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Mechanical Performance of Fibre-Reinforced Self-Healing Quaternary Blended Concrete

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Abstract

Concrete cracking greatly influences its durability and performance properties by facilitating the entry of water and aggressive materials. In this research work, the effect of mechanical behaviour of M25 grade quaternary blended fibre reinforced concrete with crystalline admixture is studied. Quaternary blended concrete mix containing 20% ground granulated blast furnace slag, 15% fly ash, and 10% Alccofine was used as cement replacement. Varying amounts of nylon fibres of 0.5%, 1% and 1.5% were employed for examining their effects on strength properties.

Specimens of concrete were cast and subjected to testing for their compressive and split tensile strengths at various curing ages of 14, 28, and 56 days. After curing for 28 days, loading was applied in a controlled manner to initiate cracks, and the recovery in strength was investigated at additional curing ages of 14, 28, and 56 days.

Among all the combinations, it was found that the concrete containing 1.0% of nylon fibre performed better in terms of having high compressive and tensile strengths and maximum strength gain after healing. It can be concluded from this study that fibre-reinforced quaternary blended concrete performs well in mechanical terms.

Keywords: Quaternary blended concrete, nylon fibre reinforced concrete, crystalline admixture, self-healing concrete, compressive strength, split tensile strength, sustainable concrete, Alccofine.

I. INTRODUCTION

Concrete is among the most commonly used construction material because of its ability to withstand pressure and be flexible; nevertheless, the susceptibility of the material to cracking poses a challenge in relation to its durability. Cracks that develop as a result of shrinking, high temperatures, and loads act as openings through which water and other substances that corrode concrete enter. The conventional methods of repair are not only expensive but also less efficient; thus, a solution to such problems lies in exploring new approaches. SHC is a technique that can help in addressing the problem of cracks since it ensures that cracks are automatically fixed. Among the various ways of fixing cracks, crystalline additives stand out as important because they aid in forming calcium silicate hydrates (C-S-H) and insoluble crystals in presence of moisture.

Apart from fiber reinforcement, the use of supplementary cementitious materials like fly ash, ground granulated blast furnace slag (GGBS), and Alccofine is becoming increasingly significant in contemporary concrete technology. They aid in improving the microstructure via secondary hydration, resulting in higher strength and denser matrix formation. The synergistic effect of these materials yields a quaternary blended system, which helps in improving both early and late-age properties.

The crystalline additives, while mostly utilized for enhancing durability, also help indirectly in increasing the strength by aiding in more hydration and compaction within the concrete body. The reaction of these components with water and the unhydrated cement particles results in the creation of more binding agents, thus improving their strength.

Even though the advantages of fibres and mineral admixtures have been explored individually, there are very few works that have concentrated on the synergistic effects of both on mechanical behavior, especially in varying curing and loading conditions. Thus, the objective of this research is to investigate the compressive strength, split tensile strength, and strength recovery characteristics of quaternary blended concrete containing crystalline admixture with fiber reinforcement.

II. Research Objectives:

The main goal of this study is to investigate the mechanical behavior and self-healing properties of fiber-reinforced quaternary blend concrete with crystalline admixtures. The specific goals are as follows:

1. To examine the effect of crystalline admixture and nylon fibres on the crack healing behavior of M25 grade concrete.

2. To evaluate the influence of quaternary blended materials (GGBS, fly ash, and Alccofine) on the mechanical properties of concrete.

3. To assess the strength recovery behavior of cracked concrete specimens after 28 days of curing.

To compare the performance of different fibre dosages in terms of mechanical strength and post-cracking recovery.

III. Materials and Mix proportion:

3.1 Materials

The mixture of concrete used for the present investigation was prepared by using standard ingredients, in addition to supplementary cementitious materials, and self-healing materials. Ordinary Portland Cement (OPC) with 53 grade was taken as the base cement. For developing the quaternary mixture of concrete, the proportion of OPC was reduced by replacing it with ground granulated blast furnace slag (GGBS), fly ash, and Alccofine, which is in 20%, 15%, and 10%, respectively. Crystallization-based self-healing material was added in 1% quantity to enable self-healing process, and this involves the development of insoluble crystalline material in the presence of cracks in concrete. Nylon fibres were mixed in different percentages (0.5%, 1%, and 1.5%) for controlling the growth of cracks and enhancing the self-healing process. Zone-II river sand was used as fine aggregate, and crushed aggregates having the nominal size of 20 mm were used as coarse aggregate. All the aggregates were used in saturated surface dry state. Pure water was used as mixing water and curing water.

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3.2 Mix Proportions and Trial Mix

The concrete mix was designed for M25 grade using a quaternary blended cementitious system. In this study, cement was partially replaced with ground granulated blast furnace slag (GGBS) at 20%, fly ash at 15%, and Alccofine at 10% by weight of cement. A crystalline admixture was added at a constant dosage of 1% to enhance self-healing characteristics. Nylon fibres were incorporated at varying percentages of 0.5%, 1%, and 1.5% by volume of concrete to evaluate their influence on crack control and mechanical performance. Trial mixes were initially conducted with different percentages of fly ash to achieve the desired 3strength and workability. The final mix proportions were selected based on compressive strength results and overall performance of the concrete.

Table 1

Concrete mix used for 1m3 of concrete for 0.45 water-cement ratio

Mix		Mix 1	Mix 2	Mix 3
Cement	%	55	55	55
	Kgs	187.32	187.32	187.32
Accofine	%	10	10	10
	Kgs	34.059	34.059	34.059
Flyash	%	15	15	15
	Kgs	51.09	51.09	51.09
GGBS	%	20	20	20
	Kgs	68.12	68.12	68.12
Fiber (kg)		5.7	11.4	17.1
F.A (Kgs)		707.67	707.67	707.67
C.A (Kgs)		1245.9	1245.9	1245.9
water (ltr)		153.26	153.26	153.26
Crystalline (ltr)		3.406	3.406	3.406
Super plasticizer (ltr)		4.087	4.087	4.087

Note: Mix 1- 0.5% of Nylon fibers, Mix 2- 1.0% Nylon fibers, and Mix 3- 1.5% Nylon fibers

The trial mix for M25 grade concrete was developed by varying the percentage of fly ash as 5%, 10%, and 15% to evaluate its influence on the mechanical properties of concrete. During the mix development process, the proportions of GGBS and Alccofine were maintained constant at 20% and 10%, respectively. The selection of these replacement levels was based on findings reported in previous research titled *"A Study on Compressive Behavior of Ternary Blended Concrete Incorporating Alccofine"* by A. Narender Reddy et al.[1], in which the combined use of GGBS and Alccofine demonstrated improved strength and enhanced microstructural properties of concrete.

Fig.1. Casting of cubes for trial mix (a), curing of trial mix cubes(b)

Several trial mixes were prepared and tested to achieve the required workability and target strength for M25-grade concrete. Based on the performance of the trial mixes, the optimum fly ash content was selected for further experimental investigation.

Table 2

Trial mix for M25 grade concrete for various percentages of fly ash

S.no	Mix	Compressive strength for 7days (MPa)	Average (MPa)
1	5%	18.65 20.00 17.24	18.63
2	10%	19.40 19.81 22.00	20.40
3	15%	21.90 22.15 21.17	22.09

The 7-day compressive strength results showed a gradual increase in strength with higher fly ash content. Among all the mixes, the specimen containing 15% fly ash achieved the highest average compressive strength of 22.09 MPa, followed by the 10% mix with 20.40 MPa. The improvement in strength indicates the beneficial effect of fly ash, GGBS, and Alccofine on early-age strength development of quaternary blended concrete.

IV. Experimental methodology

The experimental program was carried out to evaluate the mechanical properties of fibre-reinforced quaternary blended concrete incorporating crystalline admixture. The methodology included material preparation, specimen casting, curing, and mechanical testing at different stages.

Concrete was prepared using the selected mix proportions with partial replacement of cement by ground granulated blast furnace slag (20%), fly ash (15%), and Alccofine (10%). A crystalline admixture was added at a constant dosage, and nylon fibres were incorporated at varying percentages of 0.5%, 1%, and 1.5% by volume of concrete. The materials were thoroughly mixed to obtain a uniform and workable concrete mix.

4.1 Compressive strength

Concrete was prepared using the selected mix proportions and cast into standard moulds. Cube specimens of size 150 × 150 × 150 mm were used for compressive strength testing. All specimens were demoulded after 24 hours and cured in water.

Mechanical properties were evaluated at curing periods of 14, 28, and 56 days. Compressive strength tests and split tensile strength tests were conducted using a universal testing machine (UTM) is showed in Fig. 1. The load was applied gradually and continuously without any shock at a constant loading rate of 5.2 kN/s, as per standard practice. Care was taken to maintain proper alignment of the specimen to avoid eccentric loading. The load was increased steadily until visible cracks appeared. To study strength recovery, controlled cracking was induced in specimens at 28 days, and subsequently tested for strength recovery after healing periods of 14, 28, and 56 days. The regain percentage of compressive strength and split tensile strength is calculated as in Eq. (1)

$$R = \text{Regain strength} / \text{Original strength} \times 100 \quad (1)$$

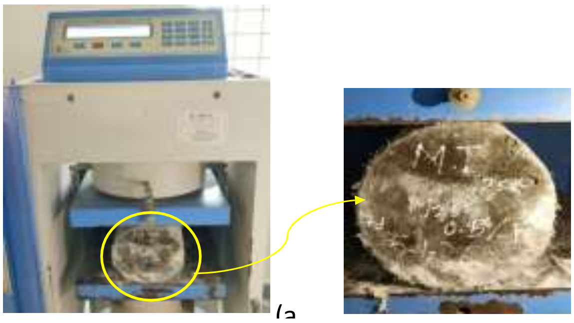


Fig. 1. Testing of specimen (a), Specimen (cube) under loading (b)

4.2 Split tensile strength

The split tensile strength test was conducted on cylindrical specimens of 150 mm diameter and 300 mm height using a Universal Testing Machine (UTM). The specimen was placed horizontally between the loading platens, ensuring proper alignment along its vertical diameter.

The load was applied gradually at a constant rate of 0.2 kN/**s** until failure occurred. During loading, tensile stresses were developed perpendicular to the applied load, resulting in splitting of the specimen along its vertical axis. The load was increased continuously until the first visible crack appeared and propagated through the specimen. The maximum load at failure was recorded and used to calculate the split tensile strength.

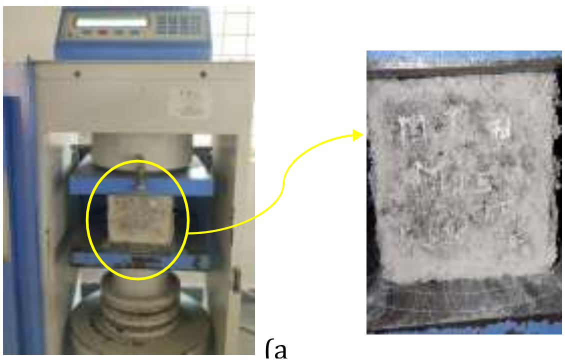


Fig. 2. Testing of specimen (a), Specimen (cylinder) under loading (b)

Selected samples, which were cured for 28 days, were exposed to loading to create cracks in them. After that, the samples underwent curing, and the strength recovery was measured after 14 days, 28 days, and 56 days of curing. The effect of the amount of fibres and blended materials on the strength of the concrete was analyzed by comparing the initial strength to the recovered strength

V. Results and Discussion

5.1 Mechanical Properties

Mechanical properties of the concrete mixes developed were evaluated through compression strength test and splitting tensile strength test at various curing and healing stages. It is evident from the results that fiber percentage is a vital factor in determining strength and recovery performance after cracks have formed.

5.1.1 Compressive strength

The compressive strength of the fiber reinforced quaternary concrete blend was assessed using various periods for curing and healing. It is evident from the findings that the fiber ratio has an effect on the development of compressive strength and healing.

After the curing period of 28 days, all samples had adequate compressive strength, with the sample having 1.0% nylon fibres registering the best compressive strength when compared with other fibres (0.5% and 1.5%). After creating the cracks on day 28, the samples were left to cure for another period after which compressive strengths were obtained on day 14, 28, and 56.

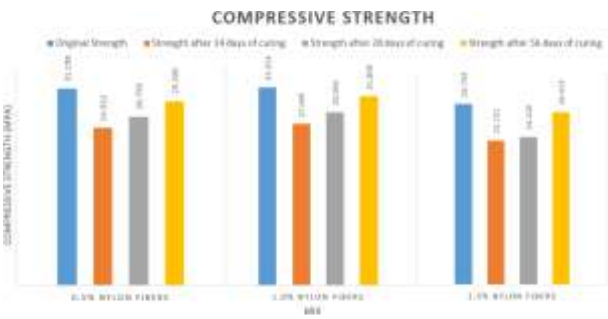


Fig. 3. Regain Compressive strength for various mixes

From all mixes, it was noted that the mix containing 1.0% fibre had a high strength regain of about 95.47%. It was observed that fibre mixes with concentrations of 0.5% and 1.5% gave low strength regain because the use of too much or too little fibre makes the gain of strength less efficient. This improvement in 1.0% fibre mix concentration can be attributed to the effectiveness of crack bridging.

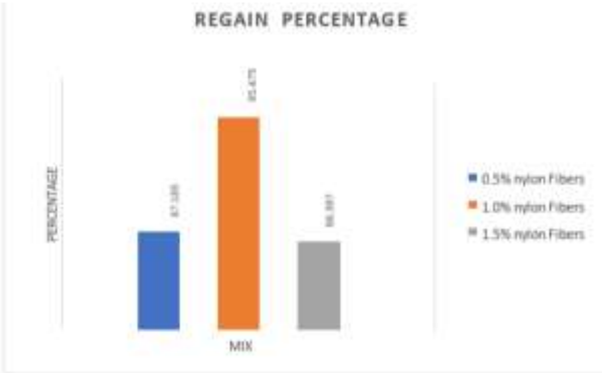


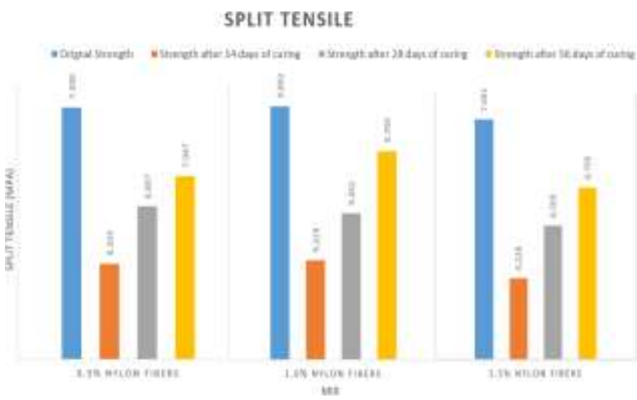
Fig. 4. Regain Compressive strength percentages for various mixes

5.1.2 Split tensile Strength

Similar findings were recorded from the split tensile strength test findings, whereby an increase in tensile strength with increase in curing period was noted, and the addition of fibres greatly enhanced tensile strength.

At 28 days after the crack was induced, the strength recovery of the specimen was carried out at different curing times. The concrete mix containing 1.0% nylon fibre had the highest tensile strength and recovery strength, with a recovery strength of about 98.04% at 56 days.

Fig. 5. Split tensile strength for various mixes



Better performance of the reinforced concrete mixtures is due to the cumulative effect of fibre bridging and self-healing processes. Bridging by fibres prevents widening of cracks, thereby creating favorable conditions for the chemical reaction necessary for healing. Crystalline admixtures increase the effectiveness of the process by forming hydration products, which fill the cracks and consolidate the structure from the inside. Therefore, the concrete exhibits better resistance over time.

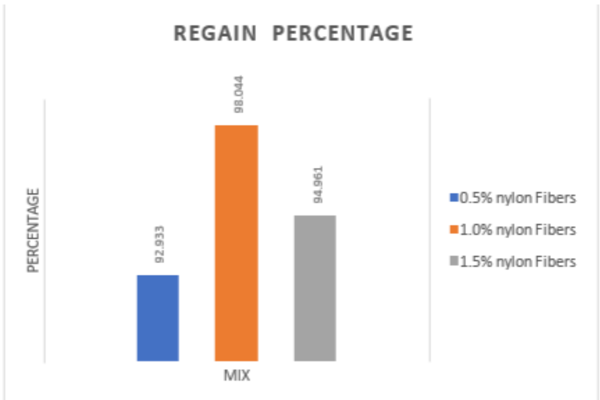


Fig. 6. Regain Split tensile strength percentages for various mixes

5.2. Discussion

It is evident from the above findings that the quantity of fibre is an important factor influencing the mechanical behavior of concrete. It was observed that the ideal quantity of fiber was 1.0%. In the case of lower quantity of fibers, it was not sufficient to control cracks. An excessive quantity of fibers could cause dispersion problems.

The fourth system that included a blend of GGBS, fly ash, and Alccofine also helped increase strength by improving the microstructure and bonding inside the matrix. Both the fiber reinforcement and blends worked together to improve the structural efficiency of the building.

In summary, it can be seen that the results of the experiments conducted show that the fiber reinforced quaternary mixed concrete is an excellent construction material due to its strength recovery and crack resistance capabilities.

VI.CONCLUSION

The present study investigated the mechanical performance of fibre-reinforced quaternary blended concrete. Based on the experimental results, the following conclusions can be drawn:

1. The inclusion of nylon fibres significantly improved the mechanical properties of concrete, particularly compressive strength and split tensile strength.
2. The quaternary blended system consisting of GGBS (20%), fly ash (15%), and Alccofine (10%) contributed to enhanced strength development due to improved microstructure and better bonding within the matrix.
3. Among the different fibre dosages, the mix containing 1.0% nylon fibres exhibited optimum performance in both compressive and split tensile strength.
4. The recovery of strength after cracking revealed the potentiality of fibre-reinforced concrete in regaining a substantial amount of strength. The strength regain percentage was around 95.47% for compression strength and 98.04% for split tensile strength within 56 days.
5. Lower fibre content resulted in insufficient crack control, while higher fibre content reduced effectiveness due to possible fibre clustering and reduced workability.
6. The combined effect of fibre reinforcement and blended materials improved load-carrying capacity, crack resistance, and overall mechanical behavior of concrete.

As such, from the findings, one can conclude that quaternary blended fibre reinforced concrete is effective in enhancing mechanical properties and ensuring structural safety through optimization of fibre amount.

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