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. It has been observed that proper curing forms an important step in enhancing the strength and durability of concrete, which has been found to exert a significant influence on its overall development. A study on the structural properties of self-curing concrete is discussed in the following research article. SCBA and 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 is based on the discussion of the properties of the new concrete mixture. The study looks into how the components will influence 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, copper slag (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% sugarcane bagasse ash (SCBA) in self-curing concrete, which contains 1% PEG-400. Investigations were conducted to prove the possibility of self-curing concrete admixed with CS and SCBA. Slump cone, compressive, split tensile and flexural strengths are explored during these tests.

Keywords: Self-curing concrete; PEG-400; Copper slag (CS); Sugarcane bagasse ash (SCBA).

1. INTRODUCTION

The need for construction is always growing owing to the recent rapid population development, with concrete, the most widely used building material globally, being preferred (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 highly used natural resource in the building 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. The most common material used today, concrete, needs a significant amount of water and any size construction project cannot ignore this need. It is important to use strategies that reduce reliance on water during construction. Water is becoming scarcer due to the increased demand for it worldwide. We urgently need to find ways to reduce the amount of water we use. For every cubic metre of concrete, roughly 3.0 cubic metres are required for construction purposes, with the majority being water used in 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 a large amount of water to remain moist, the degree of hydration depends on its moisture content (Ali *et al.* 2022). To maintain a relative humidity of 80%, moisture must be present continuously. The hydration ceases in the capillaries if the relative humidity falls below 80%. During typical curing, external water application keeps the relative humidity (R.H.) 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. Since water is a resource that is used to its fullest, the water table is gradually declining. The expense of construction projects rises considerably when water must be sourced (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 and involve the application of water or covering concrete surfaces with plastic sheets or wet burlap. Thus, several researchers have been interested in creating self-curing concrete (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). According to several studies, 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, which had a thickness of approximately 2 nm, developed on each water particle found in the concrete. Concrete prevents water from evaporating owing to the formation of such shells. This resulted in a decrease in the evaporation rate, ensuring that water was 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 utilised 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 utilisation of copper slag (CS), a previously discarded waste material (Manjunatha *et al.* 2021). During the process of extracting metals from copper concentrates using pyrometallurgy, a by-product that is known as copper slag is produced. This material is considered to be a waste product of this process (Phiri *et al.* 2021). The production of one tonne of copper results in the formation of two to three tonnes 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 utilisation 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. Numerous research studies demonstrate 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 recognised 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 additional cementing materials (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). Many studies have established by a great number of researchers that 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, 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 useable 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). SCBA has been shown to contain a larger proportion of silicon dioxide (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

It is necessary to have cement in order to construct anything that has to do with the building. Cement is an essential component. When water is added to cement, it solidifies and acts as an adhesive when mixed with fine and coarse aggregates. Cement is an essential component of the mixture that is used to make concrete because it serves to bind the aggregates together and fill up the spaces that exist between them. The cement had a consistent color, described as grayish with a mild greenish hue and it did not include any hard lumps throughout its entirety. 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. The aggregates contribute to roughly seventy percent of concrete's overall 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 millimetres are classified as fine, whilst those exceeding 4.75 millimetres are considered coarse. The distinction is based on the aggregate's capacity to either pass through or be held by a sieve of this particular size. A void area of thirty to forty percent 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 particular operation, coarse aggregates that were readily available in the area and had a maximum size of twenty millimeters 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. Whilst excessive water in concrete may lead to separation, it is best to add water in small quantities. 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. The water utilized in this operation fulfills the standards for concreting, as per IS: 456-2000.

2.4 Superplasticizer

This study utilises the 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)

For the purpose of this undertaking, the self-curing agent that will be utilized is polyethylene glycol (PEG), which is a material that is very hydrophilic (Rizzuto *et al.* 2020) and has a molecular weight of 400. 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 served as a plasticising agent in concrete mixtures, adhesive compounds, binding materials and soldering flux formulations, improving their fluidity and ease of manipulation. In addition, it was utilized as a water-retention agent. PEG-400 was also utilized as an accurate distribution property (Colangelo *et al.* 2013). The chemical compound polyethylene glycol is distinguished by a number suffix consisting of groups that have determined average molecular weights. PEG's molecular mass can vary from 300 g/mol to 1 × 1078 g/mol (Colangelo *et al.* 2013). Regarding the curing agents, the main attributes of polyethylene glycol (PEG-400) were described by manufacturer and are presented in Table 1.

2.6 Copper Slag

For the purpose of this project, copper slag was obtained from Sterlite Industries Ltd. (SIL), which is located in 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 percent of the available resources (Sivasakthi *et al.* 2021). Comparable gradations of copper slag and sand met Zone II of the grading criteria. It was discovered that there was approximately 26% silica in the copper slag, which is favorable because silica is a component of fine natural aggregates that are often utilized in concrete processes (Wu *et al.* 2010). Figure 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

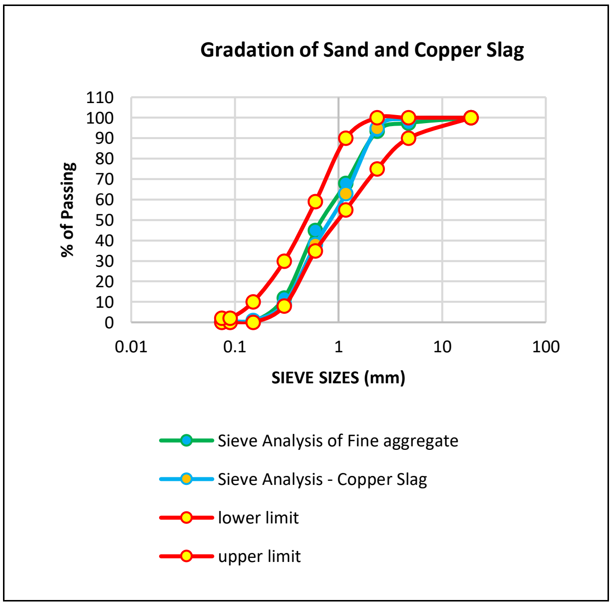

Fig. 1: Gradation comparison of copper slag and fine aggregate

2.7 SCBA

The composition of sugarcane bagasse ash (SCBA) consists of roughly 50% cellulose, with the remaining half equally divided between hemicellulose and lignin, each accounting for about 25%. Moisture contents of 50 percent and 0.62% of the residual ash are produced by each ton of sugarcane, which results in around twenty-six percent bagasse. SiO_2 is the primary component of the chemical makeup of the remaining ash, which is mostly composed of silicon dioxide (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 utilise 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). Figure 2 illustrates a comparative analysis of the chemical compositions between cement and SCBA, which was utilized as a cement substitute. Their properties are presented in Table 2.

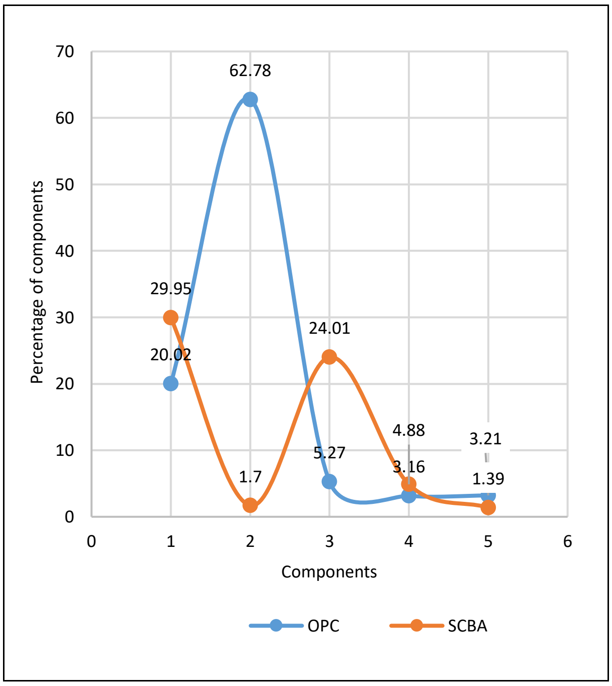

Fig. 2: Chemical composition of SCBA and OPC

3. MIX PROPORTION

Concrete mix design is a process for selecting suitable concrete ingredients: the cement, the aggregates and water and the relationship in which they should be proportioned to develop the economical concrete mix at minimum requirements on strength, workability and durability. The purpose is to achieve the optimal balance of all these properties considering economic factors. It was to be made of nine mixes, one of the regular mixes (CC). 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% has been utilized in place of fine aggregate as constant condition maintained as per earlier research (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 by incorporating SCBA with variation of 5% to 20%. All other parameters remained unchanged for comparison purposes with the control mixture: quantity of water, cement and plasticizer used.

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 the slump test. Figure 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. 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

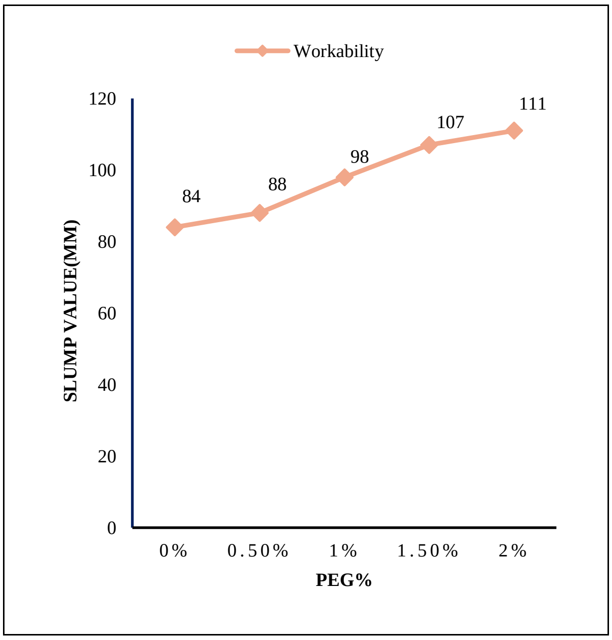

Fig. 3: Workability of concrete at various percentages of PEG-400

On the other hand, the slump value reached its highest point at mix id PCSA-5 and when compared to the CC mix, the slump value rose by 25% at PCSA-5, 16.66% at PCSA-10, 10.71% at PCSA-15 and 4.76% at 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).

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

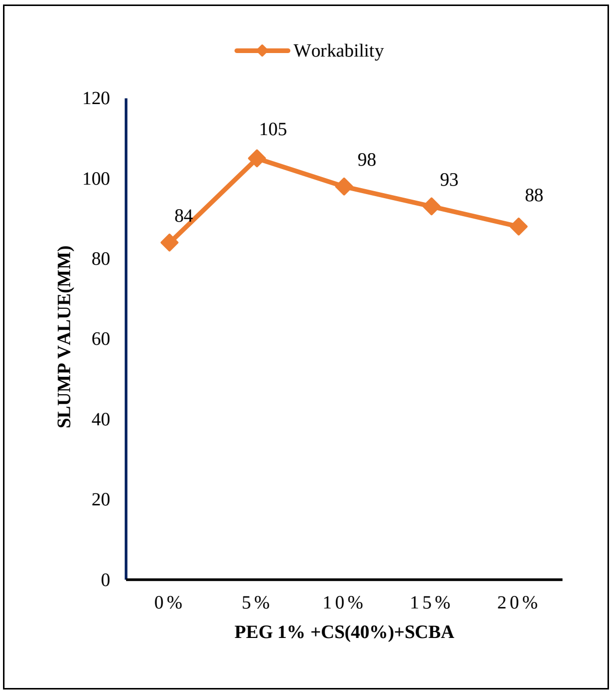

Fig. 4: Workability of concrete at various percentages of PCSA

5.2 Compressive Strength

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.

Table 5. Mean compressive strength of concrete cubes

Type of concrete	Mix id	% of PEG-400	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	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

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).

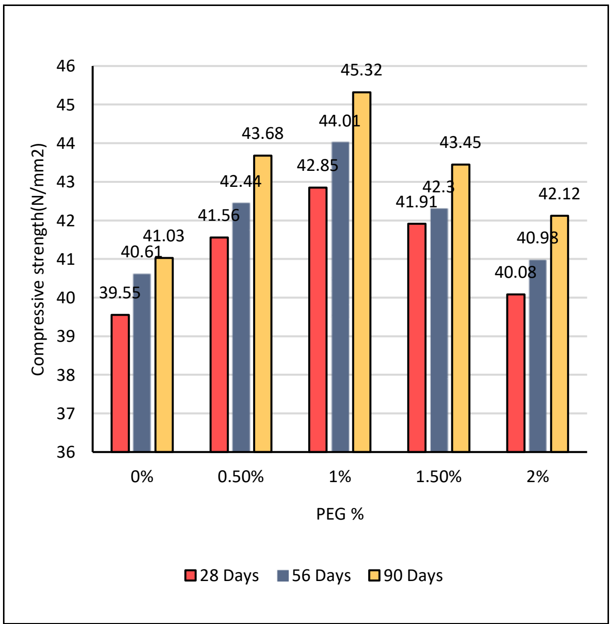

Fig. 5: Compressive Strength variation of concrete at various percentages of PEG-400

Using a mixture of 1% PEG-400, 40% copper slag and various dosages 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

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

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.

Table 6. Mean Compressive Strength of Concrete Cubes

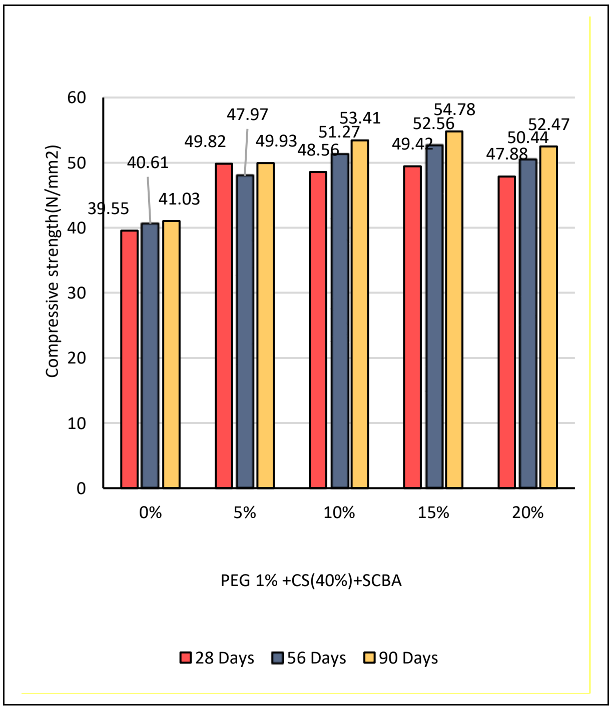

Fig. 6: Compressive Strength variation of concrete at various percentages of PCSA

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 SCBA's pozzolanic hydration of SCBA gradually increased. Pozzolans shared the traits of having low early strengths and developing later strengths. In contrast, the strong responsiveness of SCBA was shown in older age groups (Rajasekar *et al.* 2019; Quedou *et al.* 2021).

Table 7. Mean ST Tensile Strength of Concrete cylinders

Type of concrete	Mix id	% of PEG-400	Average ST tensile strength (N/mm^2)		
			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

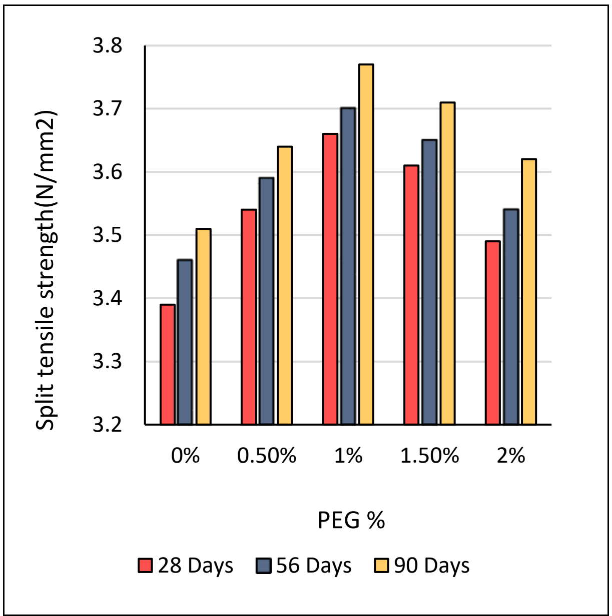

Fig. 7: Split Strength variation of concrete at various percentages of PEG-400

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%. Next, 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. Table 10 displays the remaining average values at various ages up to 90 days. 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.

In contrast, the PCSA-1, PCSA-2, PCSA-3 and PCSA-4 mixes that included 1% PEG, 40% Copper slag and varying amounts of SCBA had ST tensile strengths that were 15.63%, 18.28%, 23.30% and 17.69% higher than the CC mix (traditional mix), suggesting that the ideal doses of PEG-400, 40% Copper slag 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.

Table 8. Mean ST Tensile Strength of Concrete cylinders

Type of concrete	Mix id	PEG (1%) + CS (40%) + SCBA	Average ST tensile Strength (N/mm^2)		
			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

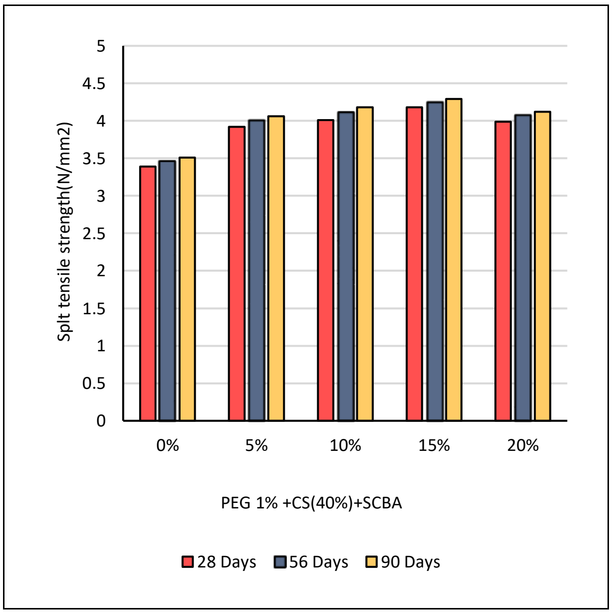

Fig. 8: Split Strength variation of concrete at various percentages of PCSA

This shape promotes cohesion within the concrete matrix, ultimately improving its tensile strength (Wang *et al.* 2021). 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.

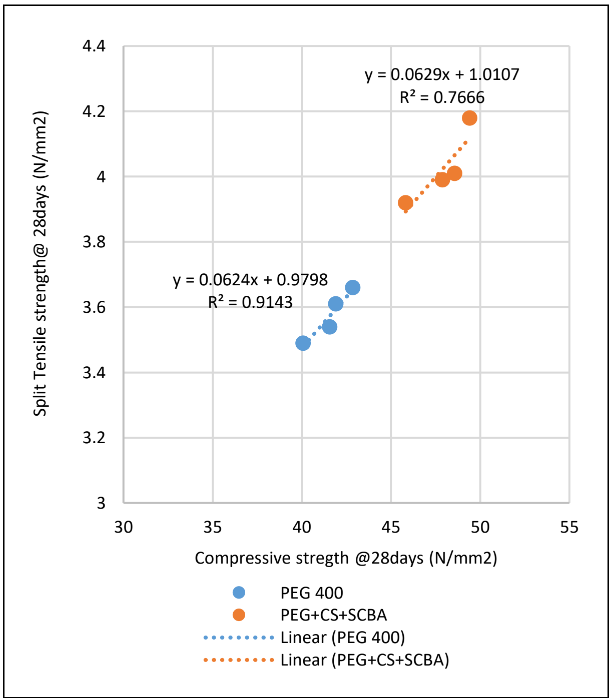

Fig. 9: Correlation between compressive strength and ST tensile strength at 28 days

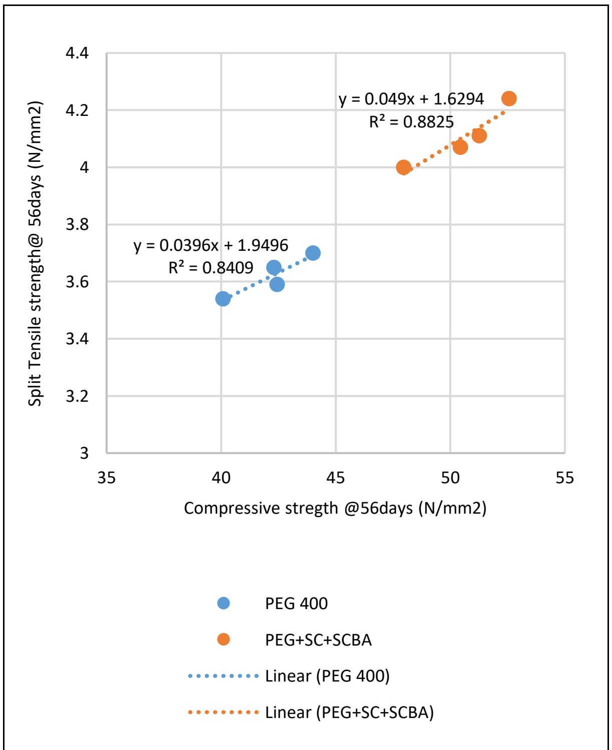

Fig. 10: Correlation between compressive strength and ST tensile strength at 56 days

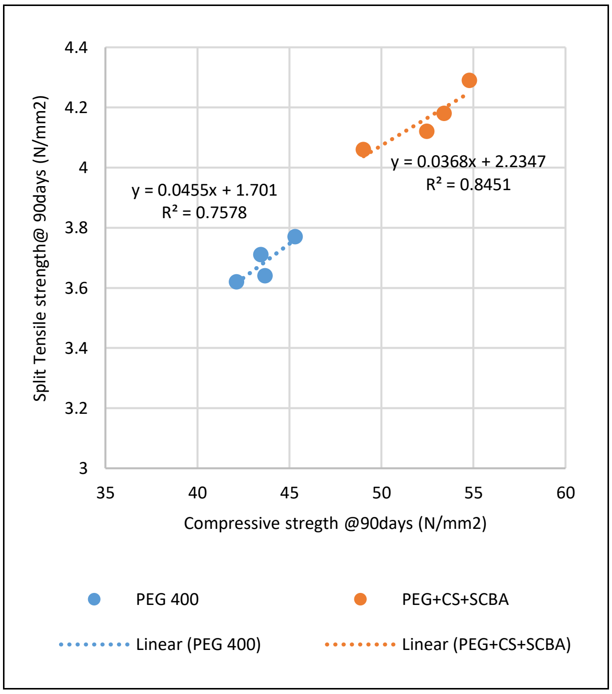

Fig. 11: Correlation between compressive strength and ST tensile strength at 90 days

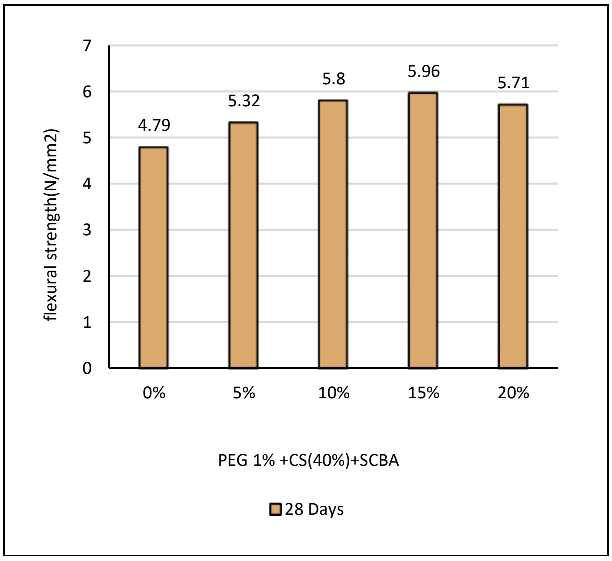

Fig. 12: Flexural Strength variation of concrete at various percentages of PCS

5.4 Flexural Strength

Figure 12 illustrates the flexural strengths 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 strengths 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% Copper slag 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 ITZ, or interfacial transition zone, which is the area where the cement paste and aggregate meet (Amin *et al.* 2022).

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

An experimental program has been designed to study the performance characteristics of two different sets of self-curing concretes. The first set of concretes included control concrete and concrete with different doses of PEG-400, 0.5%, 1%, 1.5% and 2% by cement weight, respectively. For the second batch of concrete, the optimal proportion of PEG-400 was 1% and copper slag as 40% in place of sand and different percentages of SCBA were used instead of cement.

The following were concluded:

1. The workability of fresh concrete was improved by more use of PEG-400, a self-curing agent; the slump values increased from 84 to 111 mm. The slump values of the self-curing concrete decreased from 105 to 88 mm when the dosages of copper slag added with appropriate percentages of SCBA were used for the optimal PEG-400 mix. Slump values of the concrete were impacted by the dosage range of SCBA from 5 to 20%.

2. A self-curing agent in the form of PEG-400 was added to the concrete mix with a view to ensuring the right compressive strength. The addition of 1% PEG-400 resulted in an increase of about 8.34% at 28 days and 10.45% at 90 days over the CC samples. The dose was adequate.

3. The reference mix (CC) had the percentage optimum copper slag and cement replaced by SCBA at 15% in place of ideal PEG-400, thus compressive strength increased by 24.95%. The maximum compressive strength of 49.42 MPa was obtained at 28 days for a mixture containing SCBA (15%), copper slag (40%) and 1% PEG.

4. Furthermore, the maximum compression strength of the mixes after 90 days was 54.78 MPa, which is 33.51% greater than the capacity of the reference mix (CC).

5. The research suggests that the most effective concentration of 1% PEG-400 is determined by the 7.96% enhancement in split tensile strength observed after 28 days when compared with control concrete specimens.

6. In comparison to the control mixture (CC), the addition of 1% PEG-400, 40% copper slag and different amounts of SCBA led to a 23.30% improvement in the ST tensile strength of the concrete. The optimal split tensile strength values of 4.18 MPa and 4.29 MPa were achieved at 28 days and 90 days, respectively, using a mixture of 15% SCBA, 40% copper slag and 1% PEG-400.

7. Partial replacement of the cement with SCBA at 15%, copper slag with a total percentage of 40% in sand and 1% PEG-400 along with the control concrete (CC) showed around 24.42% increase in flexural strength. When the percentages were 15% SCBA, 40% copper slag and 1% PEG-400, the maximum flexural strength at 28 days was obtained as 5.96 MPa.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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