Research Article

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Mechanical Characteristics of Copper Slag and Sugarcane Bagasse Ash-based Sustainable Concrete Prepared with PEG-400 as Internal Curing Agent

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ABSTRACT

In recent years, scientists have extensively investigated the use of internal curing methods in concrete to improve its ability to retain water. Proper curing forms an important step in enhancing the strength and durability of concrete, which exerts a significant influence on its development. This study discusses the structural properties of self-curing concrete. Sugarcane bagasse ash (SCBA) and copper slag (CS) are used as supplementary materials along with the concrete mix. PEG-400 is used as the self-curing agent in the concrete mix. This research looks into the properties of the new concrete mixture and the influence of the components on the mechanical behavior of the concrete. For testing purposes, two mixtures of the concrete were prepared. The first lot involved five mix ratios of the concrete, with the control mixture containing 0.5% to 2% PEG-400 relative to cement weight. For the second mix, CS replaced part of the fine aggregate and was at the age of 40%, while the cement was partially substituted with an amount of 5-20% SCBA in self-curing concrete, which contains 1% PEG-400. Investigations were carried out to evaluate the feasibility of self-curing concrete incorporating CS and SCBA. The study involved tests on slump, compressive strength, split tensile strength, and flexural strength.

Keywords: Self-curing concrete; PEG-400; Copper slag; Sugarcane bagasse ash.

1. INTRODUCTION

The demand for construction continues to rise due to rapid population growth, with concrete remaining the most widely used and preferred building material worldwide (Rahimi *et al.* 2023). Specifically, adequate curing enhances the pore structure of concrete, which is crucial for achieving a high early strength (Malathy *et al.* 2020). Water is a vital and extensively utilized natural resource in the construction industry The amount of water available per person has drastically decreased; this might be because people are not aware of how to use water efficiently or are using it improperly (Lokeshwari *et al.* 2021). Casting and curing are the two primary uses of water in construction. Concrete, the most widely used construction material today, requires a substantial amount of water, making it an essential consideration in projects of all scales. It is important to use strategies that reduce reliance on water during construction. Water is becoming scarcer due to its increased demand worldwide. We urgently need to find ways to reduce the amount of water used. For every cubic metre of concrete, approximately 3.0 cubic metres of water are required for construction purposes, with the majority consumed during the curing process (Lokeshwari *et al.* 2021; Zeyad *et al.* 2023). The fundamental aim of curing concrete is to sustain a consistent level of moisture, ensuring the ongoing hydration of cement. Consequently, the ongoing hydration process facilitates the formation of concrete that exhibits enhanced strength and reduced permeability (Amin *et al.* 2021). Because concrete requires substantial water to remain adequately moist, the degree of hydration is directly influenced by its moisture content (Ali *et al.* 2022). To sustain a relative humidity of about 80%, continuous moisture availability is essential. During typical curing, external water application keeps the relative humidity at 80%. As the relative humidity drops below 80%, the hydration process slows down and it ceases completely when the internal relative humidity falls under 30% (Shravan *et al.* 2021). Maintaining moisture levels is essential to the cement's continuous hydration. This, in turn, facilitates the formation of concrete's porous structure and microstructure. It is necessary to stop water from evaporating out of capillaries since cement can only hydrate in water-filled capillaries. Moreover, external water must be permitted to infiltrate the concrete to replace the moisture depleted internally through self-desiccation (a result of chemical processes during the hydration of cement). Consequently, shrinkage cracks form on the concrete's upper surface (Madduru *et al.* 2020). This is accomplished in traditional curing by applying external curing following mixing, putting and finishing. As water is being extensively utilized, groundwater levels are gradually declining. Consequently, construction costs increase significantly when water has to be sourced from distant or limited

supplies (Chaitanya *et al.* 2019). For tall concrete structures, vertical elements, inclined roofs and road surfaces, uninterrupted curing poses significant challenges. Concrete curing is a key construction difficulty, particularly in water-scarce places (Kamal *et al.* 2018). Furthermore, conventional curing techniques can be labor- and time-intensive, requiring continuous water application or the use of coverings such as plastic sheets or wet burlap to retain moisture. Consequently, there is growing research interest in the development of self-curing concrete as a more efficient alternative (Ali *et al.* 2022). Consequently, self-curing or internal curing represents an advanced application. The ACI-308 code defines "internal curing as the process by which hydration of cement occurs because of the availability of additional internal water that is not part of the mixing water" (Madduru *et al.* 2020). Concrete that cures itself does not require external curing regimes, which saves a large amount of water that would otherwise be squandered during traditional curing (Elwakkad *et al.* 2022). Additives can be used in a variety of ways. These include crystalline admixtures, superabsorbent polymers, lightweight aggregates and other moisture-holding materials. These ingredients enable a more regulated and extended curing process by absorbing and holding the water inside the concrete matrix during mixing. However, some studies have employed polyglycol products as self-curing ingredients in concrete mixtures (Mousa *et al.* 2015). Concrete containing polyethylene glycols (PEGs) forms shells around the water particles. These shells with a thickness of approximately 2 nm, develop on each water particle found in the concrete. Concrete prevents water from evaporating owing to the formation of such shells. This results in a decrease in the evaporation rate, ensuring that water is constantly accessible during periods of high hydration. Water does not need to be cured because evaporation does not occur (Bashandy *et al.* 2017; Lokeshwari *et al.* 2021).

The ecological balance is at risk due to the excessive use of natural resources and the worldwide accumulation of industrial pollutants. This dual threat of resource exhaustion and waste buildup poses significant challenges to the environment. Concrete that uses Portland cement as a binder in addition to other aggregates is becoming increasingly popular in building and infrastructure sectors. As natural aggregates comprise 70 % of the materials used to build concrete, there is a constant need for their use (Rajasekar *et al.* 2019; Sivasakthi *et al.* 2021). The supply of natural aggregates has been decreasing recently, which has increased their cost and negatively impacted the cost of building as a whole (Siddique *et al.* 2020). Efforts have been made to replace natural aggregates with synthetic alternatives derived from industrial by-products in concrete production, aiming to reduce the dependence on naturally occurring materials (Sivasakthi *et al.* 2021). Using industrial byproducts, nearly all traditional concrete-making ingredients can be modified (Rajasekar *et al.* 2019). River sand, the most extensively utilized fine aggregate, is no longer sufficient to meet the requirements of the construction industry. The need for river sand in the construction sector is growing tremendously (Khawaja *et al.* 2021). Beyond exhausting natural resources, it adversely affects the environment (Maharishi *et al.* 2021). The ecology of rivers is still severely damaged by illicit mining, even though the majority of nations have enacted laws against it. To create cement-based materials, it is important to locate substitute resources for river sand (Shi *et al.* 2021). In recent times, numerous investigations have explored the use of alternative materials to replace river sand, including manufactured sand (M-sand), slag from copper processing, sand from foundries and dust from quarries. However, the building industry uses these replacement materials, which are disposed of as trash. This research investigates the potential utilization of copper slag (CS), a previously discarded waste material (Manjunatha *et al.* 2021). During the pyrometallurgical extraction of metals from copper concentrates, a by-product known as copper slag (CS) is generated. This material is considered to be a waste product of this process (Phiri *et al.* 2021). The production of one tons of copper results in the formation of two to three tones of slag (Rajasekar *et al.* 2019). Global CS output is estimated to exceed 40 million tons per year (Sharma *et al.* 2021). This output is anticipated to rise in the upcoming years owing to population expansion and the need for copper in numerous technical domains (Lemougna *et al.* 2020). Over the past decade, fine aggregate which is used in concrete preparation has been replaced with copper slag. When processed, both air-cooled and granulated copper slag exhibit mechanical characteristics that make them appropriate for utilization as aggregate materials. These attributes include increased concrete density, which enhances the concrete's self-weight, excellent soundness characteristics and high stability (Panda *et al.* 2020). This phenomenon is ascribed to the exceptional hardness of copper slag and the consequent reduction in drying shrinkage of concrete (Sandra *et al.* 2021). Because the total content of the three oxides (SiO_2, Fe_2O_3 and Al_2O_3) is greater than 70 %, CS is a pozzolanic material (Sambangi *et al.* 2021). According to many studies, CS is the most effective substitute for sand. Research demonstrates that the elevated specific gravity of copper slag results in a 6–7 % increase in concrete density, regardless of the proportions of sand or slag used. Approximately 40 % of copper slag is recommended to provide excellent mechanical qualities (Rekha *et al.* 2021).

Cement, second only to water in global consumption, is considered an essential material on Earth. By 2050, it is anticipated that the world will consume 5 billion tons of cement (Quedou *et al.* 2021; Ahmad *et al.* 2021; Amin *et al.* 2022). The process of making cement is harmful to both the environment and the public (Rajasekar *et al.* 2018). Conversely, OPC is recognized globally as the most commonly used

construction material, despite its substantial expense and detrimental impact on the environment. The global surge in population has led to an increased demand for construction materials worldwide. Waste biomass ash from industrial sources is expected to meet cement demands by serving as a cement substitute in the form of supplementary cementitious materials (SCM). This approach can substantially reduce the ecological impact resulting from industrial waste products (Channa *et al.* 2022). The use of SCM has a number of positive effects on properties of the concrete. Such materials are able to consume calcium hydroxide which is considered to be a waste during cement hydration and thus contribute even more to the creation of C-S-H gel during the process (Joshaghani *et al.* 2017). Agricultural waste can be utilized as an alternative resource for cementitious materials (Ameri *et al.* 2020). It has been suggested that this trash is the primary focus, because it is readily available and possesses pozzolanic properties. Ash from rice husks and bagasse from sugarcane are examples of agricultural wastes that are regarded as mineral admixtures because of their favorable pozzolanic qualities (Jha *et al.* 2021).

In the sugar industry, sugarcane bagasse ash (SCBA), sometimes commonly referred to as "bagasse ash," is a by-product that is created when the juice from sugarcane is extracted (Rajasekar *et al.* 2018). This material is not usable and is disposed of in landfills, contributing to environmental contamination (Zareei *et al.* 2018). After extracting juice from sugarcane, the residual fibrous material, which is referred to as bagasse, is commonly employed in the production of paper and board, as well as serving as a biofuel source. A typical practice in many sugarcane-growing countries is the burning or incineration of bagasse for the purpose of creating electricity. This results in the production of bagasse ash (Joshaghani *et al.* 2017; Farrant *et al.* 2022). Sugarcane bagasse ash has been shown to contain a larger proportion of SiO_2 than cement, according to the findings of several studies. Additionally, X-ray diffraction revealed that the SCBA components consisted of quartz as one of its constituents. The EDX analysis reveals that SCBA is predominantly composed of SiO_2 and exhibits a higher degree of crystallinity compared to amorphous structures, resulting in a limited pozzolanic reaction. In addition to this, SCBA is offered in the form of quartz and it was employed as a supplemental material, which suggests the incorporation of an inert substance. The reaction between SCBA and calcium hydroxide takes place owing to the existence of a calcium silicate hydrate (C-S-H) solution, which serves as an indicator of the pozzolanic activity exhibited by SCBA (Amin *et al.* 2022). According to the findings of a few investigations, there have been improvements in durability. Research has demonstrated that adding SCBA to concrete affects the physical and chemical characteristics of the hardened material (Zareei *et al.* 2018).

2. MATERIALS

2.1 Cement

Cement is an essential component for construction projects. When water is added to cement, it solidifies and acts as an adhesive when mixed with fine and coarse aggregates. Cement is the primary component used in the production of concrete, as it binds the aggregates together and fills the voids between them. The cement exhibited a uniform gray color with a slight greenish hue and was free from any hard lumps throughout. The cement was tested in accordance with Indian Standards 12269:2013 and 4031:1988.

2.2 Aggregates

A significant portion of concrete is composed of inert and less expensive aggregates. These aggregates contribute to the longevity and strength of concrete. Aggregates are a combination of natural elements that are both coarse and fine in size. They contribute to roughly 70% of concrete's strength. The process of weathering rocks results in the formation of natural aggregates, whereas crushing rocks results in the formation of artificial aggregates. Aggregates measuring less than 4.75 mm are classified as fine, whilst those exceeding 4.75 mm are considered coarse. The distinction is based on its capacity to either pass through or be held by a sieve of this particular size. A void area of 30 – 40% was created in the concrete as a result of the placement of coarse aggregates. The interstices are occupied by small particles, whilst the gaps between these fine aggregates are filled with even smaller components, such as cement. There are several different standards for aggregates in accordance with IS 383:1970. In this study, coarse aggregates that were readily available and had a maximum size of 20 mm were utilized. Evaluations of coarse aggregates were carried out in accordance with IS: 383–1970.

2.3 Water

In addition to causing cement to hydrate, water also gives concrete its strength, durability and workability. Water is added in small quantities as excessive water in concrete may lead to separation. The water-to-cement ratio must adhere to IS 456:2000 standards. For the purposes of mixing and curing, potable water with the required pH level (ranging from 6.2 to 7.5) should be used, as specified in IS 456:2000 and the water utilized in this study complies with these standards for concreting.

2.4 Superplasticizer

This study utilizes superplasticizer Sika Visco flow-615 KE, which is yellowish in colour, has a specific gravity of 1.07 and comprises 35% solid content.

2.5 Polyethylene Glycol (400)

In this study, polyethylene glycol (PEG), a highly hydrophilic material with a molecular weight of 400 is used as a self-curing agent. Polyethylene glycol is a substance derived from the polymer ethylene oxide. It is formed through the addition of water to the general formula H (OCH_2CH_2) nOH. In this formula, n typically falls within the range of 4 to 180, which indicates the quantity of recurring ethylene oxide units (Malathy *et al.* 2020; Singh *et al.* 2021). One characteristic that appears to be shared by PEG is its ability to dissolve in water. Polyethylene glycol possesses numerous beneficial properties, including being non-irritating, non-toxic, odourless, colourless, viscous, low-molecular-weight, neutral, lubricating and non-volatile. Due to these characteristics, it finds extensive use in various pharmaceutical product applications (Rizzuto *et al.* 2020), particularly with regard to hygienic standards (Lokeshwari *et al.* 2021).

PEG-400 serves as a plasticizing agent in concrete mixtures, adhesive compounds, binding materials and soldering flux formulations, improving their fluidity and ease of manipulation. In addition, it is utilized as a water-retention agent. PEG-400 has been employed earlier due to its effective dispersion properties (Colangelo *et al.* 2013). Polyethylene glycol is classified by a numerical suffix that denotes its average molecular weight. Its molecular mass can vary from 300 g/mol to 1 × 1078 g/mol (Colangelo *et al.* 2013). The main attributes of PEG-400 as described by the manufacturer are presented in Table 1.

2.6 Copper Slag

Copper slag was obtained from Sterlite Industries Ltd. (SIL), Tuticorin, Tamil Nadu, India. Currently, approximately 2600 tons of CS are generated each day and the total amount of CS that has been accumulated is approximately 1.5 million tons. The remaining material is discarded as trash, which contributes to environmental contamination. These applications employ only approximately 15–20 % of the available resources (Sivasakthi *et al.* 2021). Comparable gradations of copper slag and sand met Zone II of the grading criteria. Copper slag contains approximately 26 % silica, which is beneficial as silica is a key component of natural fine aggregates commonly used in concrete (Wu *et al.* 2010). Fig. 1 displays the gradation comparison of copper slag and natural fine aggregate.

Table 1. Characteristics of PEG-4

Characteristic	Value
Typical Molecular Mass	380 - 420 g/mol
Viscosity at 20 °C	85 - 105 cs
Maximum Acid Content	0.05%
Mass per Unit Volume at 20 °C	1.120 - 1.126 gm

Table 2: Various chemical compositions of cement and SCBA

Constituents	OPC (%)	SCBA (%)
SiO_2	20.02	29.95
CaO	62.78	1.70
Al_2O_3	5.27	24.01
Fe_2O_3	3.16	4.88
MgO	3.21	1.39

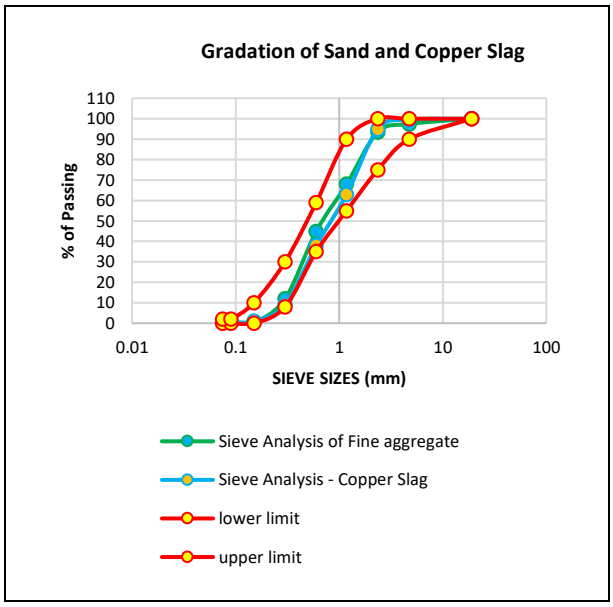


Fig. 1: Gradation comparison of copper slag and fine aggregate

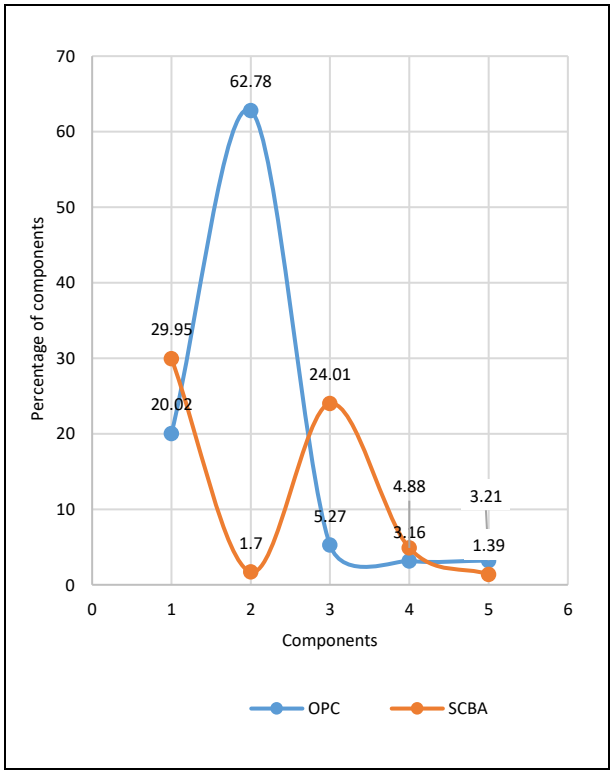


Fig. 2: Chemical composition of SCBA and OPC

2.7 Sugarcane Bagasse Ash

The composition of sugarcane bagasse ash consists of roughly 50 % cellulose, with the remaining half equally divided between hemicellulose and lignin, each accounting for about 25 %. About 50 % moisture content and 0.62 % of the residual ash are produced by each ton of sugarcane, which results in around 26 % bagasse. The remaining ash is primarily composed of SiO_2 (Zareei *et al.* 2018; Ramakrishnan *et al.* 2021). Owing to its high carbon content, it has a dark black hue. Typically, sugar mills utilize sugarcane bagasse as fuel for their furnaces. This process yields ash, which constitutes roughly 10% of the output and comprises substantial quantities of silica, aluminum and calcium oxides, along with incompletely combusted particles (Ramakrishnan *et al.* 2021). Fig. 2 illustrates a comparative analysis of the chemical compositions between cement and SCBA, which was utilized as a cement substitute. Properties of cement and SCBA are presented in Table 2.

3. MIX PROPORTION

Concrete mix design is a process for selecting suitable concrete ingredients, the cement, the aggregates and water and determining their optimal proportions to produce an economical concrete mix that meets the required standards of strength, workability, and durability. The purpose is to achieve the optimal balance of all these properties considering economic factors. Nine mixes and one regular mix (CC) were prepared. Four mixes consisted of only PEG-400, called P-0.5, P-1, P-1.5 and P-2. Variation in the addition of PEG-400 by cement weight is between 0.5 % and 2 %. The residual mixture was maintained at constant 1 % PEG-400, copper slag 40 % was utilized as a replacement of fine aggregate at a maintained constant condition (Wu *et al.* 2010; Sridharan *et al.* 2021; Usha Kranti *et al.* 2021). PCSA-5, PCSA-10, PCSA-15 and PCSA-20 names are given for the cement substitutes incorporating SCBA with variation of 5 % to 20 %. All other parameters (quantity of water, cement and plasticizer used) remained unchanged for comparison purposes with the control mixture.

4. TESTING METHODS

To examine the effects and performance of the blend that included PEG-400, copper slag and SCBA on the properties of concrete both when it was freshly prepared and then hardened, several tests were conducted on the samples. The tests included evaluations in workability, compressive strength, ST tensile strength and the tests for flexural strength. The results were then compared with those samples from the control concrete in depth examination. These numbers matched the average findings that were recorded and are displayed in bar charts.

4.1 Compressive Strength Test

The hardened concrete can undergo a compressive strength test through which the maximum compressive load as well as stress that the concrete can withstand before failure occurs can be determined. In total, cube specimens of dimensions 150 mm × 150 mm × 150 mm were tested for compressive strength at ages 28, 56 and 90 days. Testing was conducted in accordance with stipulations set under IS: 516:1959. The cube samples were mounted in the center of the supporting plate, which formed part of the test equipment used in compressive strength testing. The applied load was ensured to be evenly balanced on two opposite sides. The underside of the cube was subjected to a steadily rising force applied at a constant rate of 0.3 N/mm^2 per second. The cube was removed as it was almost cracking and the unusual failure mode was confirmed. Compression testing equipment recorded the load at the point of failure.

4.2 ST Tensile Test

The indirect tensile strength, also referred to as ST tensile strength, is utilized to evaluate concrete's capacity to withstand tensile stress. This assessment was conducted by subjecting a cylindrical concrete specimen to a diametrical compressive force until it fractured into two parts. Following the guidelines of IS 5816:1999, all cylindrical specimens measuring 300 mm × 150 mm underwent ST tensile testing at 28, 56 and 90 days. The two ends of the specimen were tagged with a marker to determine the axis position.

4.3 Flexural Strength Test

The concrete flexural strength test aims to assess a sample's ability to withstand bending or flexural forces. Flexural strength was assessed on 100 mm x 100 mm x 500 mm beams under two-point loading for a duration of 28 days, in compliance with IS 516:1959.

5. RESULTS

5.1 Workability

The most basic technique for assessing a material's workability is slump test. Fig. 3 illustrates a comparison of concrete slump values, contrasting samples with and without the inclusion of self-curing agent, copper slag and SCBA. In comparison to the CC mixture, the percentage of slump values increased by 4.7 %, 16.66 %, 27.3 % and 32.14 % by the utilization of PEG at concentrations of 0.5 %, 1 %, 1.5 % and 2 %, respectively. The outcomes are not comparable to those of concrete that does not include PEG. It is possible that the presence of water-soluble polymers is responsible for the rise in slump. Plasticizing, lubricating (Amin *et al.* 2021) and air entraining (Rizzuto *et al.* 2020) are

properties that are shown by water-soluble polymers. Table 3 shows the workability of concrete at different percentages of PEG-400.

Table 3. Workability of concrete at different percentages of PEG-400

Type of concrete	Mix id	% of PEG-400	Workability Slump Value(mm)
Conventional Concrete	CC	0%	84
Self-Curing Concrete	P-1	0.5%	88
	P-2	1%	98
	P-3	1.5%	107
	P-4	2%	111

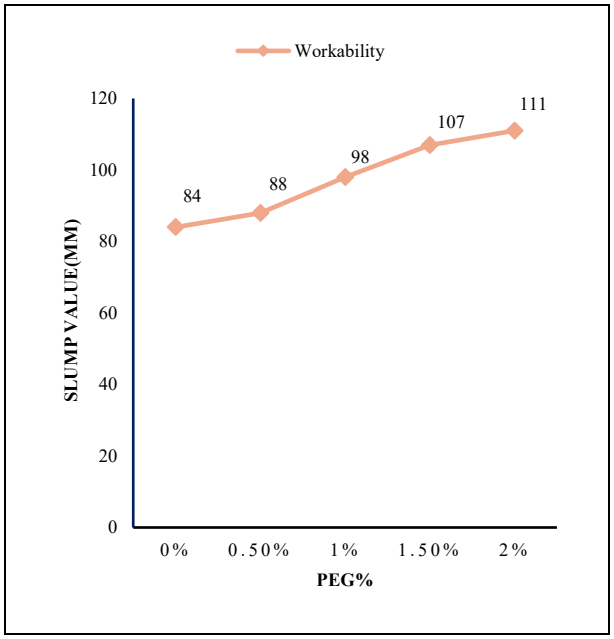


Fig. 3: Workability of concrete at various percentages of PEG-400

On the other hand, the slump value reached its highest point for mix id PCSA-5 and when compared to the CC mix, the slump value rose by 25 % for PCSA-5, 16.66% for PCSA-10, 10.71% for PCSA-15 and 4.76% for PCSA-20. This clearly demonstrates that the slump values continue to drop as the SCBA content increases and the slump values are displayed in Table 4. This phenomenon can be explained by the SCBA particles absorbing some of the water used in the mixture, owing to their high porosity and surface area (de A. Mello *et al.* 2020). Fig. 4 shows the workability graph of concrete at various PCSA percentages.

In contrast, copper slag and PEG-400 function as lubricants for solid particles, diminishing the frictional forces between particulate matter and water molecules. These substances are drawn towards the particles due to their high reactivity, thereby enhancing the mixture's fluidity (Wang *et al.* 2021) in comparison to the CC mix.

Table 4. Workability of concrete at different percentages of PCSA

Type of concrete	Mix id	PEG (1%) +CS (40%) +SCBA	Workability Slump Value (mm)
Conventional Concrete	CC	0%	84
Self-Curing Concrete	PCSA-5	5%	105
	PCSA-10	10%	98
	PCSA-15	15%	93
	PCSA-20	20%	88

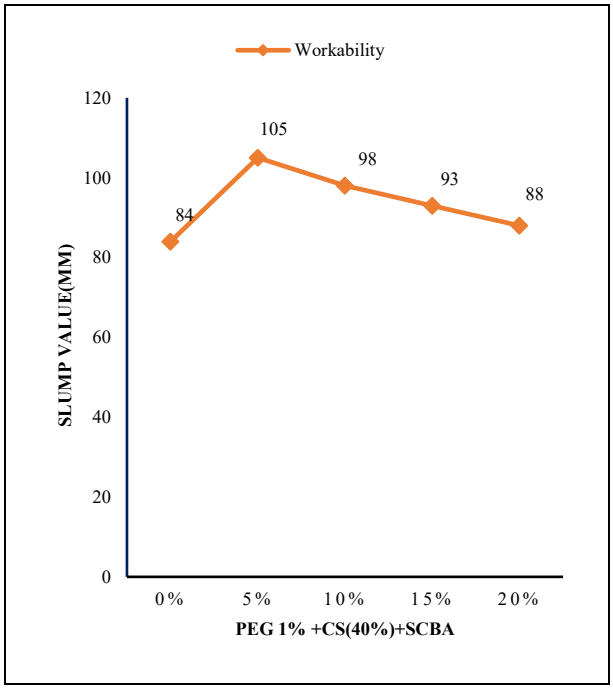


Fig. 4: Workability of concrete at various percentages of PCSA

5.2 Compressive Strength

Table 5. Mean compressive strength of concrete cubes

Type of concrete	Mix id	% of PEG-400	Average Compressive Strength (N/mm²)		
			28 days	56 days	90 days
Conventional Concrete	CC	0%	39.55	40.61	41.03
Self-Curing Concrete	P-1	0.5%	41.56	42.44	43.68
	P-2	1%	42.85	44.01	45.32
	P-3	1.5%	41.91	42.30	43.45
	P-4	2%	40.08	40.98	42.12

In order to assess the compressive strength of the reference mixture (CC) and all other concrete mixtures, PEG-400, a self-curing agent, was added in different proportions: 0.5 %, 1 %, 1.5 % and 2 %. After a period of 28 days, the compressive strength of CC that contained these quantities of PEG-400 exhibited improvements of around 5.08 %, 8.34 %, 5.96 % and 1.34 %, respectively, as compared to the sample that served as

the control. The remaining average values at various ages up to 90 days are presented in Table 5.

The compressive strength systematically increased when PEG-400 was used in concrete, obtaining optimum results for mix ID P-2 (i.e., PEG-400 is 1%). The enhancement of strength development in concrete at early stages may be attributed to the presence of hydroxyl and ether functional groups. These groups may play a role in promoting the establishment of an uninterrupted gel network (Younis *et al.* 2022). Moreover, the continuous hydration process of the mixture in subsequent phases, facilitated by the water supplied by the curing agent, leads to further enhancements in strength (Amin *et al.* 2021).

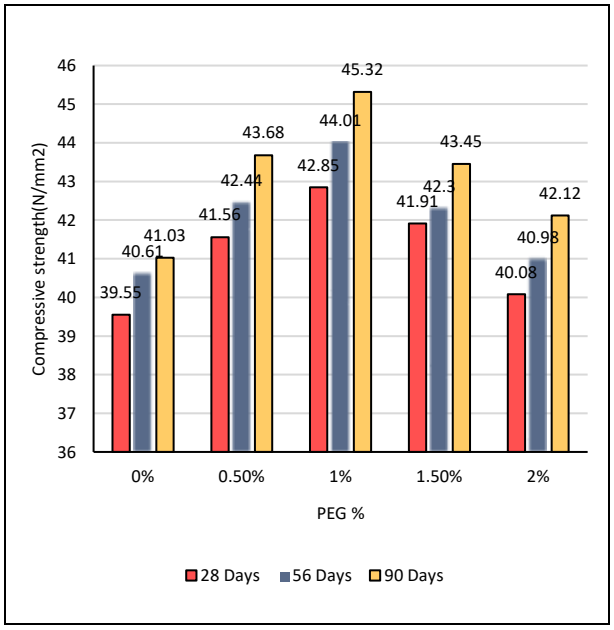


Fig. 5: Compressive Strength variation of concrete at various percentages of PEG-400

Table 6. Mean Compressive Strength of Concrete Cubes

Type of concrete	Mix id	PEG (1%) +CS (40%) +SCBA	Average Compressive Strength (N/mm^2)		
			28 days	56 days	90 days
Conventional Concrete	CC	0%	39.55	40.61	41.03
Self-Curing Concrete	PCSA-5	5%	45.82	47.97	49.93
	PCSA-10	10%	48.56	51.27	53.41
	PCSA-15	15%	49.42	52.56	54.78
	PCSA-20	20%	47.88	50.44	52.47

Using a mixture of 1% PEG-400, 40 % CS and various doses of SCBA, the compressive strength of the PCSA-1, PCSA-2, PCSA-3 and PCSA-4 mixes increased by approximately 15.85 %, 22.78 %, 24.95 % and 21.06 %, respectively. This indicated that the optimal doses of PEG-400, copper slag and SCBA in concrete were 5 %, 10 %, 15 % and 20 %, respectively, for a period of 28 days. Table 6 additionally presents the remaining mean values for various ages up to 90 days. The notable enhancement in compressive strength can be attributed to the properties of copper slag particles. Their high density, abrasive nature and compressibility enable the effective distribution of concentrated stress within the concrete matrix. Fig. 5 shows the compressive strength variation of concrete at various percentages of PEG-400

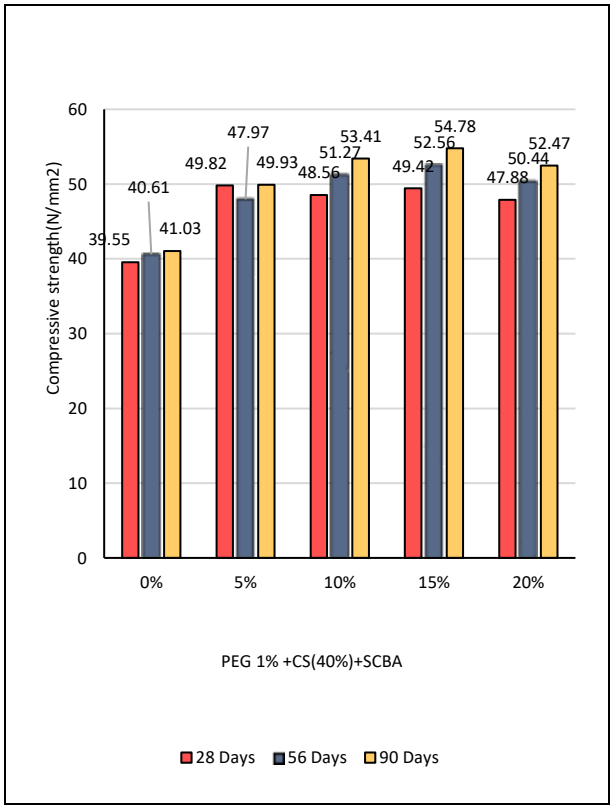


Fig. 6: Compressive Strength variation of concrete at various percentages of PCSA

Additionally, the sleek finish of the copper slag particles and their sharp edges strengthened the bond between the concrete matrix and concrete (Wang *et al.* 2021) and after 90 days, the same mixes showed improvements of approximately 21.69 %, 31.07 %, 33.51 % and 21.88 %, respectively. It was noted that the proportion of strength progressively increased at later ages, that is, 56 days and 90 days. The increase in strength after 90 days demonstrated that the pozzolanic hydration of SCBA gradually increased. Pozzolans shared the traits of having low strengths in early stages and developing higher strengths later. In contrast, the strong responsiveness of SCBA was shown in older age groups (Rajasekar *et al.* 2019; Quedou *et al.* 2021).Fig. 6 shows compressive strength variation of concrete at various percentages of PCSA

Table 7. Mean ST Tensile Strength of Concrete cylinders

Type of concrete	Mix id	% of PEG-400	Average ST tensile strength (N/mm²)		
			28 days	56 days	90 days
Conventional Concrete	CC	0%	3.39	3.46	3.51
Self-Curing Concrete	P-1	0.5%	3.54	3.59	3.64
	P-2	1%	3.66	3.70	3.77
	P-3	1.5%	3.61	3.65	3.71
	P-4	2%	3.49	3.54	3.62

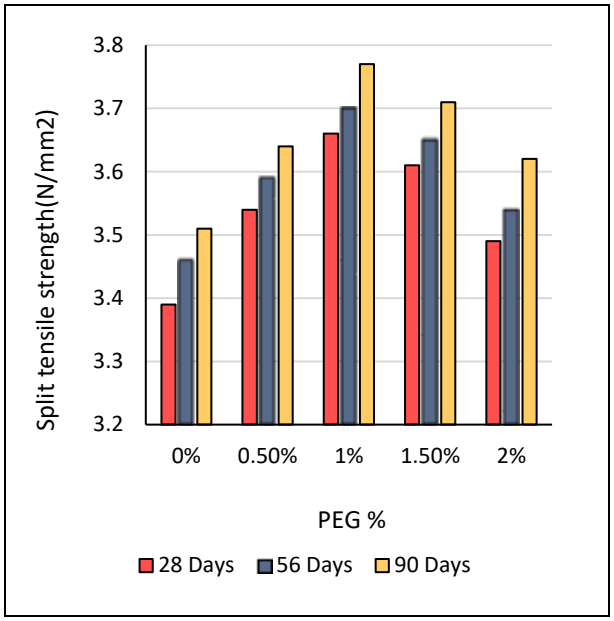


Fig. 7: Split Strength variation of concrete at various percentages of PEG-400

5.3 ST Tensile Strength

In comparison to regular concrete, the ST tensile strength was measured after adding varying dosages of PEG-400 additive to the concrete in ratios of 0.5 %, 1 %, 1.5 % and 2 %. Each dose % for the three samples was calculated and the average result was used to determine the final outcome, which is displayed in Table 7. At 28 days, the concrete mixture incorporating PEG-400 exhibited enhanced ST tensile strength relative to the control sample. Specifically, the additions of 0.5 %, 1 %, 1.5 % and 2 % PEG-400 resulted in strength improvements of roughly 4.42%, 7.96%, 6.48% and 2.31%, respectively. ST tensile strength systematically increases when PEG-400 is used in concrete; the highest tensile strength achieved is 3.66 MPa, which occurs with the P2 combination containing 1 % PEG. Fig. 7 shows the split strength variation of concrete at various percentages of PEG-400.

In contrast, the PCSA-1, PCSA-2, PCSA-3 and PCSA-4 mixes that included 1 % PEG, 40 % CS and varying amounts of SCBA had 15.63 %, 18.28 %, 23.30 % and 17.69 % ST tensile strengths higher than the CC mix (traditional mix), suggesting that the ideal doses of PEG-400, 40 % CS and SCBA incorporation into concrete were 5 %, 10 %, 15 % and 20 %, respectively, after 28 days. The sharp-edged character of CS particles may be the cause of the significant improvement in ST tensile strength that was seen in concrete mixtures that had CS replacement. It promotes cohesion within the concrete matrix, ultimately improving its tensile strength (Wang *et al.* 2021). Fig. 8 shows the split strength variation of concrete at various percentages of PCSA.

Table 8. Mean ST Tensile Strength of Concrete cylinders

Type of concrete	Mix id	PEG (1%) + CS (40%) + SCBA	Average ST tensile Strength (N/mm²)		
			28 days	56 days	90 days
Conventional Concrete	CC	0%	3.39	3.46	3.51
Self-Curing Concrete	PCSA-5	5%	3.92	4.00	4.06
	PCSA-10	10%	4.01	4.11	4.18
	PCSA-15	15%	4.18	4.24	4.29
	PCSA-20	20%	3.99	4.07	4.12

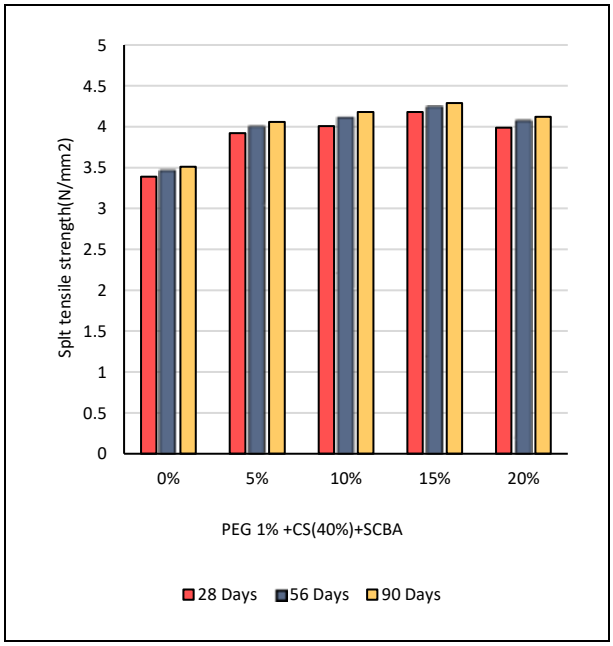


Fig. 8: Split Strength variation of concrete at various percentages of PCSA

Furthermore, the development of a strong link between the aggregate and the SCBA matrix may potentially enhance the concrete's tensile strength (Amin *et al.* 2021). Table 8 presents the remaining average values for various ages up to 90 days. Regarding the ST tensile strength, the PCSA-3 mix demonstrates significantly superior performance compared to other mixtures. The proportion of strength is seen to rise progressively at later ages, which were 56 and 90 days. Fig. 9-11 show the correlation between compressive strength and ST tensile strength at 28 days, 56 days and 90 days, respectively.

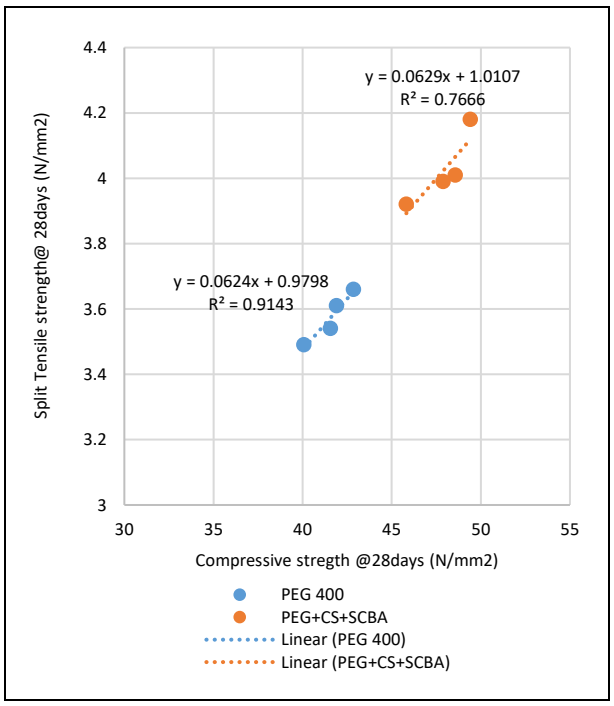


Fig. 9: Correlation between compressive strength and ST tensile strength at 28 days

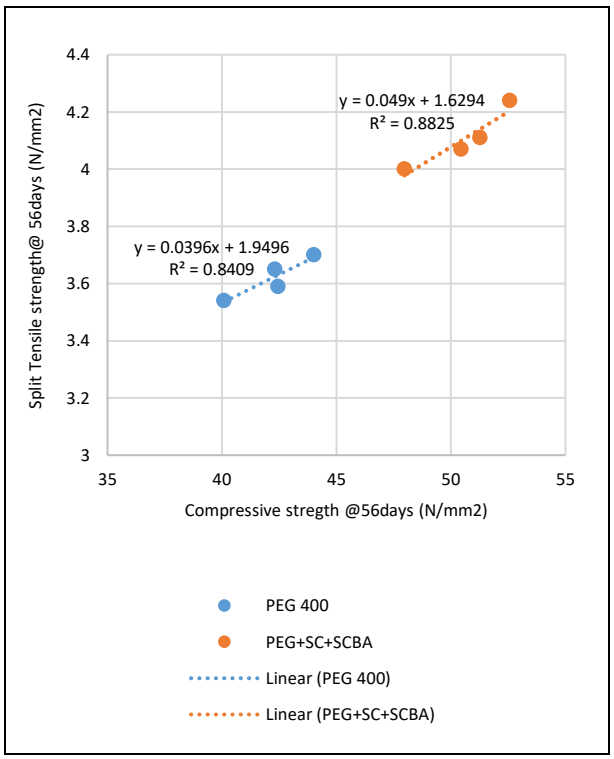


Fig. 10: Correlation between compressive strength and ST tensile strength at 56 days

5.4 Flexural Strength

Fig. 12 illustrates the flexural strength of self-curing concrete after 28 days, incorporating 1% PEG, 40% copper slag and various quantities of SCBA. The results demonstrate that, in contrast with the control mixture, the flexural strength of mixes PCSA-1, PCSA-2, PCSA-3 and PCSA-4 exhibited increases of 11.06%, 22.28%, 24.42% and 19.20%, respectively. Within the range of mixtures examined, PCSA-3 exhibits the highest flexural strength when compared to its other mechanical parameters, including compressive and ST tensile strength. This particular mixture consists of 1% PEG-400, 40% CS and 15% SCBA. The enhancement in flexural strength can be attributed to the C-S-H-driven hydration process, enabled by the significant quantity of silica in the SCBA. Additionally, this procedure enhanced the interfacial transition zone, which is the area where the cement paste and aggregate meet (Amin *et al.* 2022). Table 9 shows the average flexural; strength values.

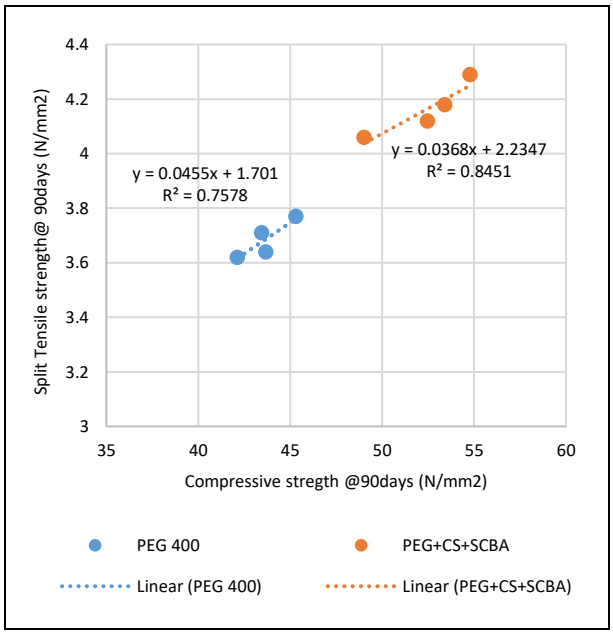


Fig. 11: Correlation between compressive strength and ST tensile strength at 90 days

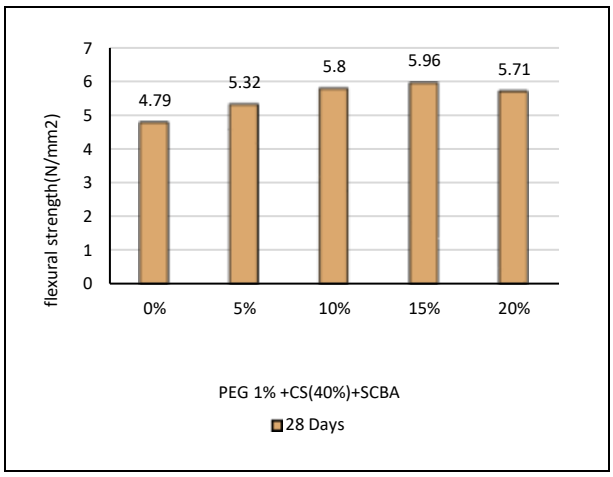


Fig. 12: Flexural Strength variation of concrete at various percentages of PCS

Table 9. Average flexural strength

Type of concrete	Mix id	PEG (1%) + S(40%) + SCBA	Average Flexural Strength (N/mm^2) 28 days
Conventional Concrete	CC	0%	4.79
Self-Curing Concrete	PCSA-5	5%	5.32
	PCSA-10	10%	5.80
	PCSA-15	15%	5.96
	PCSA-20	20%	5.71

6. CONCLUSION

The experimental study evaluated the performance of self-curing concrete using PEG-400, copper slag and SCBA. Results indicate that PEG-400 improved workability, with slump values increasing significantly, while the inclusion of CS and SCBA slightly reduced slump. An optimal dosage of 1% PEG-400 enhanced compressive strength by 8.34% at 28 days and 10.45% at 90 days compared to control concrete. The combination of 15% SCBA, 40% CS, and 1% PEG-400 yielded the highest compressive strength, showing increases of 24.95% at 28 days and 33.51% at 90 days. Similarly, split tensile strength improved, with an optimal increase of 23.30% over the control mix, achieving peak values at the same proportions. Flexural strength also showed a notable improvement of about 24.42%. Thus, a mix containing 1% PEG-400, 40% CS, and 15% SCBA provides the best mechanical performance among the tested combinations.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Ahmad, W., Ahmad, A., Ostrowski, K. A., Aslam, F., Joyklad, P. and Zajdel, P., Sustainable approach of using sugarcane bagasse ash in cement-based composites: A systematic review, *Case Stud. Constr. Mater.,* 15, e00698 (2021). https://doi.org/10.1016/j.cscm.2021.e00698

Ali, K. R., Gupta, C. and Alam, S., Strength and durability of self-curing concrete developed using calcium lignosulfonate, *J. King Saud Univ. - Eng. Sci.,* 34(8), 536–543 (2022). https://doi.org/10.1016/j.jksues.2021.02.002

Ameri, F., Shoaei, P., Reza Musaeei, H., Alireza Zareei, S. and Cheah, C. B., Partial replacement of copper slag with treated crumb rubber aggregates in alkali-activated slag mortar, *Constr. Build. Mater.,* 256, 119468 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119468

Amin, M., Attia, M. M., Agwa, I. S., Elsakhawy, Y., El-hassan, K. A. and Abdelsalam, B. A., Effects of sugarcane bagasse ash and nano eggshell powder on high-strength concrete properties, *Case Stud. Constr. Mater.,* 17, e01528 (2022). https://doi.org/10.1016/j.cscm.2022.e01528

Amin, M., Zeyad, A. M., Tayeh, B. A. and Saad Agwa, I., Engineering properties of self-cured normal and high strength concrete produced using polyethylene glycol and porous ceramic waste as coarse aggregate, *Constr. Build. Mater.,* 299, 124243 (2021). https://doi.org/10.1016/j.conbuildmat.2021.124243

Bashandy, A. A., Meleka, N. N. and Hamad, M. M., Comparative study on the using of PEG and PAM as curing agents for self-curing concrete, *Chall. J. Concr. Res. Lett.,* 8(1), 1 (2017). https://doi.org/10.20528/cjcrl.2017.01.001

Chaitanya, C., Prasad, P., Neeraja, D. and Ravitheja, A., Effect of LECA on mechanical properties of self-curing concrete, *Mater. Today Proc.,* 19, 484–488 (2019). https://doi.org/10.1016/j.matpr.2019.07.640

Channa, S. H., Mangi, S. A., Bheel, N., Soomro, F. A. and Khahro, S. H., Short-term analysis on the combined use of sugarcane bagasse ash and rice husk ash as supplementary cementitious material in concrete production, *Environ. Sci. Pollut. Res.,* 29(3), 3555–3564 (2022). https://doi.org/10.1007/s11356-021-15877-0

Colangelo, F., Roviello, G., Ricciotti, L., Ferone, C. and Cioffi, R., Preparation and Characterization of New Geopolymer-Epoxy Resin Hybrid Mortars, *Materials (Basel),* 6(7), 2989–3006 (2013). https://doi.org/10.3390/ma6072989

de A. Mello, L. C., S. dos Anjos, M. A., V. A. de Sá, M. V. and S. L. de Souza, N., de Farias, E. C., Effect of high temperatures on self-compacting concrete with high levels of sugarcane bagasse ash and metakaolin, *Constr. Build. Mater.*, 248, 118715 (2020). https://doi.org/10.1016/j.conbuildmat.2020.118715

Elwakkad, N. Y., Tayeh, B. A., Hekal, G. M. and Heiza, K. M., Experimental and numerical investigation of the behavior of self-curing R.C. flat slabs, *Case Stud. Constr. Mater.,* 17, e01457 (2022). https://doi.org/10.1016/j.cscm.2022.e01457

Farrant, W. E., Babafemi, A. J., Kolawole, J. T. and Panda, B., Influence of Sugarcane Bagasse Ash and Silica Fume on the Mechanical and Durability Properties of Concrete, *Materials (Basel),* 15(9), 3018 (2022). https://doi.org/10.3390/ma15093018

Jha, P., Sachan, A. K. and Singh, R. P., Agro-waste sugarcane bagasse ash (ScBA) as partial replacement of binder material in concrete, *Mater. Today Proc.,* 44, 419–427 (2021). https://doi.org/10.1016/j.matpr.2020.09.751

Joshaghani, A. and Moeini, M. A., Evaluating the effects of sugar cane bagasse ash (SCBA) and nanosilica on the mechanical and durability properties of mortar, *Constr. Build. Mater.,* 152, 818–831 (2017). https://doi.org/10.1016/j.conbuildmat.2017.07.041

Kamal, M. M., Safan, M. A., Bashandy, A. A. and Khalil, A. M., Experimental investigation on the behavior of normal strength and high strength self-curing self-compacting concrete, *J. Build. Eng.,* 16, 79–93 (2018). https://doi.org/10.1016/j.jobe.2017.12.012

Khawaja, S. A., Javed, U., Zafar, T., Riaz, M., Zafar, M. S. and Khan, M. K., Eco-friendly incorporation of sugarcane bagasse ash as partial replacement of sand in foam concrete, *Clean. Eng. Technol.,* 4, 100164 (2021). https://doi.org/10.1016/j.clet.2021.100164

Lemougna, P. N., Yliniemi, J., Adesanya, E., Tanskanen, P., Kinnunen, P., Roning, J. and Illikainen, M., Reuse of copper slag in high-strength building ceramics containing spodumene tailings as fluxing agent, *Miner. Eng.,* 155, 106448 (2020). https://doi.org/10.1016/j.mineng.2020.106448

Lokeshwari, M., Pavan Bandakli, B. R., Tarun, S. R., Sachin, P. and Kumar, V., A review on self-curing concrete, *Mater. Today Proc.,* 43, 2259–2264 (2021). https://doi.org/10.1016/j.matpr.2020.12.859

Madduru, S. R. C., Shaik, K. S., Velivela, R. and Karri, V. K., Hydrophilic and hydrophobic chemicals as self curing agents in self compacting concrete, *J. Build. Eng.,* 28, 101008 (2020). https://doi.org/10.1016/j.jobe.2019.101008

Maharishi, A., Singh, S. P. and Gupta, L. K., Shehnazdeep, Strength and durability studies on slag cement concrete made with copper slag as fine aggregates, *Mater. Today Proc.,* 38, 2639–2648 (2021). https://doi.org/10.1016/j.matpr.2020.08.232

Malathy, R. and Chung, I.-M., Prabakaran, M., Characteristics of fly ash based concrete prepared with bio admixtures as internal curing agents, *Constr. Build. Mater.,* 262, 120596 (2020). https://doi.org/10.1016/j.conbuildmat.2020.120596

Manjunatha, M., Reshma, T. V., Balaji, K. V. G. D., Bharath, A. and Tangadagi, R. B., The sustainable use of waste copper slag in concrete: An experimental research, *Mater. Today Proc.,* 47, 3645–3653 (2021). https://doi.org/10.1016/j.matpr.2021.01.261

Mousa, M. I., Mahdy, M. G., Abdel-Reheem, A. H. and Yehia, A. Z., Self-curing concrete types; water retention and durability, *Alexandria Eng. J.,* 54(3), 565–575 (2015). https://doi.org/10.1016/j.aej.2015.03.027

Panda, S. and Sarkar, P., Leaching behavior of copper slag aggregate cement-mortar by atomic absorption spectroscopy (AAS), *Mater. Today Proc.,* 33, 5123–5129 (2020). https://doi.org/10.1016/j.matpr.2020.02.856

Phiri, T. C., Singh, P. and Nikoloski, A. N., The potential for copper slag waste as a resource for a circular economy: A review – Part II, *Miner. Eng.*, 172, 107150 (2021). https://doi.org/10.1016/j.mineng.2021.107150

Quedou, P. G., Wirquin, E. and Bokhoree, C., Sustainable concrete: Potency of sugarcane bagasse ash as a cementitious material in the construction industry, *Case Stud. Constr. Mater.,* 14, e00545 (2021). https://doi.org/10.1016/j.cscm.2021.e00545

Rahimi, M. Z., Zhao, R., Sadozai, S., Zhu, F., Ji, N. and Xu, L., Research on the influence of curing strategies on the compressive strength and hardening behaviour of concrete prepared with Ordinary Portland Cement, *Case Stud. Constr. Mater.,* 18, e02045 (2023). https://doi.org/10.1016/j.cscm.2023.e02045

Rajasekar, A., Arunachalam, K. and Kottaisamy, M., Assessment of strength and durability characteristics of copper slag incorporated ultra high strength concrete, *J. Clean. Prod.,* 208, 402–414 (2019). https://doi.org/10.1016/j.jclepro.2018.10.118

Rajasekar, A., Arunachalam, K., Kottaisamy, M. and Saraswathy, V., Durability characteristics of Ultra High Strength Concrete with treated sugarcane bagasse ash, *Constr. Build. Mater.,* 171, 350–356 (2018). https://doi.org/10.1016/j.conbuildmat.2018.03.140

Ramakrishnan, K., Ganesh, V., Vignesh, G., Vignesh, M., Shriram, V. and Suryaprakash, R., Mechanical and durability properties of concrete with partial replacement of fine aggregate by sugarcane bagasse ash (SCBA), *Mater. Today Proc.,* 42, 1070–1076 (2021). https://doi.org/10.1016/j.matpr.2020.12.172

Rekha, S. and Jagadheeswari, Arunprasath, Sumathy, Durability properties of copper slag and fly ash based concrete for a sustainable environment, *Mater. Today Proc.,* 37, 2535–2541 (2021). https://doi.org/10.1016/j.matpr.2020.08.490

Rizzuto, J. P., Kamal, M., Elsayad, H., Bashandy, A., Etman, Z., Aboel Roos, M. N. and Shaaban, I. G., Effect of self-curing admixture on concrete properties in hot climate conditions, *Constr. Build. Mater.,* 261, 119933 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119933

Sambangi, A., E., A., Fresh and mechanical properties of SCC with fly ash and copper slag as mineral admixtures, *Mater. Today Proc.,* 45, 6687–6693 (2021). https://doi.org/10.1016/j.matpr.2020.12.144

Sandra, N., Kawaai, K. and Ujike, I., Effect of copper slag fine aggregate on corrosion processes and behavior in reinforced concrete prism specimen, *Constr. Build. Mater.,* 271, 121909 (2021). https://doi.org/10.1016/j.conbuildmat.2020.121909

Sharma, R. and Khan, R. A., Sulfate resistance of self compacting concrete incorporating copper slag as fine aggregates with mineral admixtures, *Constr. Build. Mater.,* 287, 122985 (2021). https://doi.org/10.1016/j.conbuildmat.2021.122985

Shi, J., Tan, J., Liu, B., Chen, J., Dai, J. and He, Z., Experimental study on full-volume slag alkali-activated mortars: Air-cooled blast furnace slag versus machine-made sand as fine aggregates, *J. Hazard. Mater.,* 403, 123983 (2021). https://doi.org/10.1016/j.jhazmat.2020.123983

Shravan, K. A., Gopi, R. and Murali, K., Comparative studies on conventional concrete and self-curing concrete, *Mater. Today Proc.,* 46, 8790–8794 (2021). https://doi.org/10.1016/j.matpr.2021.04.149

Siddique, R., Singh, M. and Jain, M., Recycling copper slag in steel fibre concrete for sustainable construction, *J. Clean. Prod.,* 271, 122559 (2020). https://doi.org/10.1016/j.jclepro.2020.122559

Singh, K., Mechanical properties of self curing concrete studied using polyethylene glycol-400: A-review, *Mater. Today Proc.,* 37, 2864–2871 (2021). https://doi.org/10.1016/j.matpr.2020.08.662

Sivasakthi, M., Jeyalakshmi, R. and Rajamane, N. P., Fly ash geopolymer mortar: Impact of the substitution of river sand by copper slag as a fine aggregate on its thermal resistance properties, *J. Clean. Prod.,* 279, 123766 (2021). https://doi.org/10.1016/j.jclepro.2020.123766

Sridharan, M. and Madhavi, T. C., Investigating the influence of copper slag on the mechanical behaviour of concrete, *Mater. Today Proc.,* 46, 3225–3232 (2021). https://doi.org/10.1016/j.matpr.2020.11.195

Usha Kranti, J., Naga Sai, A., Rama Krishna, A. and Srinivasu, K., An experimental investigation on effect of durability on strength properties of M40 grade concrete with partial replacement of sand with copper slag, *Mater. Today Proc.,* 43, 1626–1633 (2021). https://doi.org/10.1016/j.matpr.2020.09.767

Wang, R., Shi, Q., Li, Y., Cao, Z. and Si, Z., A critical review on the use of copper slag (CS) as a substitute constituent in concrete, *Constr. Build. Mater.,* 292, 123371 (2021). https://doi.org/10.1016/j.conbuildmat.2021.123371

Wu, W., Zhang, W. and Ma, G., Mechanical properties of copper slag reinforced concrete under dynamic compression, *Constr. Build. Mater.,* 24(6), 910–917 (2010). https://doi.org/10.1016/j.conbuildmat.2009.12.001

Younis, M. O., Amin, M. and Tahwia, A. M., Durability and mechanical characteristics of sustainable self-curing concrete utilizing crushed ceramic and brick wastes, *Case Stud. Constr. Mater.,* 17, e01251 (2022). https://doi.org/10.1016/j.cscm.2022.e01251

Zareei, S. A. and Ameri, F., Bahrami, N., Microstructure, strength and durability of eco-friendly concretes containing sugarcane bagasse ash, *Constr. Build. Mater.,* 184, 258–268 (2018). https://doi.org/10.1016/j.conbuildmat.2018.06.153

Zeyad, A. M., Shubaili, M. and Abutaleb, A., Using volcanic pumice dust to produce high-strength self-curing concrete in hot weather regions, *Case Stud. Constr. Mater.,* 18, e01927 (2023). https://doi.org/10.1016/j.cscm.2023.e01927