. To operationalize the GBR-GSO model, the dataset including input variables—specifically, the proportion of copper tailings, sand-cement ratio, and water content—is segregated into training and testing sets. The model is first trained on the majority subset and then GSO is used to determine the optimal combination of hyperparameters such as tree depth, learning rate, and number of estimators. The model is calibrated to accurately forecast the compressive strength of cement mortar after thorough adjustment and validation against the testing subset.

This GBR-GSO technique is more applicable because it only requires data sets of any size, be it tiny, small, or large, which is common in experimental settings.

Algorithm: Predicting Compressive Strength using GBR-GSO

Inputs:

X - Input Variables: Copper tailings, Sand Cement Ratio, Water Content

Y - Target Variable: Compressive Strength (MPa)

1. Obtain the Compressive Strength Dataset from Experiments:.

2. Split the dataset into train (80%) and test (20%) subsets:

X_train, Y_train: Training dataset (80% of the total dataset)

It will use X_test and Y_test (testing dataset, 20% of the total dataset).

3. Parameter Selection for the Gradient Boosting Regressor (GBR) Model:

a. Identify proper hyper-parameters of the GBR model: for example, the number of estimators, maximum depth, learning rate, etc.

b. Fit the GBR model to the training data.

4. GBR Model Optimization with Grid Search Optimization:

a. Define a grid of values over which to optimize the parameters.

a. Use GSO to find the best combination of parameters that gives the least prediction error.

5. Tune the GBR model with the optimized hyperparameters:

a. Adjust the learning rate, tree depth, number of estimators, and subsampling rate according to the GSO results.

b. Refit the GBR model to the training data using these tuned parameters.

6. Predict the compressive strength on the testing dataset:

a. Use the tuned GBR model to predict the compressive strength of the testing data (X_test).

b. Compare the predictions with the actual values (Y_test) to check the accuracy.

7. Perform an accuracy check:

a. Calculate the accuracy metrics such as R-squared, Mean Squared Error (MSE), etc., to evaluate the model's performance.

b. If the model's accuracy is satisfactory, finalize the model. Otherwise, go back to step 3 and iterate on the parameter selection and tuning process.

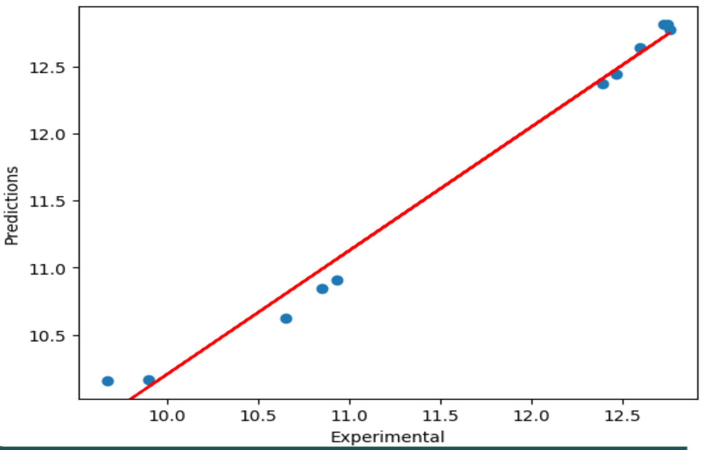
Outputs:

- Predicted Compressive Strength values for the testing data.

- Accuracy metrics of the model.

The GBR-GSO model was simulated on the Google Collab cloud environment for all 3CT and 6CT mix combinations. Figures 14 and 15 demonstrate the prediction curves for training and testing, respectively. The Evaluation matrices for both 3CT and 6CT mix were present in table 6, respectively.

a)



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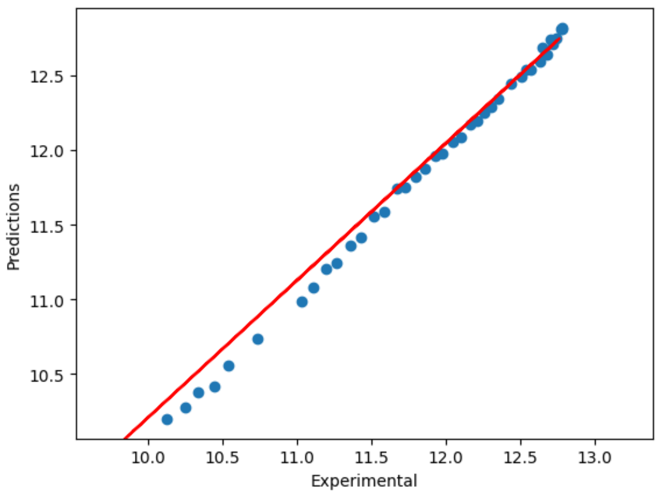
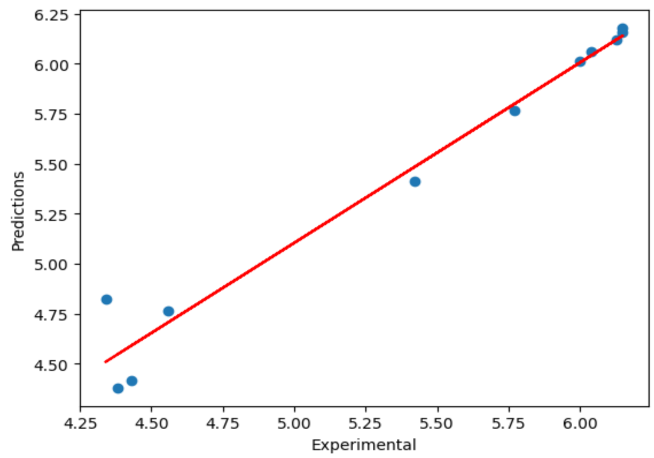
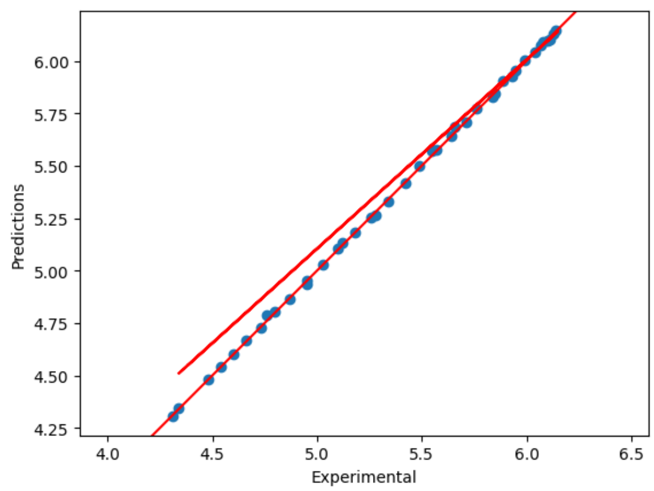


b)

Figure 13a) Testing of the Data for 3CT Mix Combinations for "Compressive Strength"



a)



b)

Figure 14. Testing of the Data for 6CT Mix Combinations for "Compressive Strength".

Table 6. Evaluation Metrics for Compressive Strength (CS) Target using GBR-GSO ML. Model

Metrics Error	Short name	3CT Model	6CT Model
Mean Squared Error	MSE	0.0292	0.0252
Root Mean Squared Error	RMSE	0.1709	0.1587
R Square	R2	0.9783	0.9565

The Gradient Boosting Regressor-Grid Search Optimization (GBR-GSO) machine learning model performs well in predicting the compressive strength (CS) of cement mixtures, as shown in Table 6. Evaluation metrics show that the model with 6% copper tailings (6CT) superior to the model with 3% copper tailings (3CT), with a reduced Mean Squared Error (MSE) of 0.0252 compared to 0.0292 and a more favourable Root Mean Squared Error (RMSE) of 0.1587 versus 0.1709. The 6CT model has a strong R Square (R^2) value of 0.9565, showing a high level of variance explanation. However, the 3CT model's R^2 of 0.9783 is slightly higher, indicating outstanding predictive accuracy.

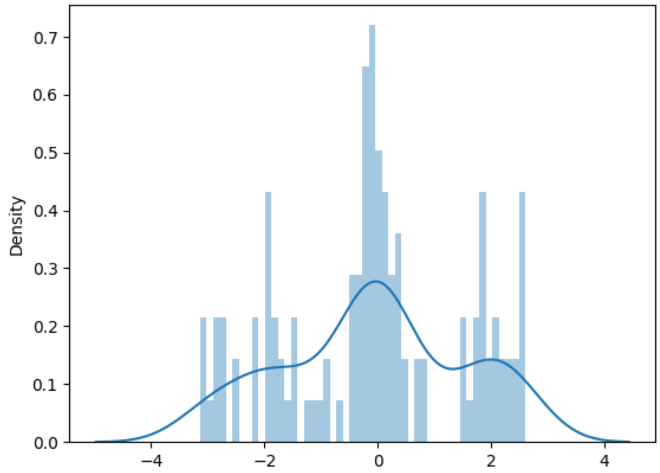


Figure 15. Error Plot of Compressive Strength (CS) for 3CT Mix Combinations.

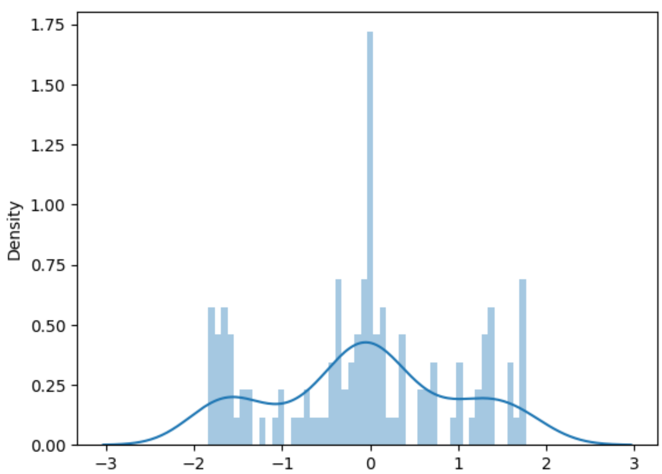


Figure 16. Error Plot of Compressive Strength (CS) for 6CT Mix Combinations.

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Figures 16 and 17 illustrate the error plots for the 3CT and 6CT models, respectively. These charts aid in understanding the model's error distribution; both the 3CT and 6CT models performed well and had the least amount of error during the modeling and testing phases.

Conclusion

In this study, waste copper tailings were used instead of river sand to cast the cement mortar, and the impact of the copper tailings on the cement mortar's strength parameters was investigated. The current study also helped to determine the importance of machine learning models in material prediction development. In the current study, the GBR-GSO model is trained and tested using experimental compressive strength data for both 3CT and 6CT mix designs. The general outcome of the study was following:

- Mixtures with copper tailings (3CT series) have stronger tensile bond, flexural, and compressive strength than those with 6% copper tailings (6CT series).
- The highest compressive strength is observed in the 3CT2 mixture, indicating an optimal balance of components.
- An increase in copper tailings content corresponds to a decrease in fresh bulk density and an increase in both air voids and water absorption percentages.
- The 3CT series exhibits a progressive increase in water absorption and air voids with the rise in tensile bond strength, suggesting a trade-off between strength and porosity-related properties.
- The study suggests that, while copper tailings can improve some mechanical qualities, there is a limit beyond which additional tailings may result in declining returns in structural integrity.

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Conflict of Interest

The authors state that they have no known competing financial interests or personal relationships that could have influenced the work presented in this study.

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