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Experimental Toughness and Durability Evaluation of FRC Composite Reinforced with Steel–Polyester Fiber Combination

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Abstract

This study investigates the influence of steel and polyester fibers on the mechanical and durability properties of steel–polymer hybrid fiber reinforced concrete (HyFRC) and toughness under indirect tensile loading conditions. Steel and Polyester fibers are used as a single type (FRC) and in combination (HyFRC) in an M45 grade composite with the addition of fly ash and silica fume as a supplementary cementitious material. Steel as a single fiber exhibited a 10% improvement in compressive strength for a 0.75% volume fraction and a maximum of 14% improvement for a 0.5% volume fraction in comparison to plain concrete. The toughness under split tension capacity was enhanced between 26 and 72% for hybrid fibers in comparison with polyester fiber, and it was between 10 and 18% when compared to the steel fiber reinforcement. Water sorpitivity results were improved with the presence of hybrid fiber. Electrical resistivity decreases with the increase in fiber content and the addition of steel fiber in hybrid FRC increases the conductivity value 1.65–2.23 times greater than the control concrete because of the free movement of electrons.

Keywords Compressive strength, Split tensile toughness, Water absorption, Carbonation, Water sorptivity, Hybrid fiber reinforced concrete

1 Introduction

Concrete is the most popular building material used in civil engineering applications, possessing good resistance to compressive load and showing excellent mechanical and durability properties. It is a man-made construction material, and its raw materials are abundant in nature at relatively low cost (Kusuma et al., 2015; Naik, 2008). However, cement is an important ingredient in the production of concrete, and its manufacturing process is highly energy intensive and responsible for greenhouse emission. Currently, many alternative cementitious materials are being explored and widely preferred by the construction industry to enhance sustainability and reduce the environmental footprint. On the other hand, the brittleness due to poor tensile strength and high shrinkage properties makes the concrete more susceptible to cracking. Therefore, small discrete fiber elements are added, bridging across the micro-cracks and enhancing the tensile strength and post-cracking toughness of the concrete. The genesis of fiber-reinforced concrete started in 1900 with the development of asbestos fiber-reinforced cementitious matrix in which the fibers are added to improve the ductile properties of concrete. Meanwhile, other fibers such as steel, glass and aluminum have become popular and a few synthetic fibers such as basalt,

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polyethylene (PE), polypropylene (PP), polyvinyl alcohol (PVA), polyolefin (PO), carbon, coconut, sisal, jute, have been recently developed in the field of fiber reinforced concrete. It is clear that the physical and mechanical properties of all the fibers are not at all same, and they are utilized in different forms in different applications and are known to be in different terminologies, such as FRC, UHPC, ECC, HSC and so on. Small discrete fibers used for improving the mechanical properties including tensile strain capacity, impact energy and post-cracking strength are termed Fiber Reinforced Concrete (FRC). Few scientists have investigated the ultra-high-performance concrete (UHPC) reinforced with fibers produces high tensile properties, ductility and durability. Engineered cementitious composite (ECC) is another family of UHPC that is designed to exhibit a high tensile strain hardening response. Further, many supplementary cementitious materials are added to FRC to densify the pore structure and enhance the strength, and the permeability characteristics of concrete are known as high-strength concrete (HSC) (Dadmand et al., 2020a, 2020b, 2022). These small discrete fibers are effective in bridging across micro-cracks, and they transfer a large amount of tensile stress to the surrounding matrix (Aslani et al., 2020). Through several experimental studies, it is strongly proven that the addition of randomly oriented discrete fibers would address the multiscale cracking in the critical zone of concrete, which is eventually not possible by the conventional reinforcement bars placed in the concrete structures. Another advantage of FRC is that it can be developed by adding fibers of different elastic moduli, strength, length, diameter, aspect ratio, specific gravity and so on. Hence, the combination of different fibers in the same composite is also possible and it is termed Hybrid Fiber Reinforced Concrete (HyFRC).

Hybrid fiber composite extracts the benefit of individual fiber components and are the most attractive engineering material (Banyhussan et al., 2016). The present construction industry expects a tailor-made composite that meets the specific application for its intended purpose (Gao & Zhang, 2018; Karadelis & Lin, 2015; Leone et al., 2018; Luccionia et al., 2017; Mertol et al., 2015; Mo et al., 2017; Seok-Joon Jang & Hyun-DoYun, 2018; Wang et al., 2012). A severe exposure environment reported the metallic fibers to be corrosive and their excess dosage beyond 0.75% leads to the loss of workability, thus making the concrete very harsh and difficult. Additionally, steel fibers are well known for the high carbon footprint in their manufacturing process. Therefore, synthetic fibers are added to replace the steel fiber position, and they act as a suitable reinforcement in the development of mono and hybrid FRC composites. Positive interaction between the individual fibers in the hybrid composite improves their complete performance, and sometimes their overall response exceeds the summation of the individual. This behavior is termed as synergy phenomenon of HyFRC. For example, in hybrid FRC composite, PP fibers are particularly added to control the early age shrinkage of concrete and when they are combined with steel fibers they bridge across the micro-cracks developed under different stress levels. Fibers added in low or high-volume fractions give a better response depending on their performance in different substrates. For example, the optimal range of high modulus steel fibers is reported to be 2–4.5% for strength improvement and resilience. However, low modulus synthetic fibers improve the crack resistance and durability at the best dosage ranging from 0.4% to 1.2% (Zhao et al., 2023). In most hybrid systems, the fiber combination produced with steel and polymer appeals for its outstanding phenomenal behavior. Therefore, many research results have been published on the synergic response of hybrid composites made with the combination of steel and synthetic fibers.

Mainly the improvement in strength and toughness properties of concrete made with the combination of steel and polymer fibers is attempted in earlier investigations. Similar to steel fibers, polymer fibers are also becoming popular and they are light in weight, non-corrosive, uniform in distribution, and low in modulus. Among the various aspects of hybrid FRC, significant efforts have been made to improve the ductility (toughness) properties that gains more importance in earlier FRC literatures. Toughness is measured as the area below the load deflection(deformation) curve of the FRC composite. This could be done in many ways as per the guidelines mentioned in RILEM TDF-162, fib model 391(2010), ASTMC 1018, JG/T 472-2015 and Report 544.2R, etc.

Hybrid FRC composites produce several benefits in terms of strength and toughness in many ways. Li et al. observed a positive trend in the split tensile and flexural behavior of hybrid composites produced with the combination of steel (straight/hooked/corrugated) and polypropylene fibers. Mechanical interlocking, high elastic modulus, crack bridging effect, and increased fiber volume fraction showed the highest tensile capacity, flexural strength, and post-peak ductility (Li et al., 2018). Alberti et al. explored the enhanced tensile strength and ductility of steel–polymeric fiber combination (Alberti et al., 2017). Bentur and Mindess reported the toughness and ductility properties of composites made with mixtures of steel fibers of different sizes and claimed that short discrete steel fibers are effective in bridging across micro-cracks and that long steel fibers are involved in arresting the propagation of macro-level cracks (Bentur & Mindess, 2006).

Deng et al. performed a uni-axial cyclic tensile test on concrete specimens and concluded that the ductile failure of a hybrid series made up of 0.15% steel and polyester fibers added in the range between 0.10% and 0.15% improved the resistance against deformation and energy dissipation capacity of the matrix (Fangqian et al., 2021). Hence it is concluded in many ways that the combination of metallic (steel) and non-metallic (polyester and polypropylene) fibers significantly influences the tensile strength and toughness characteristics of the concrete and yields superior results through fiber hybridization. A synergic effect was observed in the 0.9% metallic and 0.1% non-metallic fiber combination, in which the fibers at different scales are effective in controlling the cracks formed at different stress levels. Improvement in split tensile and flexural strength is reported between 36.30% and 42.20% in hybrid composites (Banthia & Gupta, 2004).

It is clear that steel–polymer HyFRC has proven its post-cracking behavior and toughness characteristics under different loading cases. It is understood that the load–deformation measurement in FRC under uni-axial tension is the best possible way to measure the toughness properties. However, all sophisticated instruments are needed to realize strain-controlled measurement involving advanced instrumentation techniques, which is a difficult task. Therefore, the author has made an attempt to measure the toughness properties of steel–polyester fiber combinations under split tensile loading conditions. The authors of this paper conducted trial experiments in the same composite and found that the strength enhancement under split tensile loading (in direct) conditions produces superior results, and it is of further interest to determine the toughness capacity under the same loading condition. To the best of the authors' knowledge, the toughness evaluation under split tensile loading conditions for steel–polyester combinations remains limited and inadequate. Hence, the studies presented herein focus on the influence of fiber combinations and their volume fractions on the pre-peak and post-crack behavior of HyFRC along with the initial cracking stress measurement under indirect tensile loading conditions. In addition to characterizing the strength and toughness properties, some additional information on durability aspects such as water absorption, water sorptivity, carbonation and electrical conductivity properties are also evaluated. Experimental outcomes performed on the single and HyFRC are useful in the development of steel–polyester hybrid fiber reinforced composite design models.

2 Experimental Investigations

2.1 Materials

2.1.1 Binder Material

Locally available Ordinary Portland Cement 53Grade (OPC 53) conforming to IS 12269: 2013 with a specific gravity of 3.10 is selected as a primary binding material. Table 1 gives the properties of OPC53 Grade Cement. Class C Fly ash obtained from the Tuticorin Thermal Power project conforming to IS 3812:2003 is used as a replacement material up to 15% of the total binder content. It is available at no cost, necessitates the desired workability in the fresh state and enhances the permeability characteristics in the hardened state (Balaguru & Shah, 1992). Silica fume is another important substitute in the development of high-strength concrete, and it is added up to 7% as a supplementary cement replacement material. The specific gravity of silica fume used in the present study is 2.73 and it appears to be in white powdered form. It is well known that the industrial by-products such as fly ash and silica fume are added along with the nominal cement content to reduce the issues related to shrinkage problems in concrete (Sahoo et al., 2020).

2.1.2 Aggregate

River sand and crushed stone aggregate sizes between 12.5 mm and 20 mm with good particle size distribution are used as natural aggregate in the production of concrete. The main properties of both fine and coarse aggregates are shown in Table 2. Combined gradation analysis for the aggregate is performed as per IS 383: 1980 requirements.

2.1.3 Plasticizer and Water

Polycarboxylic ether-based high range water reducing admixture MASTER GLENIUM B233 with solid content not less than 30% is added to attain the desired workability of fiber-reinforced composites. The dosage of PC-based super plasticizers is adjusted between 0.8 and 1.0% of the binder amount to exhibit slump values ranges

Table 1 Properties of OPC53 grade cement and fly ash.

S. no.	Requirements	OPC 53 Grade	Fly ash
1	Fineness amount	282.45 m^2/kg	379.40 m^2/kg
2	Compressive strength 3 days Compressive strength 7 days Compressive strength 28 days	29.50 MPa 41.90 MPa 55.15 MPa	22.80 MPa 30.92 MPa 43.35 MPa
3	Initial setting time	165 min	171 min
4	Final setting time	303 min	309 min
5	Soundness value	0.75 mm	0.93 mm
6	Standard consistency	30%	29%
7	Specific gravity	3.10 g/cc	2.16 g/cc

Table 2 Physical properties of coarse and fine aggregates.

S. no.	Properties	Fine aggregate	Coarse aggregate	
		Passing 4.75 mm	20 mm	12.5 mm
1	Fineness modulus	3.30	2.04	2.83
2	Specific gravity	2.53	2.76	2.75
3	Loose bulk density (kg/m^3)	1632	1530	1506
4	Dry rodded bulk density (kg/m^3)	1732	1656	1576
5	Water absorption (%)	1.2	0.3	0.4

between 100 and 120 mm. PC-based admixture mediate the cement grains to disperse well within the cement matrix and they produce longer and lateral poly-ether groups chains, promoting the long-lasting flowability of concrete and reducing the water content up to 30%. Potable water confirmed to IS 456-2000 is used for mixing and curing purposes.

Table 3 Engineering properties of fibers used.

Properties	Steel fiber	Polyester fiber
Aspect ratio	80	–
Length (mm)	60	12
Diameter (mm)	0.75	12–15 µ
Specific gravity (g/cc)	7.80	1.35
Tensile strength (MPa)	1700	400

2.1.4 Steel and Polyester Fibers

Bright galvanized hooked end low-carbon steel fibers of high tensile strength and ductile nature are used in this study. Hooked end steel fibers have a high elastic modulus and are most common in engineering projects. They are effective in bridging across macro-cracks and preventing crack propagation in the cement matrix. In addition, polyester fibers 12 mm long are chosen as a second fiber in the matrix system because they are effective in suppressing the growth of micro-cracks at the macro-level. Fibers with a high aspect ratio are preferred over their effectiveness in improving the post-cracking performance of FRC composites (Markovic, 2006). Normally, micro-fibers are available in larger numbers in the cement matrix due to their high specific surface area, and they are normally added at lower dosages ranging between 0.2 and 0.9% volume fraction of concrete. In this study, the effects of adding steel and polyester fibers on the toughness and durability aspects of concrete are also explored in detail. Fiber type and volume fraction are taken as the influential factors, and the details of these four series, namely, No fiber concrete, Mono Steel FRC with 0.3%, 0.5%, 0.75% fibers, Mono Polyester FRC with 0.5%, 1.0%, 2.0% fibers and Hybrid FRC with steel polyester fiber combinations are 0.5% S + 1.00% P, 0.5% S + 0.5% P, 0.5% S + 2.0% P, 0.75% S + 1.0% P (S—steel fiber, P—polyester fiber).

Fig. 1 Steel fiber.

Fig. 2 Polyester fibers.

2.2 Mixture Proportion and Specimen Preparation

Two different types of fibers, namely, steel and polyester, were combined to develop the hybrid fiber-reinforced concrete system, and its engineering properties obtained from the manufacturer are given in Table 3. Figs. 1 and 2 show the steel and polyester fibers. Mix design for the production of concrete was performed as per IS 10262:2009 (IS, 10262 2009) guideline to achieve the desired compressive strength of 45 MPa. The concrete mixture proportion of binder:water:sand:gravel is adopted in the mix ratio of 500:172:677:1110 and an effective water–cement ratio of 0.344 is used in all the series to gain the highest strength.

Mixing, placing, and finishing of fiber-reinforced concrete specimens requires special care and attention to attain sufficient workability and hardened properties. A pan type mixer with a capacity of 40 L was employed in the mixing process, and this type of mixer is capable of applying varying acceleration to mix the concrete constituents and fibers together. The varying acceleration action eliminates the formation of dry fiber balls in the production of FRC (Production information brochure 1986). Mixing was performed as per standard guidelines mentioned in the literatures published in FRC technology (Chen et al., 2022; Koniki & Prasad, 2019; Tauqeer et al., 2022; Yao et al., 2003a). FRC needs external vibration, and hence, the fresh mix is poured into steel molds of various sizes and vibrated for 30 s by a table vibrator. After 24 h, the specimens were demolded and continuously kept under immersion curing for 28 days.

Cube specimens with a size of 150 mm are made in each series to test the compressive strength of the composites. Cylinders 150 mm in diameter and 300 mm long were made for the measurement of the split tensile strength and split toughness characteristics. Some durability-related aspects, such as water absorption, water sorptivity, carbonation, and specific electrical conductivity, are tested in 100-mm cube specimens.

2.3 Test Setup and Procedure

2.3.1 Slump Test

The workability characteristics of the freshly prepared mix were obtained by a slump cone test performed according to the ASTM C143 procedure. In the slump test, fresh concrete mix is placed in three equal layers, and each layer is compacted with 25 blows in the frustum of the cone. It is then raised in the vertical direction, and the amount of subsidence is calculated as the slump value in each series. Fig. 3 shows the slump test.

Fig. 3 Slump test.

2.3.2 Compressive and Split Tensile Strength Test

The traditional methods of testing the compressive and split tensile strength are very easy to construct, and their guidelines are well established in IS codal specifications. The compressive strength was obtained in 150-mm cube specimens, and cylindrical specimens 150 mm in diameter and 300 mm long were used to obtain the split tensile strength after 28 days of curing. A compression testing machine with a capacity of 2000 kN was employed in testing and the load was applied at a rate of 14 N/mm^2 per min for compressive strength and 1.8 N/mm^2 per min for the split tensile strength. For each series, three cubes and three cylinders were tested in the CTM, and the average value was taken.

2.3.3 Energy Absorption Capacity (Toughness) Test

Energy absorption capacity is defined as the total area under the stress–strain curve, and it is also mentioned as toughness of the concrete. The initial cracking stress is measured, and it is the point at which the non-linear part of the stress strain curve begins its post-peak behavior. Ductility is the property that makes the concrete undergo a large amount of deformation beyond its peak tensile strength. The total amount of energy measured under the load–deformation curve attains its maximum deformation is considered as toughness. Uni-axial tensile test, split tension test, three-point notched beam bending test, and wedge splitting test are useful methods to obtain the load–deformation characteristics of FRC. Among all these testing techniques, performing a uni-axial tensile test is the most appropriate method to obtain the energy absorption capacity of quasi-brittle FRC composites. Several guidelines are available for the measurement of toughness, and they involve sophisticated testing arrangements and expensive equipment, which is not always possible. Therefore, this investigation attempted to measure the toughness under split tensile loading conditions, which is also known as the Brazilian test or indirect tensile load test, to measure the energy absorption capacity in a simple way. The test is performed in a normal cylindrical specimen with a diameter of 150 mm and a length of 300 mm in a 1000-kN universal testing machine provided with two dial gauges of 0.002 mm sensitivity attached on either side of the diametral portion. Load is applied at a rate of 0.03 mm/min until it reaches peak failure and the corresponding load versus displacement measurements are taken. Fig. 4a, b shows

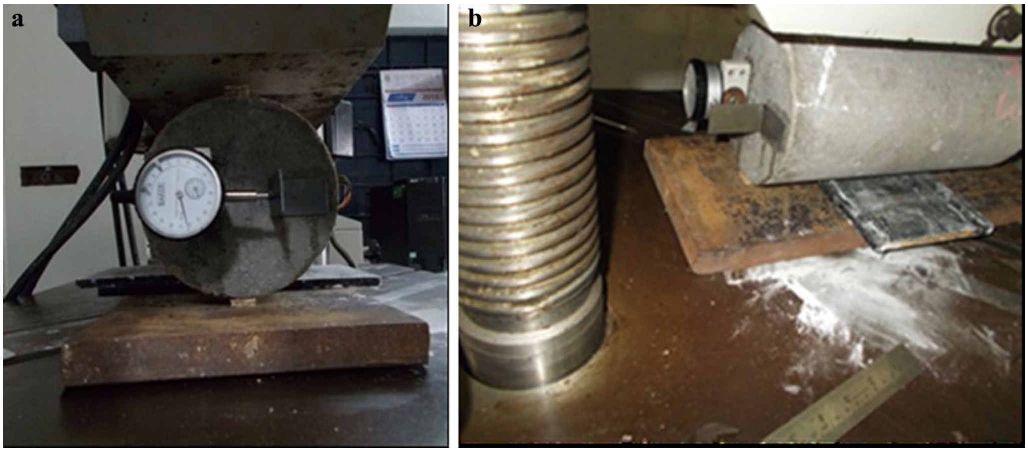

Fig. 4 **a** Testing arrangement of split tensile toughness. **b** Testing arrangement of split tensile toughness.

the testing arrangement, and three cylinders are tested for each series to obtain the load–deformation relationship. The area beneath the load–deformation curve gives the energy absorption capacity of the control, single fiber reinforced and hybrid fiber reinforced composites.

2.3.4 Durability Test

Water absorption is the volume of concrete occupied by the pores connected to the surface (Mohamed et al., 2022). It is considered as one of the most important durability aspects of concrete, and reduced water absorption further improves durability and structural safety. The water absorption test is performed as per the ASTM C-642-97 procedure on 70.5 mm × 70.5 mm × 70.5 mm size cubic specimens after 28 days of curing (Kurda & Brito, 2019; Smyl et al., 2016).

The water sorptivity test includes the water absorption on the surface and interior parts of the concrete specimen. Initial and final water absorption were measured as per the ASTM C 1585-04 procedure in a 100 mm × 100 mm × 100 mm cubic specimen. Samples were oven dried for 3 days before testing and the dry surface was sealed with adhesive tape, leaving the bottom 5 mm to be in contact with water. The actual test setup is shown in Fig. 5. The cumulative water absorption is calculated as the change in the mass of the specimen (m_t) divided by the density of water (ρ) and the exposed area of the specimen (a) in mm^2. Sorptivity is the rate of initial water absorption measured as the increase in mass of the specimen due to water absorption, and it is expressed as a square root function of time. This water sorptivity index is determined by linear regression analysis, in which the points are ranging from 1 min, 5 min, 10 min, 20 min, 30 min, 60 min, 120 min, 180 min, 240 min, 300 min,1d, 2d, 3d, 4d, 5d, 6d and 7d time duration. Ignoring the origin, the slope of the best fit line is reported as sorptivity and the results are discussed.


Fig. 5 Water sorptivity test.

Carbonization depth measurement tests were also carried out by spraying the phenolphthalein indicator solution on freshly exposed surfaces of the concrete specimen broken in the split tensile strength test. Then, it is left for 30 s to react with the alkaline solution existing in the concrete. Pores that turn into pink indicate that the concrete is in an uncarbonized state after 28 days curing, as shown in Fig. 6. Instead, the surface appears to be colorless, indicating that the pH value is less than 9. Then, the concrete is said to be carbonated, which may destroy the protective layer and expose the steel reinforcement to corrosion distress.

Bulk electrical conductivity test were conducted on cube specimens with dimension of 100 mm × 100 mm × 100 mm as per the process stated in ASTM C1760-12. A 60 V dc is applied to the concrete specimens through the steel rods fixed in the cube specimens immediately after removal from the curing tank. Then, the amount of current passing through the hardened concrete specimens was recorded for 1 min.

Fig. 6 Carbonation test.

Electrical conductivity is calculated using the formula, and Fig. 7 shows the test setup:

$$\sigma = K \times I1 \times L/(V \times D2),$$

σ: electrical conductivity, (mS/m), *K:* conversion factor = 1273.2, *I*1: current at 1 min, (mA), *L:* average length of specimen (mm), *V:* applied voltage, (V), *D:* average diameter of specimen (mm).

3 Results and Discussion

3.1 Mechanical Properties of FRC

3.1.1 Slump Values

The slump value is nothing but the subsidence of the specimen and it is expressed in millimeters. The usage of high range water reducing admixtures ensures good compaction and makes the mix workable. The control concrete without fibers showed the highest fluidity and the slump was measured to be 190 mm. However, the workability of the composite decreases with the inclusion of steel and polyester fibers. It is obvious that the addition of steel and polymer fibers causes a network of structure in fresh concrete and prevents the mobility of the coarse aggregate, subsequently decreasing the workability of the concrete. However, the introduction of PC-based admixtures improves the workability properties of concrete and maintains the plastic condition for a sufficient time period, making the slump of single and hybrid FRC in the range of 90–130 mm. This slump region is found to be sufficient for easy mixing, placing and finishing. The slump values taken for all batches of concrete just before the casting are given in Table 4.

3.1.2 Compressive Strength

Table 5 portrays the test results of the hardened concrete specimens. Fig. 8 shows the compressive strength of the control concrete, single FRC, and hybrid FRC series at the age of 28 days. Normally, the addition of fibers in concrete improves the compressive strength in the range of 3–15% greater than that of control concrete (Banthia & Gupta, 2004). The deformed ends of steel fibers play an important role in improving the mechanical anchorage and the fiber bridging capacity across the cracks improves the crack resistance up to 15% relative to control concrete. The same compressive strength decreases when the steel fiber content increases from 0.5 to 0.75% and the polyester fiber content increases from 0.5 to

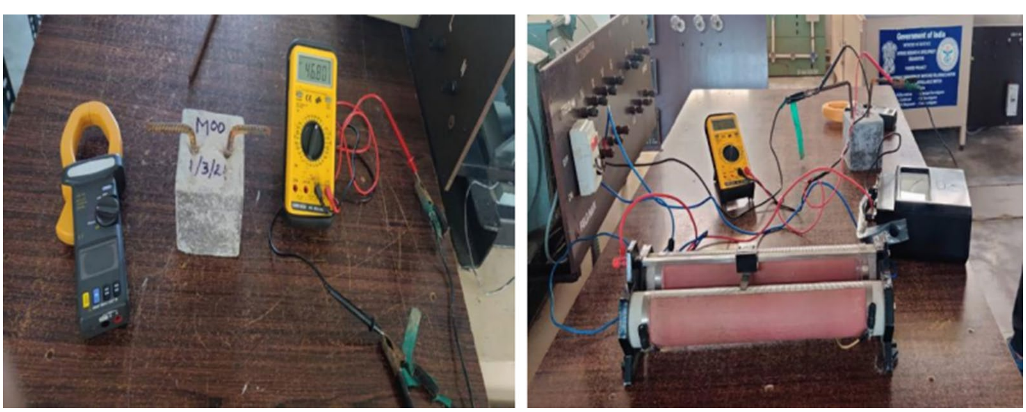

Fig. 7 Bulk electrical conductivity test.

Table 4 Slump test results.

Mix series	Category	Slump values in mm
CC	Control concrete	190
MS 0.3	Steel fiber reinforced concrete	110
MS 0.5		90
MS 0.75		110
MP 0.5	Polyester fiber reinforced concrete	90
MP 1.0		100
MP 2.0		90
HF1	Hybrid fiber reinforced concrete	130
HF2		100
HF3		100
HF4		80

1.0%. Further addition of fibers in the range of 1 to 2% reduces the compressive strength of concrete to a great extent, and these findings are in line with earlier literature results (Jian et al., 2013). This implies that the increase in fiber content decreases the compressive strength due to its improper fiber distribution, and its high porous microstructure develops a weak interfacial zone between fibers and cement paste. Excess fiber addition does not contribute to strength development, and the poor interface between the fiber and cementitious matrix increases the air content and reduces the compressive strength. On the positive side, a 15% improvement is observed in steel fibers because their elastic modulus is higher than the Young's modulus of concrete material, and they can sustain more deformation than brittle concrete. The high tensile stress of steel fibers transfers more load from the cracked matrix to the surrounding fibers, and its hoop effect contributes to a strong interface between the fiber and paste matrix. Steel fiber always leads to higher compressive strength and it is more dominant in the development of the compressive strength of HyFRC. Low modulus polyester fiber in concrete also tend to increases the compressive strength, but their influence is very limited compared to steel which is aligned with the findings reported by Sukontasukkul et al. (2018).

3.1.3 Split Tensile Strength

Fig. 9 demonstrates that the addition of 0.3%, 0.5%, and 0.75% steel fibers enhances the splitting tensile strength by 46%, 63%, and 88%, respectively, and the increase in fiber content produces excellent results. It is obvious that the higher stiffness of steel fiber and its bridging capacity gradually increases the strength of concrete to a great extent (Bentur & Mindess, 2006; Song et al., 2005). Split tensile strength of the polyester FRC first increases with

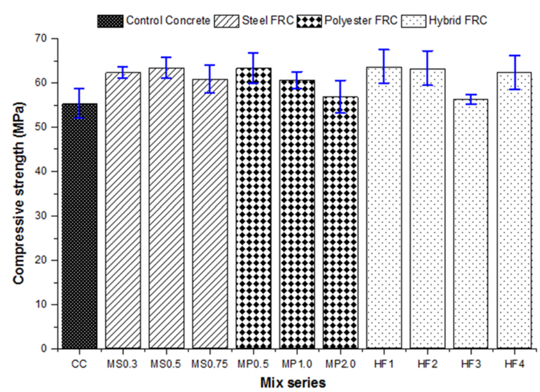

Fig. 8 Compressive strength.

Table 5 Test results of hardened concrete specimens.

Mix series	Fiber volume fraction % Vf		Compressive strength MPa	Split tensile strength MPa	Energy absorption capacity kN-mm (upto 0.4 mm deformation)
	Steel	Polyester			
CC	–	–	55.39	3.53	3.566
MS0.3	0.30	–	62.35	5.14	98.605
MS0.5	0.50	–	63.45	5.75	122.755
MS0.75	0.75	–	60.92	6.62	129.565
MP0.5	–	0.50	63.33	4.45	78.901
MP1.0	–	1.00	60.62	4.17	89.851
MP2.0	–	2.00	56.84	3.80	103.376
HF1	0.50	1.00	63.72	6.06	145.638
HF2	0.50	0.50	63.32	6.07	135.612
HF3	0.50	2.00	56.29	5.85	131.789
HF4	0.75	1.00	62.36	6.35	159.078

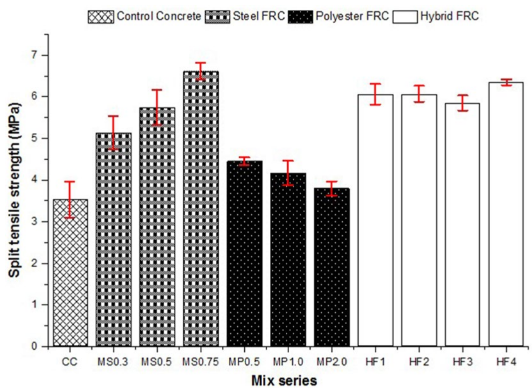

Fig. 9 Split tensile strength.

increase fiber content and then reaches the maximum improvement of 26% when compared to no fiber concrete, but this trend is altered with increasing polyester fiber volume fraction. Previous research demonstrated that steel as a single fiber increases the split tensile strength by 31%, mainly because of the improved crack resistance (Abdulaziz & Yousef, 2022). Therefore, the hybrid FRC series blended with steel and polyester fibers shows a combined effect of different materials at different scales, which controls the splitting failure of concrete due to the diametral compressive load. The hybrid series HF1 and HF2 reaches the maximum split tensile strength up to 72%, in which the micro-fibers are effective in arresting the tiny cracks at lower stress level and the macro-fibers involved in transferring the higher tensile stress wracking the concrete surface (Altalabani et al., 2020). These results emphasize the simultaneous use of metallic and non-metallic fibers in concrete that yields the most positive synergetic effect and is highly beneficial in terms of split tensile strength. Excess fiber content reduces the workability, and a larger void space lowers the split tensile strength, which is the major drawback of fiber-reinforced concrete.

3.1.4 Energy Absorption Capacity (Toughness)

Theoretically, the area enclosed by the load (stress)–displacement curve directly reflects the energy absorption capacity of fiber-reinforced composites. Energy absorption capacity is usually characterized by the term toughness in fiber reinforced concrete. The higher energy absorption capacity (toughness) and ductility of FRC allows a better response of structures subjected to seismic actions, severe loads and fatigue, etc. In this experimental study, the load–displacement (deformation) response of concrete made with polyester and steel fiber and its hybrid combinations are obtained. For comparison purpose, the toughness measurement is estimated up to 0.4 mm deformation in all the series and the results are compared.

3.1.4.1 Single Fiber System Plain concrete is brittle in nature and its sudden drop indicates that the energy absorption capacity is almost negligible. When the load exceeds the peak stress, the micro-crack propagates into the plain matrix and causes sudden explosive failure. Polyester fiber addition shows a better ductile performance in the MP0.5, MP 1.0, MP2.0 series and its absorption capacity is in the range of 78.90, 89.85, 103.38 kN-mm, respectively. The performance of the polyester fiber is truly represented in the post-crack region and its amount of deformation before uncontrollable collapse is observed by its long plateau of the load–deformation curve. As seen from Fig. 10a, the addition of polyester fibers allows unlimited advantages and the increase in fiber content in the MP1.0 and MP2.0 series increases the toughness

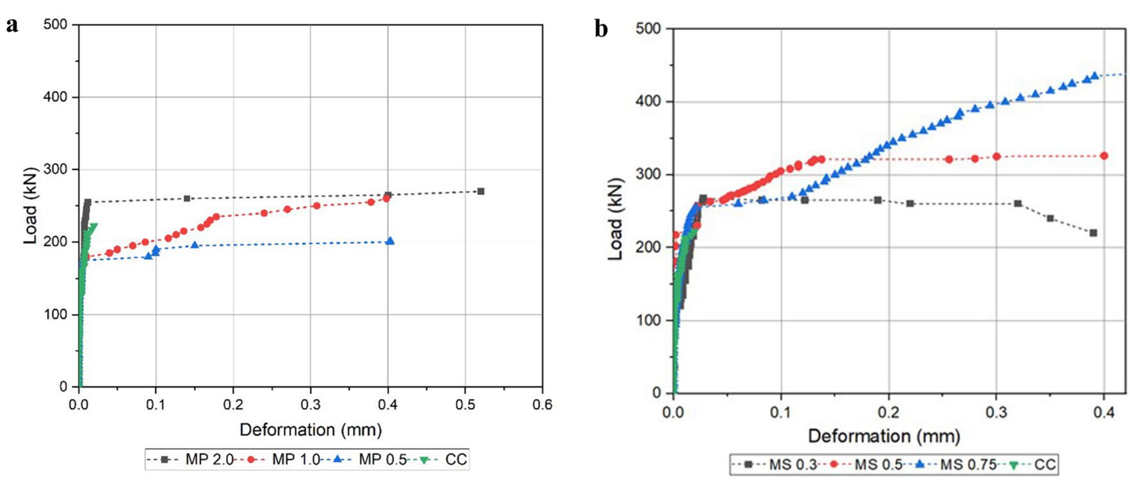

Fig. 10 **a** Effect of polyester fibers on split toughness of single FRC system. **b** Effect of steel fibers on split toughness of single FRC system.

value by 13.87% and 31.02% when compared to the 0.5% polyester fiber series. More fibers available per unit volume and the smaller spacing between them restrained the crack propagation and enhanced the toughness of the concrete, which is similar to the earlier findings reported by Deepa Raj et al. (2013) and Li et al., (2021). Most of these polyester fibers are highly flexible, and their low stiffness enhances the toughness and provides additional strain capacity in the post-cracking zone.

The steel fiber type and volume fraction strongly influence the energy absorption capacity of steel FRC, and the results are shown in Fig. 10b. Control concrete is remarkably brittle in its characteristics. However, the addition of steel fibers in three different volume fractions, namely, 0.3%, 0.5%, and 0.75%, exhibits an energy absorption capacity in the range of 98.60–129.56 kN-mm. Their post-cracking strength improvement is proportional to the fiber content. Toughness values are higher than those of the polyester fiber series and they gradually increase with the increasing steel fiber content. The high tensile strength and elastic modulus made all steel FRC specimens undergo pull-out failure rather than fracture failure in the concrete specimens.

3.1.4.2 Hybrid Fiber System The load–deformation curve for HyFRC specimens and single fiber systems is illustrated in Fig. 11a. HyFRC composite specimens made with a combination of 0.5% steel fiber and 1.0% polyester fiber produces a good energy absorption capacity of 145.64 kN-mm up to 0.4 mm deformation. The excess fiber content in the hybrid series directly affects the toughness value, and the energy absorption capacity of the HF1 series (MS0.5 + MP1.0) is 18.60% higher than that of the MS0.5 series and 62.22% higher than that of the MP1.0 series, proving the improved post-cracking toughness of the composite. Higher stiffness and superior hooked end geometry offers good interfacial bond strength and controls the expansion of cracks. They inhibit the growth of cracks at both micro- and macro-levels and improves the overall toughness and ductility of the composite. Specifically, the micro-cracks in concrete are very important and the small tiny polymeric fibers are effective in controlling the cracks at micro-level initiation. More micro-cracks developed at the tip of the main crack delays the accumulation of stress and exhibit higher toughness than a single steel or polyester fiber systems. Positive interaction between them effectively controls the development of cracks and withstand high loads, which allows larger deformation, and improves the split toughness characteristics of the concrete.

Fig. 11b illustrates the load–displacement behavior of all hybrid fiber reinforced concrete under split tensile loading condition, and all hybrid series shows the greatest energy absorption capacity compared to the single steel and polyester FRC series. The steel polyester fiber combination not only enhances the split tensile strength, but also increases the post-cracking strength in terms of energy absorption capacity. The split toughness values for HF1, HF2, HF3, and HF4 are 146, 136, 132, 159 in kN-mm, respectively. Among the four-hybrid series, HF4 made with 0.75% steel and 1% polyester fibers possesses the highest initial cracking tensile stress, and at this stage numerous micro-cracks have been developed on the surface of the concrete specimen.

Thus, it yielded more energy absorption capacity before the formation of macroscopic cracks and resulted in higher toughness properties. As foreseen, all hybrid fiber reinforced concrete presented improved toughness

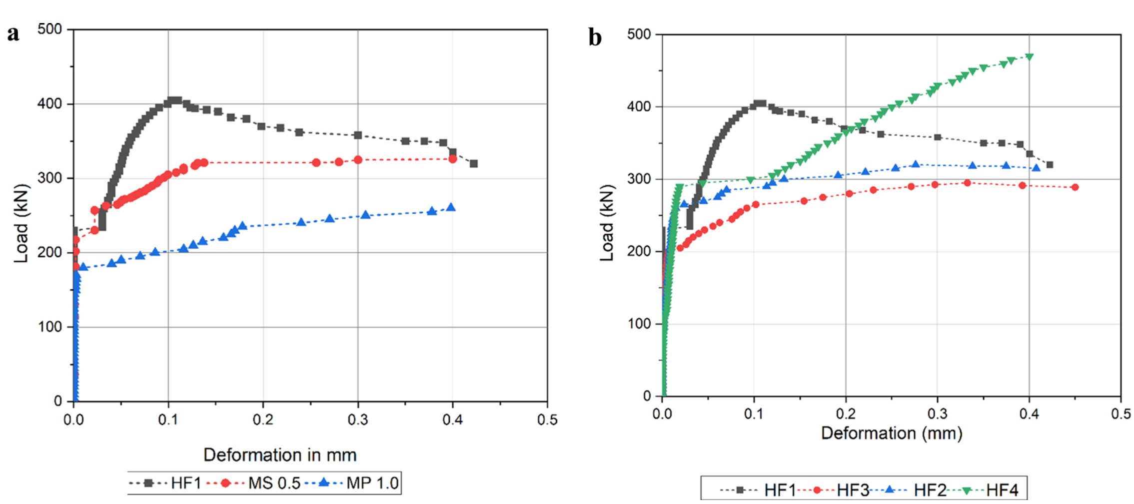

Fig. 11 **a** Load–deformation curve of single and hybrid FRC. **b** Load–deformation curve of hybrid FRC.

through fiber hybridization, and the efficient mixing procedure presented a regular distribution of steel and polyester fibers. More fibers in the hybrid series facilitates the effective dispersion of stress under loading condition and delay the crack formation. Fibers of different types at different volume fraction added to the same composite restained cracks at various levels enhancing the post-cracking behavior of the composite (Chen & Liu, 2005; Mobasher & Li, 2005; Yao et al., 2003b). Therefore, due to the synergic effect of steel–polyester fiber combinations these composites could be considered as a reasonable candidate in many practical application such as structural repair work in bridges, pavements and offshore construction works.

3.2 Durability Properties of FRC

3.2.1 Water Absorption

Fig. 12 shows the water absorption values of the concrete series made with no fiber, single polyester fiber (P), and hybrid series made with polyester steel fiber combination (P + S). The absorption percentage of 0, 0.2P, 0.3P, 0.2P + 0.3S and 0.3P + 0.5S specimens are 4.33%, 3.86%, 3.45%, 3.47%, and 3.52%, respectively. It is understood that the absorption of water is an excess in control concrete while compared to the other fiber series, and the highest water absorption affects the compressive strength properties of concrete. The addition of fibers changes the pore structure and controls the micro-cracks, and their connectivity between them led to the conclusion that the steel fiber reinforced specimens have higher water absorption than the specimens with polyester fibers (Usman Rashid, 2020). For concrete specimens containing single polyester fiber series 0.3P and hybrid series 0.2P + 0.3S and 0.3P + 0.5S the absorption percentage are almost equal. The addition of 0.3% polyester fibers shows the lowest value among all fiber series. Adding polyester fibers 0.2%, 0.3% in concrete decreases the water absorption by 10.85% and 20.32% since they are very flexible during compaction and effective in filling up the voids; subsequently, their performance is most beneficial in enhancing the durability properties of concrete (Simões et al., 2018). It is worth mentioning that these test results are consistent with Hesami et al. experiments in which the water absorption values decrease with the increase in fiber content (Hesami et al., 2016). Their dosage is also essential, and beyond the optimal level, any excess dosage may cause damage to the pore structure and increase the water absorption. Polyester fiber when added to the steel fibers in the hybrid series reduced the water absorption by 19.86% because of the fiber hybridization and the presence of both fibers in the interfacial zone between the aggregate and cement matrix decreases the water absorption percentage in all fibrous systems (Dawood & Hamad, 2015). The curling nature of polymer fibers in concrete composite make them less susceptible to water absorption and offers more benefits in enhancing the durability properties of concrete (Usman Rashid, 2020) The enhanced bond between the cement matrix and fibers increases the homogeneity and solidity of the concrete specimen and thereby reduces the water absorption in FRC series (Hesami et al., 2016; Simões et al., 2018).

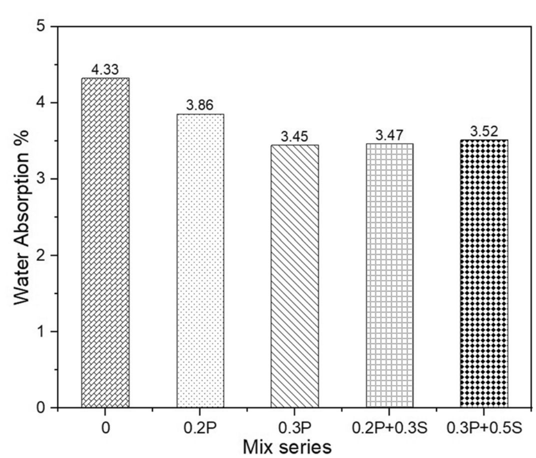

Fig. 12 Water absorption of FRC with various fiber content.

3.2.2 Bulk Electrical Conductivity

Fig. 13 shows the significant influence of fibers on the electrical properties of the concrete. The electrical conductivity value slightly increases from 12.764 to 17.688 mS/m when the polyester fiber content is increased from 0.2 to 0.3%. In hybrid fiber-reinforced mixture, the presence of steel fibers dramatically increases the conductivity and reduces the electrical resistivity of concrete. The test results of the 0.2P + 0.3S and 0.2P + 0.5S fiber combinations were reported to be 1.65- to 2.23-fold greater than the conductivity values of the control concrete. The presence of steel fibers shows enormous increases in

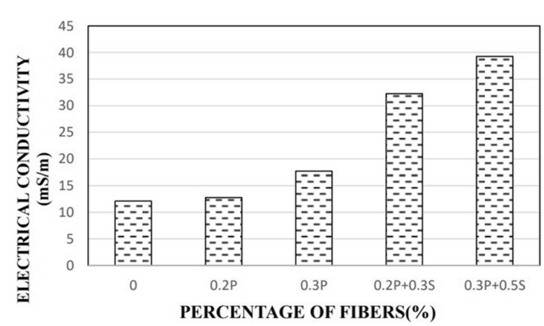

Fig. 13 Electrical conductivity of FRC with various fiber content.

electrical conductivity and their volume fraction, aspect ratio, and hooked end have a significant influence on the electrical properties of the concrete. Previous research conducted by Afroughsab et al. on polypropylene and steel fiber reinforced composites concluded that steel fiber significantly decreases the electrical resistivity of concrete (Ozbakkaloglu, 2015). Ali Ahmed et al. reported that the resistivity of concrete increases at later age due to the formation of hydrated products that fill up the voids and controls the transportation properties of the cement concrete (Ali et al., 2021).

3.2.3 Water Sorptivity

Fig. 14 represents the average water sorptivity results of hybrid fiber series 1 and 2 made with 0.2% polyester combined with 0.3% steel fiber and 0.3% polyester combined with 0.5% steel fiber. Regression analysis of the best fit slope produces the regression co-efficient greater than 0.98, indicating that the sorptivity and square root of the time relationship is linear. Water sorptivity measures the capability of cementitious materials to absorb water through the capillary pores and it gives the amount of moisture ingress through the concrete. It indirectly represents the volume of pore permeability and interconnectivity between the pores on the unsaturated concrete surface. The presence of micro-fibers changes the pore structure connectivity and controls the cracking behavior of concrete (Li et al., 2022). The test result reveals that the presence of fibers in the hybrid combination lowers the water absorption and that the sorptivity value decreases with the increase in the amount of fibers. Usman Rashid et al. worked on hybrid FRC reported that polymer fiber decreases the sorptivity and always yields durable hybrid fiber reinforced concrete (Usman Rasid, 2020). The addition of hybrid fibers demonstrated excellent quality in terms of water permeation and effectively prolonged the service life of the concrete structures exposed to aggressive environment.

4 Conclusions

This study investigated the influence of single steel fibers, polyester fibers and hybrid series made with polyester and steel fibers combinations on the mechanical and durability properties of concrete. Control concrete without any fiber is also made as a reference to analyze the performance of concrete. Based on the obtained results, the following conclusions were drawn:

(1) A single fiber series of steel and polyester improved the compressive strength by up to 14% for 0.5% volume fractions, whereas higher dosages of polyester fibers improved the compressive strength by only 3%. Although it is obvious that fiber addition improves the compressive strength, higher dosages tend to lower the percentage improvement owing to inefficient compaction and air intrusion during the mixing process, which is uncertain.
(2) Hybrid fiber-reinforced concrete made with a combination of 0.5% steel and 1% polyester fibers indicates a marginal improvement in compressive strength, and hybridization did not play any large role in enhancing the compressive strength.
(3) At the lowest percentage, the combination of polyester fiber with steel produces a 63% to 72% improvement in the split tensile strength of concrete over plain concrete. However, a larger volume fraction of polyester fibers combined with steel significantly reduced the split tensile strength. The micro-polyester fibers were effective in controlling the micro-cracks in the initial phase, and the long steel fibers activated at larger cracks in the later stage enhanced the split tensile behavior.
(4) Toughness under split tension capacity was enhanced between 26 and 72% for the hybrid FRC series in comparison with a single FRC series made with steel or polyester.
(5) The inclusion of polyester fibers increased the initial stiffness of the specimen and delayed the initial

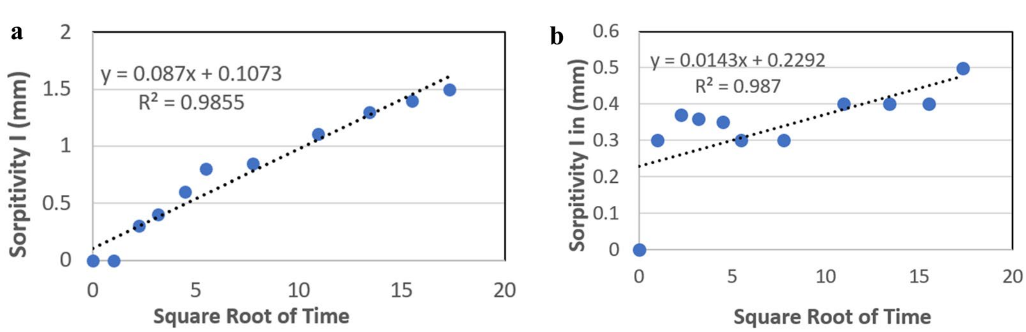

Fig. 14 **a** Sorptivity (initial water absorption). **b** Sorptivity (initial water absorption).

cracking of the hybrid FRC composites under split tensile loading conditions. Hence, the initial cracking stress of hybrid FRC was 69% greater than that of the mono-steel fiber. The synergistic effect could be attributed to the smaller length of the polyester fibers compared to that of the steel fibers, thereby mitigating the crack formation at initial stages.

(6) HyFRC combination reduces the water absorption by 10–20% compared to the control concrete. A strong ITZ zone causes no carbonation effect on the single and hybrid fiber reinforced composites. Electrical resistivity decreases with the increase in steel fiber content and the addition of steel fiber increases the conductivity value up to 2.23 times because of the free movement of electrons.

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CG (Associate Professor) contributed to problem identification, literature collection, experimentation design and data analysis and manuscript preparation. RG (Principal Scientist) contributed to conceptualization, writing—review and editing, acquisition, supervision, validation. SS (Professor) contributed to problem identification, literature collection, experimental design, manuscript preparation data analysis, manuscript preparation. DKE and DK P (UG student) contributed, experimental design and manuscript analysis. All authors read and approved the final manuscript.

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