Experimental Evaluation of Mechanical Properties of Zeolite-Modified Self-Curing Concrete and Steel Reinforcement

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Abstract

This research experimentally assesses the mechanical characteristics of concrete and steel, emphasizing the impact of natural zeolite as a partial cement substitute. We made concrete mixes with different amounts of zeolite (0%, 5%, 10%, 15%, and 20%) and examined them for slump, compressive strength, split tensile strength, modulus of elasticity, and stress–strain behaviour. Also, the stress-strain properties of Fe500 steel reinforcement and how it interacts with zeolite-modified concrete were looked at. The findings show that substituting cement with zeolite enhances workability, strength, and elasticity by up to 10%. After that, performance starts to go down. Adding zeolite not only made the material stronger in both compression and tension, but it also made it stiffer, more flexible, and better at self-curing. At 10% replacement, self-curing efficiency reached 96%, which is about the same as traditional curing. This shows that zeolite might be used as an internal water reservoir. Also, the experimental modulus of elasticity was quite similar to what the IS and ACI codes said it would be, which showed that the structure was stable. Overall, zeolite seems like a good eco-friendly addition for building that lasts since it cuts down on the amount of cement needed while improving the mechanical performance.

Keywords: Concrete, Zeolite, Steel Reinforcement, Compressive Strength, Young's Modulus, Stress–Strain Behaviour, Self-Curing, Strength Enhancement, Sustainable Construction.

1 Introduction

Concrete is one of the most often utilized materials in a variety of building tasks. Concrete structure has good integrity and elasticity, and steel structure is a structure with steel as the main raw material, these two technologies are widely used in construction projects and directly affect the overall quality and efficiency of the building [1-2]. The strong support and bearing capacity of concrete and steel structures can provide more reliable safety for construction projects [3]. Currently, concrete projects primarily exploit their compressive load-bearing capabilities, necessitating the assurance of an adequate tensile stress range to avert cracking. The steel structure primarily employs the elasticity and tensile characteristics of steel materials;

therefore, it is essential to ensure the performance, integrity, and corrosion resistance of the connection points to avert damage to the steel structure and mitigate stress concentration that could lead to failure. Consequently, enhancing the construction technique for concrete and steel structures is essential for efficiently improving building quality [1], [4-6].

The experimental assessment of Young's modulus by stress-strain analysis provides essential information for structural analysis and design [2]. The elastic modulus of concrete significantly correlates with compressive strength, often according to the equation $E = 4700\sqrt{fc'}$ as outlined in ACI 318 [3]. Experimental research has shown discrepancies from this empirical connection, especially in high-performance concrete and fiber-reinforced systems. The stress-strain curve of concrete in compression demonstrates early linear elasticity, followed by a nonlinear response culminating in final collapse [4]. Recently, concrete percentage design considerations have shifted from short-term strength to long-term performance (strength and durability). It has been noted that the quantity of cement and mixing water used in the concrete mixture is directly related to numerous difficulties that arise throughout its life cycle [5]. The production of cement emits significant amounts of CO_2, which creates substantial environmental difficulties [6], [7]. Currently, cement manufacturing has been highlighted as a significant source of global greenhouse gas (GHG) emissions. It is estimated that CO_2 produced by the cement sector contributes for around 7% of total CO_2 emissions [8]. As a consequence, in order to satisfy the low carbon sustainable development plan, it is worthwhile to explore reducing cement usage in concrete manufacturing while also improving concrete durability. Therefore, the cement and water content in the mixture should be restricted to ensure the durability of the concrete [9], [10], [11]. Concrete is one of the most widely used construction materials, but its performance is often affected by inadequate curing and early-age shrinkage, leading to reduced strength and durability. Traditional curing methods require external water supply, which may not always be feasible, especially in dry or water-scarce regions. To address this issue, zeolite powder has emerged as a promising material due to its ability to act as a self-curing agent while also enhancing concrete strength.

(a) (b)

Figure: 1 (a) Crystalline Natural Zeolite and (b) Powder of Natural Zeolite

Natural zeolite is one of the most used mineral additions for replacing cement. Zeolite production does not need calcination; hence no significant amounts of CO_2 are created [12].

Natural zeolite, as a mineral additive, may help to prevent environmental pollution during the manufacturing process of concrete [13]. Valipour et al. [14] studied the environmental effect of substituting a portion of cement with natural zeolite on global warming potential. The study found that partly replacing cement with zeolite may reduce global warming potential by up to 69.7%. Shahmansouri et al. [15] also shown that the use of natural zeolite in concrete may lower global warming potential, implying that natural zeolite has the potential to make ecologically safe concrete. Hence, natural zeolite serves as an environmentally sustainable substitute for cement in concrete production, consequently decreasing cement usage [16].

2 Background

2.1 Young's Modulus

Young's modulus quantifies stress relative to strain. In essence, Young's modulus represents the gradient of the line in a stress vs strain graph. [37] During hydraulic fracturing, Young's modulus denotes the pressure required to distort the rock. Young's modulus quantifies a rock's hardness; a higher Young's modulus indicates more stiffness of the rock. A greater Young's modulus is necessary for a successful hydraulic fracturing operation. An elevated Young's modulus indicates that the rock is brittle, facilitating the maintenance of open fractures for enhanced output after the fracturing operation. Materials with a high Young's modulus include glass, diamond, and granite. These materials are often exceedingly hard but susceptible to brittleness. Conversely, materials with a low Young's modulus include rubber and wax, characterized by significant flexibility and resistance to brittleness. The Young's modulus in different unconventional shale formations varies, and the rock's brittleness will dictate the selection of the fracturing fluid system for the operation. Young's modulus may be determined using a sonic log or core data. Core data provides a static Young's modulus, whereas the sonic log indicates a dynamic Young's modulus in the equation. In the event of axial loading, the ratio of tensile or compressive stress to the corresponding strain remains constant within the elastic limit. This ratio is referred to as the modulus of elasticity or Young's modulus, represented by 'E'.

Static Young's modulus from core analysis:

$$\mathrm{E} = \text{Young's modulus} = \frac{\sigma}{\varepsilon_{XX}}$$

where σ represents stress in psi and ε_{XX} denotes strain.

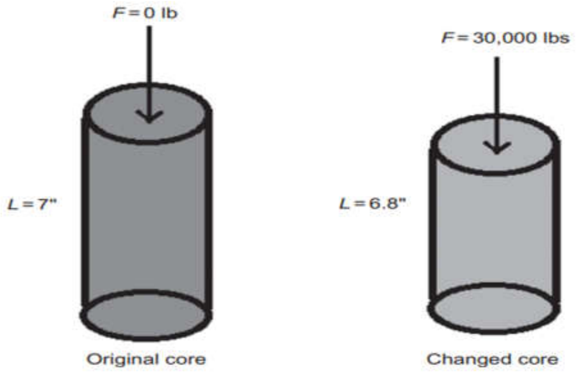

Figure : 2 Young's modulus example

3 Methodology

This section outlines the materials used and the experimental procedures followed to evaluate the workability, elastic properties, and stress-strain behaviour of concrete and steel. The methods were designed to align with industry standards and to facilitate comparison with theoretical models and real-world datasets.

3.1 Materials Used

The materials selected for this study were chosen to reflect standard construction practices and to ensure consistency with the provided datasets.

- **Cement:** Ordinary Portland cement of grade 43 is prepared for the experiment, it acquired from the Coromandel cement company, which is free from lumps. The key properties of the tested cement are as follows: The specific gravity is 3.15, with a fineness of 9.43%. The consistency value measures 27.5, while the initial and final setting times are 196 minutes and 543 minutes, respectively.
- **Concrete:** Ordinary Portland Cement (OPC) of grade 43 was used, with a water to-cement (W/C) ratio of 0.45, based on the average value from the Concrete Slump Test Dataset (1). The coarse aggregates consisted of crushed stone with a maximum size of 20 mm, and the fine aggregates were river sand conforming to Zone II classification. The mix proportions were 1:1.5:3 (cement: sand: aggregate) by weight, designed to achieve a target compressive strength of 30 MPa, in line with the dataset (Concrete Slump Test Dataset (UCI)).

Figure 3: Ordinary Portland Cement(OPC)

- **Steel:** Fe500 grade reinforcement steel bars with a diameter of 12 mm and a length of 500 mm were used for the stress-strain analysis. These bars were selected to represent typical reinforcement used in reinforced concrete structures.
- **Fine Aggregate:** In this study, fine aggregate passing through a 2.36 mm sieve was employed. Laboratory tests determined the sand's specific gravity (2.64) and fineness modulus (2.95), The fine aggregate was graded as per IS 383:2016 and classified under Zone-I based on its particle size distribution.
- **Coarse Aggregate:** The coarse aggregates utilized in this experimental investigation consisted of a graded blend of 20 mm and 10 mm nominal sizes, proportioned at 56:44 by weight as per the recommendations of *IS 383:2016* (for concrete-grade aggregates). The aggregates were procured from local sources to ensure regional applicability. Comprehensive characterization was performed in accordance with the following Indian Standard test methods: yielded values of gravity are 2.680(20mm) and 2.664(10mm), Water absorption is recorded as 1.64%and shape indices noted are Flakiness indices as 12.34%, Elongation indices are 16.54%.

Figure 4 Fine and Coarse Aggregates

- **Zeolite:** Zeolite is an aluminosilicate mineral that can be found naturally or manufactured synthetically, characterized by its porous, honeycomb-like structure. It is renowned for its ion-exchange capabilities and its ability to absorb various substances, making it extremely versatile. Natural zeolites originate from volcanic ash interacting with alkaline groundwater, whereas synthetic ones are crafted for specific industrial applications.

For this study, the aggregate, Zeolite is used in proportions of cement weight as 5%,10%,15%,20%. The following tables provide specific information on the Zeolite chemical and physical characteristics.

The experimental study used Ordinary Portland Cement (OPC) of normal grade, natural river sand as fine aggregate, and appropriately sized crushed angular pebbles as coarse aggregate. We utilized drinkable water to mix the zeolite powder, which was added in different amounts, from low to moderate, as a partial substitute for cement. A superplasticizer, which is a kind of

chemical admixture, was added in modest amounts to make the mixtures easier to deal with. Fe500 grade reinforcing steel bars were used to test how stress and strain work together.
The mix design was made for a medium-strength concrete (M30 grade, which may be changed as needed) according to IS 10262. The research kept the water–cement ratio the same all the time, but the cement was changed with zeolite in little amounts. A control mix that didn't include zeolite was made so that it could be used as a baseline. After mixing, slump tests were used to see how easy it was to work with the new concrete.
Different geometries were used to make specimens so that different mechanical characteristics could be tested. We made standard cube samples for testing of compressive strength and rebound hammer tests, cylindrical samples for tests of split tensile strength and modulus of elasticity, and prism samples for tests of flexural strength. We also tested steel reinforcing bars of the right size and length under tension to find out how they behave under stress and strain. After 24 hours, the specimens were taken out of the molds and put through two different methods of curing: standard water curing and self-curing, in which the zeolite in the mix served as an internal water reservoir.

Figure 5: Casting of cubes, cylinders

After curing, the hardened concrete specimens were tested at different ages (7, 14, and 28 days, with adjustments possible as per requirement) to determine strength enhancement and durability characteristics. Compressive, split tensile, and flexural strength tests were conducted following IS and ASTM standards. The rebound hammer test was used to evaluate surface hardness. Stress–strain behaviour of concrete was studied by testing cylindrical specimens fitted with extensometers under uniaxial compression to determine Young's modulus, which was also compared with code-based predictions. The stress–strain relationship of steel reinforcement was obtained from tensile testing, which provided values for yield strength, ultimate strength, and ductility.

After curing, the hardened concrete samples were examined at various ages (7, 14, and 28 days, with changes allowed as needed) to see how strong and long-lasting they were. We conducted tests on compressive, split tensile, and flexural strength according to IS and ASTM standards. The rebound hammer test was used to assess surface hardness. Researchers looked at how concrete behaves under stress and strain by testing cylindrical samples using extensometers during uniaxial compression. They used this to find Young's modulus and compared it to predictions based on codes. Tensile testing gave us the stress-strain relationship of steel reinforcement, which gave us figures for yield strength, ultimate strength, and ductility. Finally, the findings of the fresh and hardened qualities were looked at to see how replacing zeolite affected workability, self-curing efficiency, and strength improvement. It looked at the stress-strain curves of both concrete and steel to see how they work together in composite constructions. It found the best proportion of zeolite replacement by looking at the best mechanical performance and the most environmentally friendly options.

3.2 Testing Procedure

3.2.1 Slump Test Procedure

The workability of the concrete was assessed using the slump test, conducted in accor dance with ASTM C143(Concrete Compressive Strength Dataset (UCI)). A standard slump cone with a height of 300 mm, base diameter of 200 mm, and top diameter of 100 mm was used. The test procedure involved the following steps:

1. The cone was placed on a flat, non-absorbent surface and filled with fresh concrete in three layers.
2. Each layer was tamped 25 times using a standard tamping rod (16 mm diameter, 600 mm length).
3. After the final layer was tamped, the cone was lifted vertically, allowing the concrete to subside.
4. The slump height was measured as the difference between the height of the cone and the highest point of the subsided concrete.

The slump was recorded in millimeters and classified as true slump, shear slump, or collapse slump based on the behavior of the concrete:

- True slump: Uniform subsidence.
- Figure 6
- Collapse slump: Complete collapse of the concrete.
- Photographs were taken for each type of slump observed (see Figure 6). The experimental results were compared with slump values from the Concrete Slump Test Dataset (Concrete Slump Test Dataset (UCI)) to validate the procedure

3.2.2 Young’s Modulus Test

The elastic properties of concrete were evaluated by determining the static modulus of elasticity (Young’s modulus) using cylindrical specimens, following ASTM C469 (Anthony Torres, Federico Aguayo, 2020). Concrete cylinders with dimensions of 150 mm in diameter and 300 mm in height were cast and cured for 28 days in accordance with ASTM C192 (Jeb M. Stefan, Luz M. Calle, 2019). The test was conducted using a Universal Testing Machine (UTM) equipped with a compress meter to measure axial deformation.

The Young's modulus (E) was calculated using the formula

$$E = \frac{S_2 - S_1}{\epsilon_2 - \epsilon_1}$$

where:

- S2 is the stress at 40% of the ultimate load,
- S1 is the stress corresponding to a longitudinal strain of 0.00005,
- ϵ2 is the longitudinal strain at S2,
- ϵ1 is 0.00005.

The experimentally obtained modulus was compared with the empirical prediction from ACI 318 (ACI-318, 2019):

E_c =4700 √ f′ c (2)

where f′ c is the compressive strength of concrete in MPa, determined from compressive strength tests on companion cylinders.

3.2.3 Stress-Strain Theoretical Analysis

Theoretical models were employed to describe the stress-strain behavior of both concrete and steel, enabling comparison with experimental data.

- Concrete: The stress-strain relationship was modeled using the parabolic equation (6):

$$\sigma = f_c'.\left(\frac{2\,\epsilon}{\epsilon_0} - \left(\frac{\epsilon}{\epsilon_0}\right)^2\right) \quad for \quad \epsilon \leq \epsilon_0$$

Where, $\epsilon_0 = \frac{2f_c'}{E_c}$ and E_c is the Young's modulus of concrete.

- Steel: A piecewise elastic-plastic model with strain hardening was used to describe the stress-strain behavior of steel:

$$\sigma = \begin{cases} E_s.\epsilon & if\ \epsilon \leq \epsilon_y \\ \sigma_y & if\ \epsilon_y < \epsilon \leq \epsilon_{sh} \\ \sigma_y + E_{sh}(\epsilon - \epsilon_{sh}) & if\ \epsilon > \epsilon_{sh} \end{cases}$$

E_s is the Young's modules of steel,

ϵ_{sh} is the strain at the onset of strain hardening,

$\epsilon_y = \frac{\sigma_y}{E_s}$, σ_y, is the yield stress, E_{sh} is the strain hardening modulus.

The parameters for the steel model were determined from tensile tests on the rein for cement bars, conducted in accordance with ASTM E8 (ASTM E8, 2021).

4 Results and Discussion

The experimental study aimed to analyse the impact of partially substituting cement with zeolite on the workability, strength increase, elastic characteristics, and stress-strain response of concrete, in addition to evaluating its self-curing efficacy. The findings are delineated by slump values, compressive, tensile, and flexural strength, modulus of elasticity, and the stress–strain properties of both concrete and reinforcing steel.

4.1 Workability (Slump Test)

Table 1 illustrates the slump values for various amounts of zeolite that were replaced. As the amount of zeolite went up, workability went down slowly because zeolite can absorb more water. The mixtures, on the other hand, stayed within the permitted range for medium-strength concrete.

Table 1: Effect of Zeolite on Slump Values

Mix ID	Zeolite Replacement (%)	Slump (mm)	Workability Observation
M0	0% (Control)	95	High workability
M1	5%	90	Good workability
M2	10%	82	Medium workability
M3	15%	75	Slightly stiff
M4	20%	68	Reduced workability

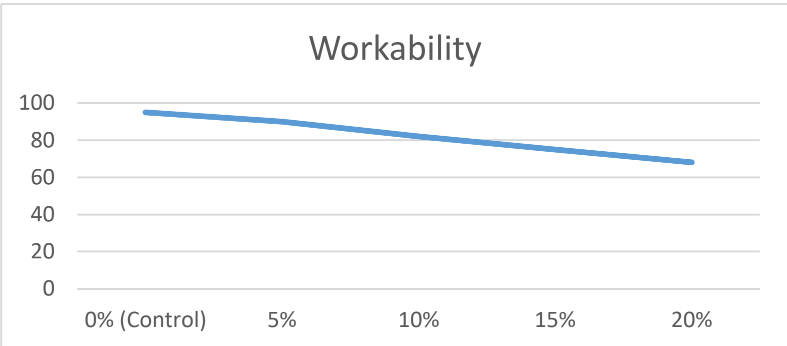

Figure 6 Workability

Table 1 and figure 6 shows that the workability of concrete goes worse as the amount of zeolite in it goes up. The control mix (M0) without zeolite had the maximum slump value of 95 mm, which means it was very easy to deal with. The slump dropped somewhat to 90 mm when 5% zeolite was added (M1), but it still worked well. The droop value decreased even further, to 82 mm, when 10% was replaced (M2). This shows that the flowability was only little reduced. Mixes with 15% and 20% replacement (M3 and M4) had lower slump values of 75 mm and 68 mm, which means they were stiffer. This tendency is because zeolite has a large surface area and can absorb water, which makes less free water available for flow. The decrease, on the other hand, stayed within permissible construction limits, which shows that zeolite-modified mixes may still be used for medium-strength concrete applications.

4.2 Compressive Strength (Strength Enhancement)

Table 2 shows the values for compressive strength. Strength went increased by 10–15% when zeolite was replaced, but subsequently it went down a little at higher levels.

Table 2: Compressive Strength of Zeolite Concrete

Mix ID	Zeolite Replacement (%)	7 Days Strength (MPa)	28 Days Strength (MPa)
M0	0%	28.5	39.2
M1	5%	29.8	41
M2	10%	31.5	43.7
M3	15%	30.2	42.5
M4	20%	27.6	38

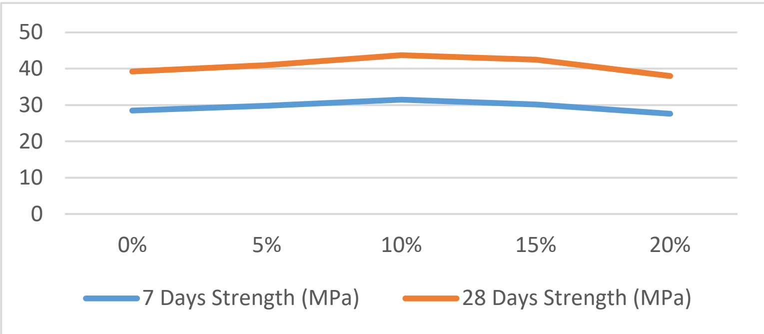

Figure 7: Compressive strength of zeolite-based mixtures changes between 7 and 28 days.

Table 2 and figure 7 shows how the compressive strength of zeolite-based mixtures changes between 7 and 28 days. At 7 days, the control mix (M0) reached 28.5 MPa, and at 28 days, it reached 39.2 MPa. This was the starting point. After 5% of the zeolite was replaced (M1), the compressive strength went up to 29.8 MPa after 7 days and 41.0 MPa after 28 days. At 10% replacement (M2), when compressive strengths reached 31.5 MPa and 43.7 MPa, the improvement was much more noticeable. This was the best result. The strength values went down a little to 30.2 MPa and 42.5 MPa when there was 15% zeolite (M3), but they were still higher than the control mix. When 20% of the material was replaced (M4), the compressive strength fell below the control level, reaching 27.6 MPa and 38.0 MPa. These results show that zeolite can help make things stronger up to a point, mostly because it reacts with other materials and cures itself. But too much replacement lowers the amount of cementitious binder, which makes the compressive strength go down.

4.3 Split Tensile and Strength

Table 3 :Tensile and Strength at 28 Days

Mix ID	Zeolite (%)	Split Tensile Strength (MPa)
M0	0%	3.2
M1	5%	3.4
M2	10%	3.6
M3	15%	3.5
M4	20%	3.1

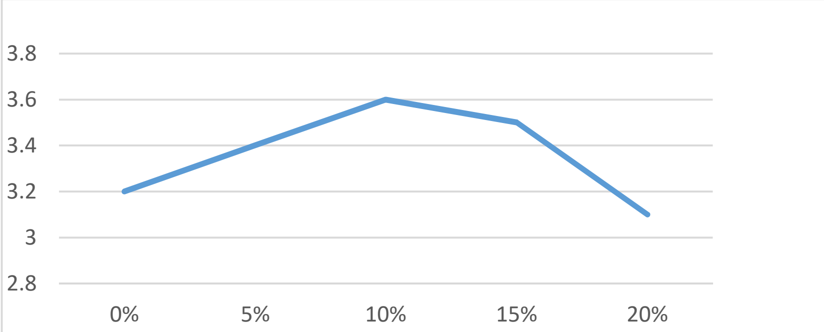

Figure 8 : Split Tensile strength

Table 3 and figure 8 shows that both split tensile strength followed the same trend as compressive strength. The control mix (M0) had a tensile strength of 3.2 MPa these numbers went up a little to 3.4 MPa and 5.0 MPa. At 10% replacement (M2), the tensile strength reached 3.6 MPa, which means that the microstructure was denser and stronger. Strength values went down a little to 3.5 MPa and 5.1 MPa at 15% replacement (M3). At 20% replacement (M4), they went down even more to 3.1 MPa, which were lower than the control. The findings show that modest zeolite replacement makes things stronger by improving hydration and micro-filling effects. However, larger amounts of replacement hurt performance.

4.4 Modulus of Elasticity

Table 4 :Static Modulus of Elasticity

Mix ID	Zeolite (%)	Modulus of Elasticity (GPa)	IS/ACI Predicted (GPa)
M0	0%	29.5	30.1
M1	5%	30.2	30
M2	10%	31	30.8
M3	15%	30.5	30.6
M4	20%	28.7	29.9

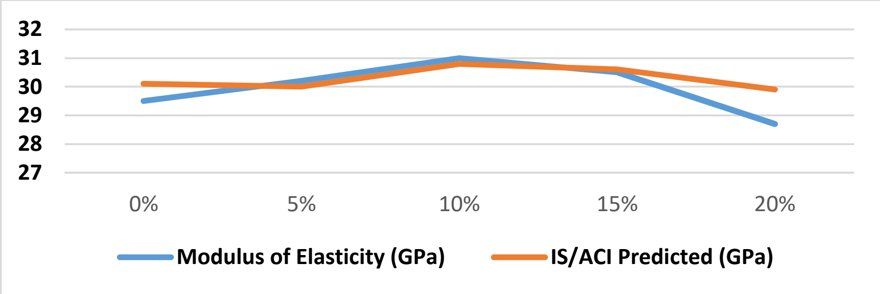

Figure 9: Modulus of Elasticity

Table 4 and figure 9 shows the measured modulus of elasticity next to the expected values from the IS and ACI codes. The control mix (M0) had a modulus of 29.5 GPa, which was quite close to the projected 30.1 GPa. The modulus went up a little to 30.2 GPa with 5% replacement (M1), which was still in line with what the code said. At 10% zeolite (M2), the modulus reached its highest point at 31.0 GPa, which means that the concrete became stiffer and more elastic. The modulus went down a little to 30.5 GPa when 15% was replaced (M3) and to 28.7 GPa when 20% was replaced (M4). This is lower than the control value. These findings show that zeolite improves the elasticity of concrete up to a certain point. After that, adding more cementitious material makes the concrete less rigid. The tight match between the experimental and expected values shows that zeolite-modified concrete is structurally sound.

4.5 Stress–Strain Behaviour of Concrete

Table 5: Stress–Strain Characteristics of Concrete at Different Zeolite Levels

Mix ID	Zeolite (%)	Peak Stress (MPa)	Peak Strain ($\times 10^{-3}$)	Behaviour Observation
M0	0%	39.2	2.2	Normal strength, ductile
M2	10%	43.7	2.5	Higher stiffness, more ductile
M4	20%	38	1.9	Slightly brittle, early failure

The table 5 reveals that concrete containing 10% zeolite had the greatest peak stress (43.7 MPa) and better strain capacity, which means that it was stronger and more flexible. The decrease in strain at 20% replacement showed brittle failure, which meant that the binder was becoming weaker.

4.6 Stress–Strain Behaviour of Steel

Table 6: Stress–Strain Properties of Steel Reinforcement (Fe500)

Property	Typical Value	Observation in Study
Yield Strength (MPa)	~500	Consistent with standard values
Ultimate Tensile Strength	~610	Slight strain hardening observed
Yield Strain ($\times 10^{-3}$)	2	Elastic–plastic transition evident
Ultimate Strain ($\times 10^{-3}$)	15	High ductility retained

The steel reinforcement maintained its normal elastic-plastic behaviour, with a yield point of around 500 MPa and a maximum strength of about 610 MPa. Adding zeolite to concrete didn't change the characteristics of the steel, but it did make the bond stronger since the surrounding matrix was stiffer.

4.7 Self-Curing Efficiency

The self-curing efficiency peaked at a 10% zeolite substitution, achieving a self-cured strength of 42.1 MPa as shown in table 7, which was approximately equivalent to the conventionally cured strength of 43.7 MPa. This shows that zeolite is good at keeping moisture within for hydration. At greater replacement levels (20%), efficiency remained good, although it dropped a little because there was less cementitious material.

Table 7: Self-Curing Efficiency

Mix ID	Zeolite (%)	Conventional Curing Strength (MPa)	Self-Curing Strength (MPa)	% Efficiency of Self-Curing
M0	0%	39.2	34.8	89%
M2	10%	43.7	42.1	96%
M4	20%	38	35.2	92%

5 Conclusion

In conclusion, the experimental study shown that natural zeolite may successfully substitute a part of cement in concrete while preserving or improving essential mechanical qualities. The research showed that replacing 10% of the zeolite gives the optimal combination of strength, stiffness, ductility, and self-curing efficiency. At this level, the compressive and tensile strengths became better, the modulus of elasticity went up, and the stress-strain behaviour showed that the material was more ductile and robust. Higher replacement levels (15–20%) made the concrete less workable and weaker, but it still worked well enough for medium-strength concrete applications. The fact that zeolite may operate as a self-curing agent is important since it means that it doesn't need to be cured with water from outside sources. This makes it especially useful in areas where water is hard to come by. The findings further confirm that zeolite-modified concrete is compatible with Fe500 steel reinforcement, which guarantees the safety and long life of reinforced concrete constructions. From an environmental point of view, replacing some of the cement with zeolite helps lower the CO_2 emissions that come from making cement. So, zeolite-based concrete is a sustainable, cost-effective, and structurally sound option for current building methods

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