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Research Article

Performance evaluation of sustainable self-curing concrete with GGBS and rice husk ash

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Abstract

In recent decades, rapid urbanization has increased the demand for high-rise construction and the continuous growth in population, the demand for water has significantly increased, leading to scarcity of water resources in construction, that leads to challenges for conventional curing practices in construction. However, extensive cement consumption contributes significantly to environmental degradation. To reduce this impact industrial and agricultural wastes are used as partial replacement. Furthermore, strength development is not possible without proper curing; hence, self-curing chemicals are used to guarantee that internal moisture is retained. The performance of self-curing concrete of M30 grade containing 30% Ground Granulated Blast Furnace Slag (GGBS), 10% Rice Husk Ash (RHA), and PEG-400 as an self-curing agent is examined in this research. Concrete specimens are evaluated for mechanical properties at different curing ages. The results show that the optimum dosage of 1% PEG-400 achieved a compressive strength of 40 N/mm^2 at 90 days along with improved tensile and flexural performance. An examination of the matrix's microstructure showed that it was denser, had better C-S-H formation, and had finer pore structure. Reduce cement use by 40% to help the environment.

1. Introduction

The strength and adaptability of concrete make it a top choice for building infrastructure. Concrete consists of cement, fine aggregate,coarse aggregate and water. However, cement production has a significant environmental impact as it releases large amounts of CO_2 into the atmosphere. To reduce this issue partial replacement of cement with industrial and agricultural by-products has gained attention as a sustainable solution, Additionally, proper curing is important for the strength development of concrete, it ensures adequate moisture for continuous hydration. However, in many construction scenarios, especially in water-scarce regions, maintaining effective curing conditions is challenging. This study focuses on developing alternative methods for cement and achieve the desired strength without depending on external curing of concrete. Previous studies indicate that GGBS is a by-product that makes concrete stronger and lasts longer by changing the way its parts are arranged within. It interacts with cement compounds to form a denser matrix, which makes it harder for water and chemicals to get through. The best protection against acids and chlorides, providing 10-15% higher resistance, was found when 30% GGBS was used in place of cement, according to the research. Using GGBS makes concrete last longer and be better for the environment [1]. This study reveals that replacing 10-30% cement with Selangor Rice Husk Ash

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markedly enhances Grade 30 concrete durability, reducing permeability, water absorption, and chloride ingress, confirming RHA's sustainability potential [2]. Concrete with 5-30% RHA as a Partial substitution of cement exhibits improved fresh, strength, properties. Finer RHA particles facilitate processing and boost pozzolanic activity, generating additional C-S-H gel for enhanced performance. Optimal incorporation of RHA addition lies within the range of 10% to 20%, which imparts improved resistance against water, chloride, and sulfate attacks. In addition to enhanced strength and higher density, RHA imparts better sustainability to concrete through the utilization of agricultural waste [3]. The use of particular agents, such as PEG inside the matrix, allows self-curing concrete to retain internal moisture, making it a form of durable concrete. PEG keeps concrete moistened and strong due to the absence of external addition of water inside the concrete for maintenance of hydration [4]. The admixture based on PEG generates hydrogen bonds with water molecules, which reduces evaporation and enhances hydration effectiveness overall. It lessens the likelihood of fracture formation and increases the material's durability. Studies have shown that 40-60% GGBS for cement, the strength of M20 concrete was increased by 10-15% with the addition of 0.5-1.0% PEG-400. Chemical durability was improved because of the pozzolanic and latent hydraulic reactivity of GGBS, leading to a denser and less permeable microstructure [5]. Incorporation of additional cementitious materials such as GGBS and RHA further improves the microstructure of SCC by inducing pozzolanic reactions and forming more C-S-H gel. The high concentration of amorphous silica in RHA increases the production of C-S-H when combined with calcium hydroxide, $Ca(OH)_2$. This improves the pore structure and, in turn, increases the strength of the concrete matrix, as shown by [6]. GGBS provides improved chemical resistance and pore refinement, while RHA provides the material with fine reactive silica, which enhances further impermeable and long-lasting ability. Thus, the incorporation of PEG along with mineral admixtures results in a denser, less permeable, and more resistant matrix to chemical and chloride aggressiveness [7]. Due to the lack of readily available water, proper curing cannot take place in dry places, resulting in inadequate hydration and decreased durability. Cures on Its Own Concrete Newly developed self-curing concrete offers an innovative approach to addressing this issue. The internal feeding is provided by water-retaining compounds like propylene glycol (PG) and polyethylene glycol (PEG) rather than by external cures [8].

Water retention in self-curing systems based on PEG is a result of hydrogen bonding with water molecules, which inhibits water loss by slowing down the rate of evaporation. the addition of RHA to PEG at 10–20% increased water retention by up to 12%, while it reduced capillary porosity, thus enhancing resistance to chemicals and durability [9]. Experimental studies on self-curing concrete using propylene glycol showed that compressive strength improved by 13–18% at a 1.5% PG dose for M30 concrete after 28 days [10]. Concrete with 25–50% treated desert sand achieved enhanced compressive strength (up to 55.45 MPa) and reduced water absorption (3.59%), confirming TDS as a sustainable, high-performance aggregate [11]. Focusing on the confinement effect and structural engineering efficiency, this investigation examines the behavior of concrete filled steel tube stub columns subjected to axial loading. The study highlights that confinement significantly enhances strength and durability by improving stress distribution within the concrete core. In relation to the present study these findings emphasize the importance of internal structure and material interaction, which is similarly achieved through the use of GGBS, RHA and self-curing agents to enhance concrete [12]. Sophisticated models of ensemble neural networks for the detection of failure modes in flat slabs of reinforced concrete. The study demonstrated that machine learning techniques can accurately predict structural behaviour and failure patterns, understand crack development and failure behaviour is essential and similar insight are considered through experimental evaluation of flexure response and performance of self-curing concrete [13]. Few studies have examined the combined impact of GGBS, RHA, and PEG on self-curing concrete performance, despite many investigations into their separate effects. For example, there hasn't been nearly enough research on how GGBS, RHA and PEG 400 interact in self-curing circumstances. This study aims to investigate: to find out how these materials affect the mechanical properties and microstructural features of self-curing concrete. This research presents a revolutionary approach to concrete by using chemical self-curing agents in conjunction with industrial and agricultural waste materials. The result is a sustainable and practical solution. Furthermore, prior research indicates that a replacement level of 30% GGBS and 10% RHA is the most effective, outperforming other proportions. Similarly, the PEG 400 dosage range of 0-1.5% was adopted based on the literature. These solutions contribute to hydration, making the microstructure denser; they improve mechanical properties with lower water consumption and lower CO_2 emission. Thereby, self-curing concrete is an encouraging development toward more environmentally friendly and long-lasting construction.

2. Materials and Methods

2.1 Cement

Cement serves as a fundamental binding material in construction, crucial for ensuring structural stability. During hydration, it hardens and functions as a bonding agent when mixed with fine and coarse aggregates, resulting in concrete. The binder sample exhibited a faint greenish hue and was free from hard lumps. It was evaluated as per Indian Standards IS 12269:2013, confirming compliance with prescribed quality requirements for construction applications. The cement's qualities are shown in Table 1.

Table 1. Measured properties of cement as per laboratory tests

Color	Grey
Specific gravity	3.14
Bulk density	1451 Kg/m^3
Fineness	329 g/cm^2
Density	3.276 g/cm^3

2.2 Aggregate

The aggregates that make up the bulk of concrete are both inexpensive and essential in establishing the material's mechanical strength and longevity. For around 70% of concrete's total strength, you may thank the mixture of coarse and tiny particles called aggregates. These particles exist in nature. The weathering of rocks produces natural aggregates, while the crushing of rocks produces artificial aggregates. Based on their capacity to flow through or be held by a 4.75 mm sieve, aggregates less than 4.75 mm are deemed fine, while those bigger than 4.75 mm are categorized as coarse, according to standard categorization. The placement of coarse aggregates in concrete creates voids, typically occupying 30–40% of the volume. These voids are filled by fine aggregates, and the remaining interstices are occupied by cement particles, ensuring a dense and cohesive matrix. The quality and grading of aggregates are governed by standards such as IS 383:1970[14]. Table.2 shows properties of aggregates

Table 2. Laboratory test results of aggregates

Properties	Fine Aggregate (FA)	Coarse Aggregate (CA)
Specific gravity	2.67	2.89
density	1.68 Kg/m^3	1.58 Kg/m^3
Finess modules	3.23	3.18
Maximum size	-	20mm
zone	II	-

2.3 Water

Concrete relies on water for hydration of cement, which in turn increases the material's strength, durability, and workability. However, excessive water can induce segregation and reduce structural integrity. To ensure optimal performance, water should be added incrementally, strictly maintaining the water-to-cement ratio as per IS 456:2000 [15]. Potable water with a pH between 6.2 and 7.5 is recommended for both mixing and curing, as specified in the standard. The water used in this process complies fully with IS 456:2000 [15] requirements for concreting, ensuring quality and reliability in construction applications.

2.4 PEG 400

Polyethylene glycol (PEG), and more especially PEG-400, will serve as the self-curing agent in this study. One example of a hydrophilic polymer is polyethylene oxide, or PEG. The conventional formula for it is $H(OCH_2CH_2)_nOH$, where n is often a figure between four and one hundred eighty, representing the number of ethylene oxide units that recur [16], [17]. Its ability to create strong hydrogen bonds with water molecules facilitated by its abundance of hydroxyl groups explains why it dissolves readily in water. [18]. PEG 400 is non-toxic, non-irritating, colorless, odorless, and viscous Fig.1.

Fig. 1. Polyethylene Glycol 400

It also has a low volatility and a neutral PH, which makes it useful for a lot of different things, especially in pharmaceuticals and hygiene products [19]. PEG-400 is a plasticizing ingredient in concrete technology that improves workability and flow better, making them easier to put and compact [20]. It also helps keep water in the mix, which is important for getting the best hydration and strength growth. PEG-400 is used as a self-curing chemical admixture and not as a binding material. It functions by retaining internal moisture within the concrete through hydrogen bonding with water molecules, thereby ensures continuous hydration and improving strength development without external curing. PEG-400 also helps to evenly distribute the parts of the concrete matrix, which makes sure that the performance is consistent and homogeneous. PEG molecular weight may range from 300 g/mol up to 300 g/mol to 1×10^{78} g/mol. with PEG-400 representing one typical example of a molecule with an average molecular weight of about 400 g/mol. Based on the information provided by the manufacturer, Table 3 summarizes the key attributes of PEG-400.

Table 3. Properties of PEG-400

Properties	Values
Standard Molecular Weight	375-430 g/mol
Viscosity measured at 20 °C	86-106 cs
Maximum allowable Acid Value	0.045%
Density at 20 °C	Gm

2.5 Rice Husk Ash (RHA)

Rice husk is an agricultural by-product obtained from farming activities. Its utilization has increased significantly in recent times. Fig. 2 indicates that this is mainly due to its local availability and relatively low cost compared to other materials. It is used as a sustainable material for enhancing cementitious properties. Table 4 presents the characteristics of RHA.

Table 4. Characteristics of RHA

Property	Observed Value
Color	Black
Specific gravity	2.24
Bulk density	0.25 - 0.32 gm%
Silica (SiO_2)	87.65%
Alumina (Al_2O)	2.61%
Ferric oxide (fe_2O_3)	2.21%
Calcium Oxide (Cao)	0.18%

Fig. 2. Rice-husk ash

2.6 Ground Granulated Blast Furnace Slag (GGBS)

This study's GGBS came from the Bhilai steel factory in Chhattisgarh. The granular byproduct of quickly cooling molten blast furnace slag in water is known as ground granulated blast furnace slag. Fig. 3 illustrates that it forms a glassy product with minimal crystallization, exhibits high cementitious characteristics and is finely ground. Table 5 shows properties of GGBS

Fig. 3. GGBS

Table 5. Properties of GGBS

Color	Off white
Specific gravity	2.9
Bulk density	1200 Kg/m^3
Fineness	350 cm^2
Calcium oxide	40%
silica	35%
Alumina	13%

2.7 Superplasticizer

To make the concrete mix more workable, a superplasticizer admixture based on polycarboxylate ether (PCE) was used. The superplasticizer available under the brand name High bond, with a pH value of 6.8, shows near to neutral characteristics. It was discovered that the chloride concentration was 1.1%, which improved the concrete's overall performance.

3. Experimental Work

The concrete mix design for the M30 grade was carried out in accordance with IS 10262:2019. The mix proportions were obtained by taking into account the requirements of IS 456:2000 and the objective mean strength. The finalized mix proportions Kg/m³ are presented in Table: 6 and IS 1199:1959 was followed in the preparation of all specimen castings [21]. Five different mixtures were cast: plain concrete (PC) with no replacement, cement mixed with 30% GGBS and 10% RHA, and three other mixes (SC1, SC2, and SC3) with varying amounts of PEG-400 (0.5, 1%, and 1.5%) by weight of cementitious material. We evaluated the specimens at 7, 28, 56 and 90 days after curing to see how well they performed; we water-cured the PC and CM specimens and kept the self-curing mixtures SC1, SC2 and SC3 in an outdoor setting. The specimens were evaluated for compressive and flexural strength in accordance with IS 516 [22] and split tensile strength as per IS 5816 [23] using a compression testing machine under a constant and uniform loading rate without shock.

(a) SC1 (b) SC2 (c) SC3

Fig. 4. Cast Specimens

Table 6. Details of mix proportion

Mix	w/c	Water Kg/m³	Cement Kg/m³	GGBS Kg/m³	RHA Kg/m³	Coarse Aggregate (20mm) Kg/m³	Coarse Aggregate (10mm) Kg/m³	Sand Kg/m³	Admixture Kg/m³	Self-Curing Kg/m³
PC	0.46	180	385	-	-	866	442	555	-	-
CM	0.46	180	231	115.5	38.5	866	442	555	1.26	-
SC1	0.46	180	231	115.5	38.5	866	442	555	1.26	1.925
SC2	0.46	180	231	115.5	38.5	866	442	555	1.26	3.850
SC3	0.46	180	231	115.5	38.5	866	442	555	1.26	5.775

4. Results and Discussion

4.1 Mechanical Properties

4.1.1 Slump Cone Test

An essential workability test for determining how new concrete flows and feels is the slump test. It provides a rapid and reliable indication of the mixture's ease of placement, compaction, and finishing under site conditions. The increase in PEG-400 dosage leads to a higher slump because the polymer forms hydrogen-bonded interactions with mixing water, improving lubrication within the cementitious matrix. This reduces internal friction between particles, enhances workability, and results in greater flowability of fresh concrete. The slump value increased progressively with higher PEG-400 dosage, indicating improved workability, while maintaining acceptable consistency without segregation for all concrete grades tested [24]. The slump values are presented in Fig. 6. It is observed that parameter increase progressively with the rise in PEG-400 dosage. For M30 concrete, the slump shows an increasing trend.

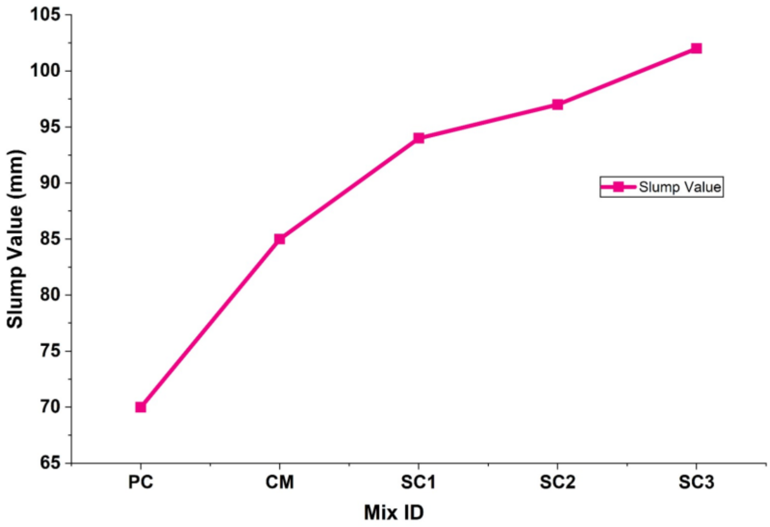

Fig. 6. Slump values for different mixes

4.1.2 Compressive Test

By acting as an internal curing agent, PEG-400 improves the overall mechanical performance of self-curing concrete by maintaining a consistent moisture content throughout hydration, increasing particle dispersion, and allowing for further strength increase [25]. According to the findings of the experiments, the strength properties of concrete are significantly improved when GGBS and RHA are used as additional cementitious materials. Although workability decreased as replacement levels increased, compressive strength rose steadily with curing time for every combination. The presence of RHA contributed to improved later- age strength, while GGBS further enhanced the overall strength development. These findings confirm that the combined use of GGBS and RHA effectively improves concrete strength while supporting sustainable construction practices [26]. The compressive strength performance of the proposed mixes was evaluated using standard cube specimens. Five concrete mixes were prepared in total, including one control mix for M30 grade concrete and four modified mix proportions. The findings shows in Fig. 7 show the outcomes of casting 12 cubes of each combination. Three specimens were assessed at 7, 28, 56 and 90 days. The research showed that the 1.0% PEG-400 dose significantly increased strength. Seven days later, the mix had reached 31.35 N/mm^2, 37.80 N/mm^2, 39.90 N/mm^2 and finally 40.07 N/mm^2 after 90 days. It surpasses all other percentages measured. When compared with the PC mix and the other self-curing variations, the 1.0% PEG 400 mix consistently registered the maximum compressive strength at both curing ages. The results indicate that this dosage level delivers the most effective performance within the experimental range. Thus, the 1.0% PEG 400 mix is identified as the optimum composition based on cube strength.

4.1.3 Split Tensile Test

Researchers found that adding a 1.0% self-curing chemical significantly increased the material's split tensile strength. while M35 concrete exhibited an increase from about 4.2 to 7 N/mm², demonstrating superior performance over conventional mixes [27]. The cylindrical specimens used for split tensile strength testing have a height of 300 mm and a diameter of 150 mm. The tests are conducted at 7, 28, 56 and 90 days, as shown in Fig. 8.

The cylinder specimen strength data show that out of all the tested proportions, the combination with 1.0% PEG-400 performed the best. On day 7, the mix reached a strength of 2.26 N/mm², on day 28, 3.11 N/mm², on day 56 3.42 N/mm², and on day 90 3.52 N/mm². Exceeding both the control mix and the remaining self-curing variations. The strength values show a consistent improvement at the 1.0% dosage across both curing ages.

4.1.4 Flexural Strength Test

Study reported that self-curing concrete incorporating GGBS exhibited improved flexural strength compared to conventional mixes. Optimal replacement levels enhanced matrix density and hydration, resulting in higher bending resistance. Excessive replacement reduced performance, confirming that balanced GGBS combinations provide superior flexural strength in self-curing concrete [4]. The strength behaviour indicates that mixes containing RHA and GGBS would show improved flexural performance at 28 days due to enhanced matrix densification. Higher RHA levels, especially with GGBS, are expected to increase bending resistance compared to conventional concrete [27]. Flexural strength test is performed for Prisms measuring 100 × 100 × 500 mm were used. The tests were conducted at 7, 28 and 56 days as illustrated in Fig. 9.

Flexural strength results for the beam specimens indicated a clear improvement for the mix incorporating 1.0% PEG-400. After 7, 28 and 56 days, this mixture reached strengths of 7.35 N/mm², 9.81 N/mm², and 10.79 N/mm², respectively. noting the most elevated results across all proportions that were examined. The strength values show a consistent improvement at the 1.0% dosage across both curing ages. Based on the experimental flexural response.

4.2 Statistical Analysis Of Mechanical Properties

The compressive strength results, along with the error bars representing standard deviation, indicate a consistent and reliable trend across all mixes and curing ages. The variability at 7 days is relatively higher, which is typical due to early-stage hydration. However, as the curing age increases to 28, 56 and 90 days, the error bars become smaller, indicating improved consistency and reduced variability. With a relatively low standard deviation and the best compressive strength throughout all curing ages, SC2 shows that it is the most stable and effective recipe. The statistical research confirms that adding PEG 400 and other ingredients to concrete improves its uniformity and strength.

The split tensile strength results demonstrate a consistent increase with curing age across all mixes. The variability, indicated by error bars, is relatively higher at early ages and decreases at later stages, reflecting improved stability. Among the mixes, SC2 shows the highest strength with comparatively controlled variation, indicating better performance. The coefficient of variation remains within acceptable limits for most cases, confirming reliability. In terms of improving tensile behavior and decreasing inconsistencies, the findings show that self-curing is successful.

The flexure strength results, along with the error bars representing standard deviation, indicate a consistent and reliable trend across all mixes and curing ages. At 7 days slightly higher variation is observed, particularly in SC1 indicating early-age variability at 28 and 56 days, the variation reduces significantly, showing improved consistency due to continued hydration. Among all mixes, SC2 exhibits the highest flexural strength with relatively low variability, indicating stable and reliable performance. Overall, the coefficient of variation remains within acceptable limits, confirming that the experimental results are statistically consistent.

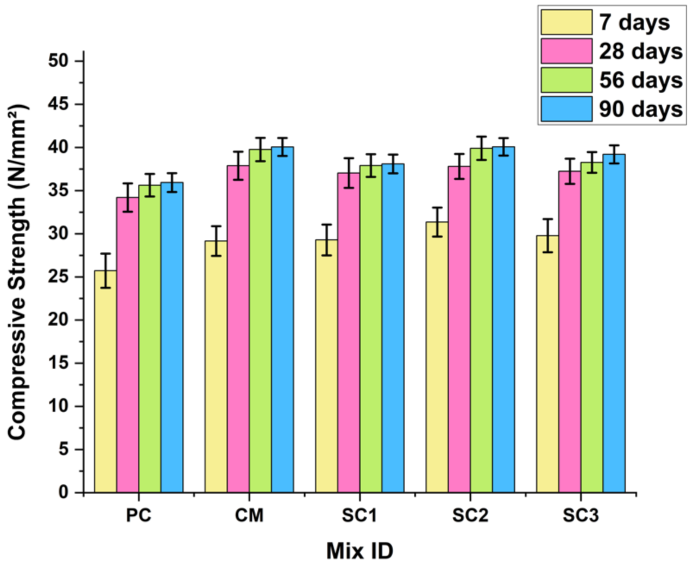

Fig. 7. Compressive test

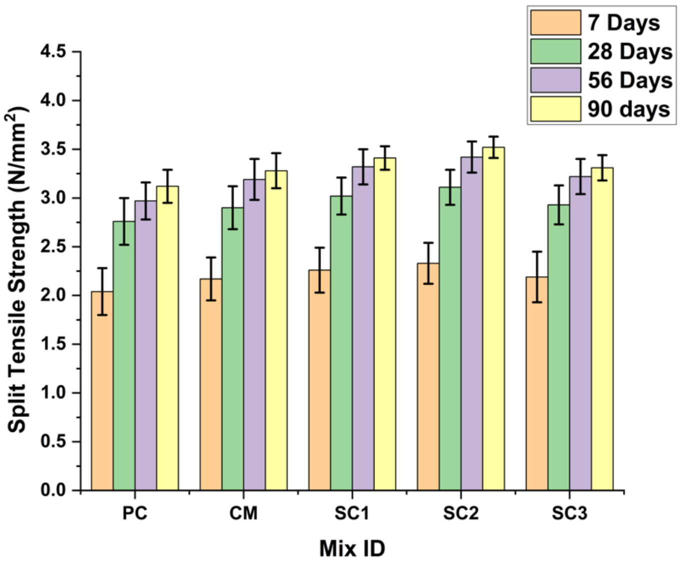

Fig.8: Split tensile test

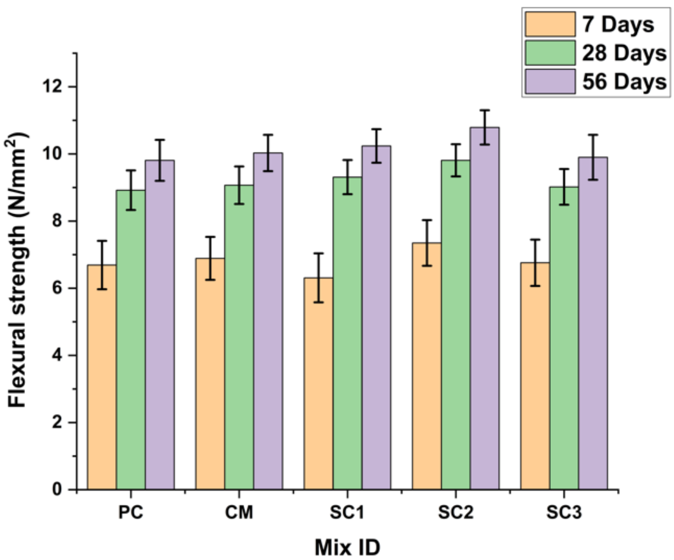

Fig. 9. Flexure strength

4.3 Co-Relation Graphs

To determine the link between the two important mechanical characteristics of concrete, a correlation graph is used. The graph shows the relationship between the compressive strength and the split tensile strength. The horizontal axis usually displays the values of compressive strength, while the vertical axis shows the equivalent values of split tensile strength. The figure enables the assessment of how variations in compressive strength influence the tensile capacity of concrete. The correlation analysis yielded R^2 = 0.6289, indicating a moderate relationship between the variables. This reflects the inherent variability in concrete behaviour and experimental conditions and therefore represents a meaningful trend rather than a strong correlation. Typically, as compressive strength increases, split tensile strength also increases in a similar fashion. This correlation suggests that enhancements to the concrete matrix and its holding properties lead to increased performance in both compression and tension. Such analyses are valuable for showing overall mechanical behaviour of alternate concrete mixtures.

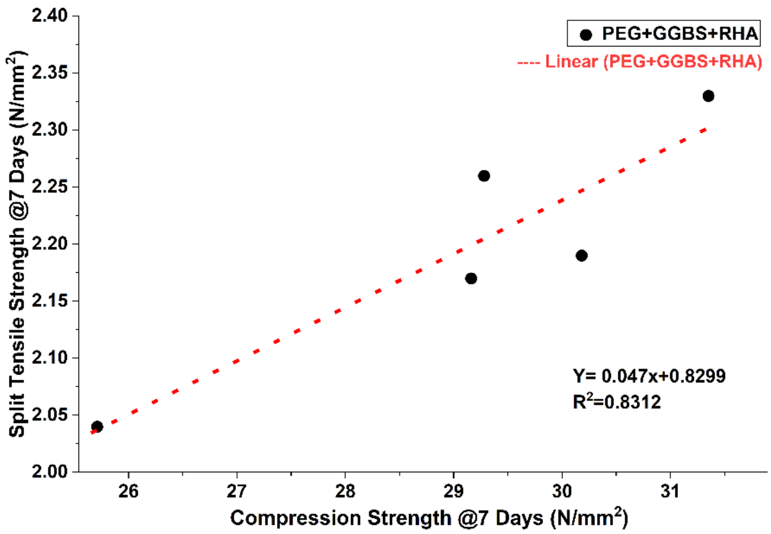

Fig. 10. Correlation between 7-day compressive strength and split tensile strength of concrete mixes

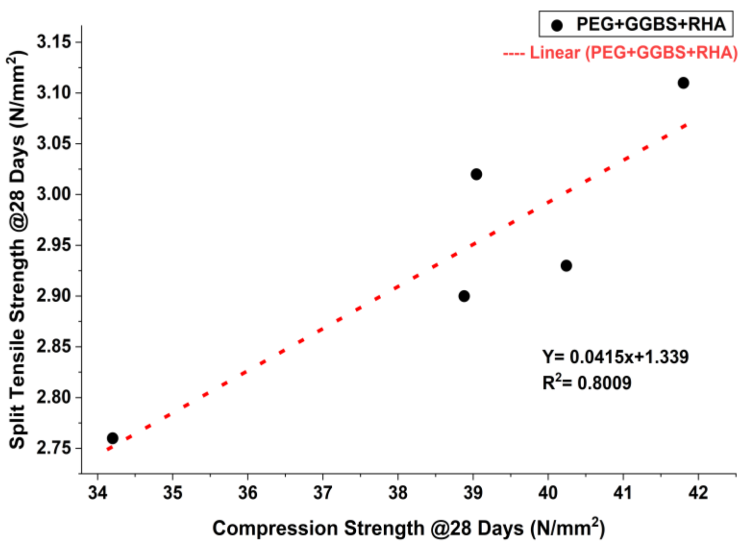

Fig.11: Correlation between 28-day compressive strength and split tensile strength of concrete mixes

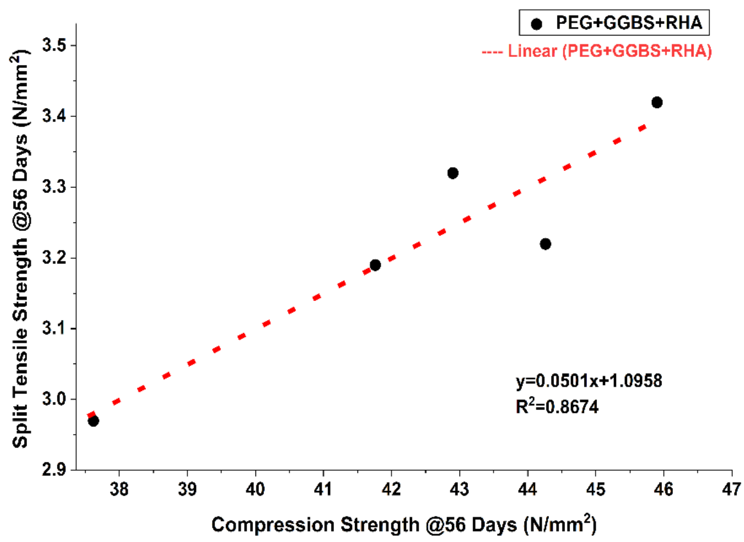

Fig. 12. Correlation between 56-Day compressive strength and split tensile strength of concrete mixes

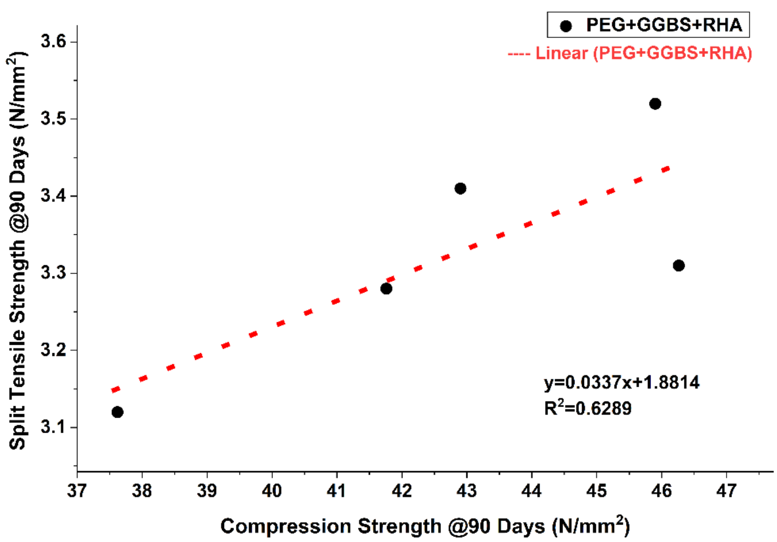

Fig.13: Correlation between 90-day compressive strength and split tensile strength of concrete mixes

4.4 Microstructure Analysis

Microstructural characteristics were examined using SEM techniques. The SEM micrographs reveal significant changes in the microstructure with the incorporation of GGBS, RHA and PEG-400. The presence of GGBS and RHA increases pozzolanic and indirect hydraulic reactions leading to the formation of additional C-S-H gel which contributes to a denser matrix. The self-curing action of PEG-400 enhances internal moisture availability, facilitating continuous hydration and reducing microcracks. As a result, the voids structure becomes more refined with less voids and improved particle packing. These microstructural improvements are consistent with the observed enhancement in mechanical properties. The SEM patterns of CM, SC1, SC2 and SC3 mixes are presented in Fig.5. The mixes were selected based on their superior mechanical performance and fracture energy. The CM mix exhibited higher porosity and visible microcracks, indicating incomplete hydration. The C-S-H gel appeared as finer, loosely packed particles, reflecting a less dense cementitious matrix. The SC1 mix indicates a comparatively lower level of matrix densification. Although hydrate products are present, unbonded and loosely packed regions are observed, suggesting incomplete particle integration and reduced microstructural continuity compared to higher PEG content mixes. The inclusion of PEG as a self-curing agent in the SC2 mix contributed to its relatively thick and homogenous matrix, which in turn improved internal moisture retention and encouraged continual hydration. The SC3 mix, the concrete matrix became noticeably denser, and crack formation was effectively reduced, indicating improved crack control and enhanced structural integrity due to efficient self-curing action. The SC3 mix exhibited a compact matrix featuring significant C-S-H gel formation. This refined microstructure ensures superior interfacial bonding with ferrochrome slag aggregates, effectively minimizing porosity and optimizing mechanical strength.

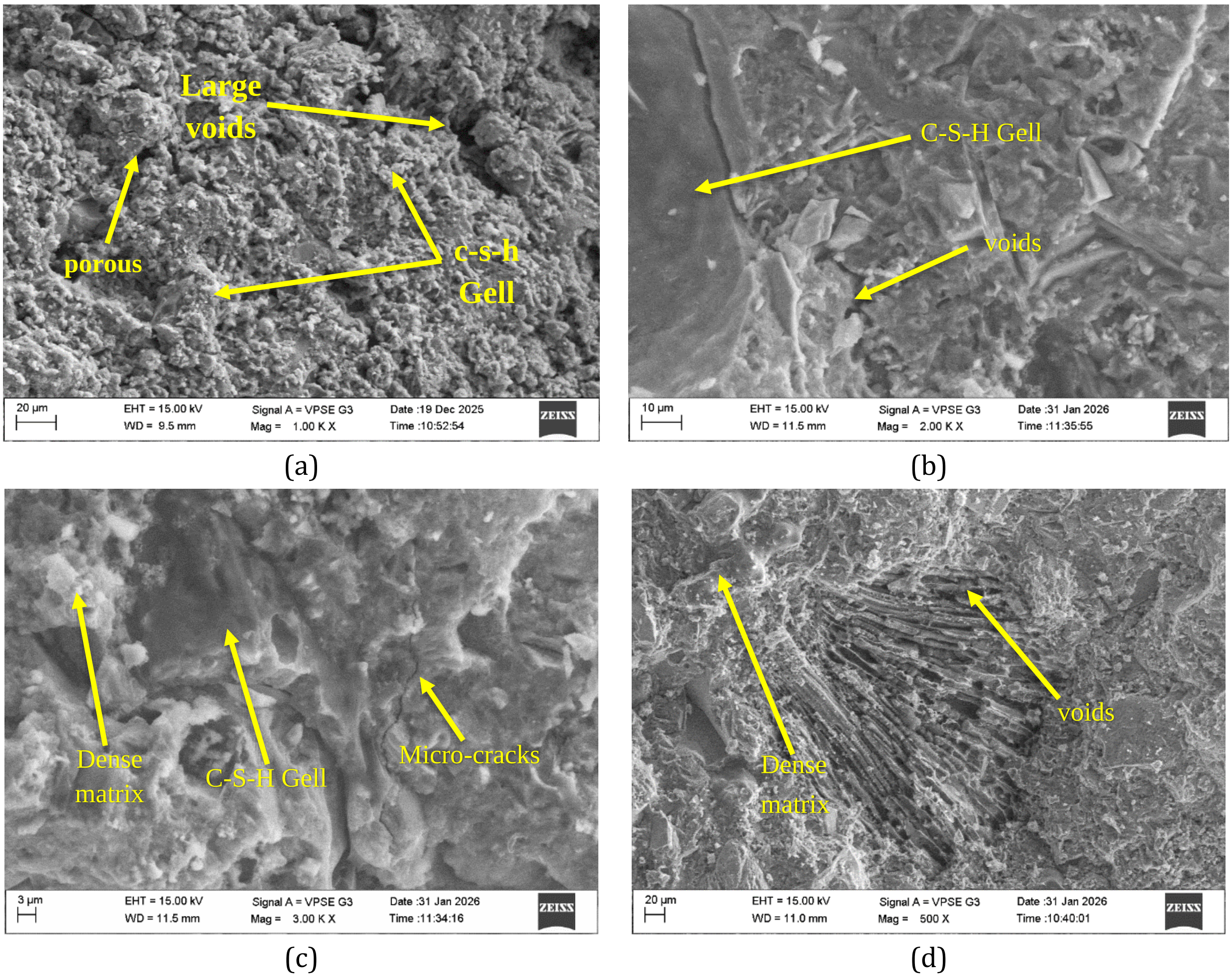

Fig. 14. SEM Analysis of (a) CM, (b) SC1, (c) SC2 and (d) SC3

5. Conclusion

From the above findings, the following key conclusion is established:

- The workability of concrete increased progressively with higher dosages of PEG-400 compared to the conventional mix, indicating improved fresh-state behaviour due to enhanced internal lubrication and moisture distribution.
- Among all the mixes investigated, the SC2 mix demonstrated the highest compressive strength, confirming that a PEG-400 dosage of 1.0% provides the most favorable performance under the conditions studied.
- Mechanical strength decreased when PEG-400 concentration was increased above the optimal level, suggesting that an overabundance of polymer dose might compromise the strength of the hardened cement matrix.
- To reduce reliance on external curing processes, PEG-400 was used as a self-curing agent. This enabled continuous strength growth under ambient curing conditions.

- The combination of PEG-400 with supplementary cementitious materials contributed to improved overall performance by facilitating better hydration continuity throughout the curing period.
- Incorporation of 30% GGBS and 10% RHA as partial replacement for cementitious material. showed improved strength performance. This approach reduces 40% of cement along with reduced water demand due to 1% PEG-400 as self-curing agent, by reducing the environmental impact and developing sustainable concrete.

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