Journal of Ceramic Processing Research. Vol. 25, No. 5, pp. 717~726 (2024)
(Received 1 December 2023, Received in revised form 10 May 2024, Accepted 11 June 2024)
https://doi.org/10.36410/jcpr.2024.25.5.717

J O U R N A L O F
Ceramic Processing Research

Sustainability development using fiber-reinforced concrete beams with partial replacement of fine aggregate with recycled waste tire rubber powder

Thiagarajan Kumanavallal[a] and Umamaheswari Nambiappan[b,*]
[a]*Assistant Professor, Department of Civil Engineering, Adhiparasakthi Engineering College Melmaruvathur 603319, Tamilnadu, India*
[b]*Professor, Department of Civil Engineering, SRM Institute of Science and Technology, Kattankulathur-603203, Tamilnadu, India*

Dumping of Waste tire rubber is growing and posing serious problems for the environment. Therefore, research on recycling and treatment of waste tire rubber is becoming practised on a large scale. Treatment of waste tire rubber by thermo-mechanical devulcanization is found to enhance both mechanical properties and environmental conditions as the process does not include chemical substances. The present research highlights the findings of experimental analysis performed on the mechanical properties of normal and rubber concretes (RC) of grade M30 and M60 and the behaviour of 5-Dimensional (5D) steel fiber (fiber provided with additional hooks at both ends) incorporated in steel-fiber reinforced concretes (SFRC) beams (M30, M30RC, M60 and M60RC). The fibres are pre-coated with zinc phosphate to increase the bond mechanism and their frictional resistance thus resulting in higher load-carrying capacity. The compressive and split tensile strength of the SFRC specimen increases by 15.54 and 69.7% for pre-coated 5D steel fiber added in M60 concrete. The modulus of elasticity of RC reduces by up to 12.26% for grade M60 concrete. The ultimate strength of pre-coated 5D SFRC beams increases by up to 13.04 and 17.94% for M60 normal and RC respectively. The performance of devulcanized crumb rubbers in concretes was identified to be better in terms of flexural strength and modulus of elasticity when compared to normal crumb rubber concrete.

Keywords: 5-Dimensional steel fiber, Chemical treatment, Flexural strength, Rubber concrete, SFRC.

Introduction

Waste tire rubber is currently affecting environmental sustainability which is becoming a global concern. Recycling and reusing the waste tire rubber is the only possibility for maintaining a sustainable and greener environment. Rather than considering normal conventional concrete, it is forced to implement sustainable alternatives in construction. Even a minimal usage of resources of recycled materials could bring some balance to environmental sustainability. Recent investigations have made it clear that the use of crumb in some cases revealed an insufficient interfacial transition area between aggregate and cement because there was more air on the surface of the rubber crumb, which resulted in poor bond quality and microcracks that caused an abrupt and premature failure as well as decreased ultimate [1, 2]. Because crumb rubber has a very high water absorption capacity, there is a chance that the cement and aggregates could form porous layers that will weaken the concrete's compressive strength [3]. As a result, it must find a different way to reuse the rubber particles from used tires. Previous researchers have examined a variety of recycling procedures, including pyrolysis, burning, pulverization, grinding, reclamation, and microwave and ultrasonic treatments. Cross-linked rubber particles have a three-dimensional network that makes the material intractable and non-melting, making devulcanization and repurposing extremely difficult [4, 5]. Waste rubber devulcanization is the process of converting recycling wastes into different rubber-induced goods by thermal milling, mechanical grinding, and chemical assistance from tire rubber industries. The reactor's several components work together to crush rubber to minuscule sizes by applying high temperatures and shear forces. The term "thermo-mechanical devulcanization" refers to this process. In this experiment, the materials gathered from the devulcanization procedure served as a substitute for fine aggregate. To compensate for the strength loss resulting from the inclusion of reused rubber particles, additional strength-infusing material must be added to the concrete. The SFRC (steel fiber reinforced concrete) has been utilized in modern constructions in recent years and has firm improvement in their concerned fields as the application has widened in composite constructions, pavement, repair and rehabilitation works. As the coral provision for FRC developed, ACI Committee 544 (1996) [6] described FRC (fiber reinforced concretes)

*Corresponding author:
Tel : +91 97916 79150
E-mail: umamahen@srmist.edu.in

as the composite material including cement, fine and/or coarse aggregates, and discontinuous discrete fibers. It is observed from the previous research that randomly oriented fibers with uniform distribution are found to possess very high-stress transfer at the concrete. The ultimate progress of the tensile, bending, and shears properties of the composite materials. The bond mechanism of 5D steel fiber with devulcanized rubber concrete proved to possess higher resistance to pullout load than the hooked end and 4D steel fiber due to its additional anchorage [7, 8]. Generally, FRC comprises fiber volume from 0.1% to 3%, based on their mixture proportion and fiber type, geometry, type of concrete and orientation (ACI 544.5R-10 2010) [9]. A higher percentage of fiber could hamper workability, leading to a non-uniform orientation of fibers and a higher material cost. The proportion of steel fiber in concrete counteracts compression and tensile forces at a particular percentage, and the workability of high concrete with the addition of fiber potentially improved with the tensile strength and toughness. It is known from research that the compressive strength of SFRC typically varies between 60-100MPa [10, 11] specifying that the compressive strength upsurges at the volume fraction of 1.5% steel fiber that portrays the highest concrete/fiber capacity is achieved at the volume fraction of 1-2%. The above research shows that high-strength concrete and other strength-inducing materials can increase those properties, which causes the fiber to slip by attaining its maximum strength, and de-bonding of fibers from the matrix occurs frequently, which leads to fiber failure [12]. The factor of increase in bond behavior of SFRC typically depends on the fiber/matrix behavior. SEM examination confirms that processing the steel fibers with zinc phosphate (ZnPh) [13] improves the fiber/matrix properties. The study's results show a good improvement in bond strength of 40-50% [14, 15].

When employed in place of cement in concrete, silica fume's high SiO_2 content allows it to absorb calcium hydroxide created during the cement's hydration process, hence improving the concrete's compressive strengths and other characteristics [16, 17]. When applied to concrete in different strengths and quantities, silica fume has a variety of notable and distinct impacts [18]. The incredibly fine powder that is obtained as the byproduct of silicon and ferrosilicon has an average diameter of 0.1 microns and a particle size of less than 1 micron, making it easy to pack with cement-based composites. Additionally, the effectiveness of silica fume was assessed empirically and experimentally about concrete's flexural strength. Empirical correlation equations were utilized to develop associations between split tensile and compressive strength as well as between flexure and compressive strengths for five distinct SF replacement percentages [19, 20]. The research determined that a percentage of 10-20% silica fume was the most effective in improving both tensile and flexural strengths. This study discusses the use of ceramic waste powder as a partial cement replacement and coir fibers as a reinforcement in concrete, aiming to enhance its tensile properties while reducing environmental impact. Results indicate that the combination of ceramic waste powder and coir fiber achieved the highest strength compared to control concrete [30-32]. The interface failure mechanism of rubber cord composites laid at symmetrical angles using a finite element method and an energy-based power law for damage evolution simulation. It highlights the role of torque in interface damage and the importance of initial interface stiffness in damage evolution, showing a positive correlation between initial stiffness and damage evolution [33]. This study introduces the mechanical properties of sustainable concrete with various replacements (15% silica fume, GGBS, and 5-20% bottom ash) in an M50 grade mix. Results show that 15% GGBS replacement offers superior mechanical properties, supported by XRD, SEM, and EDAX characterizations indicating good surface area and angular texture for improved bonding [34]. This study addresses the alternative concrete formation by using the Waste Tyre Steel Fibre (WTSF) and Waste Tyre Rubber (WTR) as a components instead of sand. Evaluate the WTSF dosage ratio, size and volumetric property and by performing the mechanical tests. The substitute cement materials and particle packing theory employed for optimizing the mixing of concrete and shows efficient improvements in the sustainability and mechanical strength [35]. This study estimates the performance of materials such as, by products of ceramic, waste sand used for instead of natural component of concrete beams with steel cord. To evaluate the methods effectiveness with varying materials in the context of finding the concrete mechanical property, this study assess the effects of various waste aggregate types and fiber-reinforcement ratios (0.0%, 0.5%, and 1.0%) on the compressive strength, modulus of elasticity, beam deflections, and crack development over a 1000-day period [36]. This study estimates the various concrete materials such as, crushed clay bricks, rubber tire and crushed glass as a substitute of eco-friendly material of a concrete. Here, assess the various properties of concretes as elasticity, compressive strength and structure also captured and compared. Then find the feasible alternative components with minimum environmental impacts concrete material serves the conventional concrete with better performance.

The addition of recycled waste materials in the research of concrete is to create an environmentally sustainable condition. This research involves experimentation on the flexural behaviour of the concrete beam with 5D steel fibers. The use of pre-coated steel fiber with devulcanized rubber is considered a novel aspect in this investigation which is extremely limited. In two distinct patterns concrete strengths (30 and 60 MPa), with and without devulcanized rubber, the fibers receive chemical treatment, and their flexural behavior is compared with that of the untreated fiber. One essential ingredient to mitigate the effects of using devulcanized rubber is silica fume. The remaining part of this paper is organized as an experimental investigation including the material and mix proportions and discussion of experimental results including compressive and split tensile strength, modulus of elasticity, and failure modes with load-deflection curves of SFRC beams.

The paper's focus on recycling waste tire rubber for concrete production aligns with global sustainability goals, highlighting the need for sustainable alternatives in construction. The use of devulcanized rubber as a replacement for fine aggregate, along with steel fiber reinforcement and silica fume, demonstrates a novel approach to enhancing concrete properties.

Experimental Investigation

Materials and Methods

This investigation examines the flexural behavior of pre-coated 5D steel fibers through experimentation. Using the dimensions of length (60 mm), diameter (0.9 mm), and aspect ratio (l/d = 65), commercially available Dramix 5D was employed. The purpose of pre-coating the fibers with zinc phosphate (ZnPh) solution is to improve the frictional resistance and contact between the fiber and the concrete matrix. To submerge steel fibers in ZnPh, they must first be surface cleaned [13]. As the surface of the steel fiber mimics a rugged topography with enhanced corrosion resistance, there is strong agreement with the chemical coating [14]. The proposed system's thermal characteristics refer to its ability to withstand and manage temperature variations. Temperature can significantly impact concrete properties, such as its strength, durability, and setting time, highlighting the importance of designing concrete mixes that can resist thermal stresses and maintain structural integrity over a wide range of temperatures.

The four concrete proportion mixes, M30, M30RC, M60, and M60RC, are each composed of different materials, including high-strength concretes with and without devulcanized rubber and standard concrete with and without devulcanized rubber and silica fume, at a water/cement (w/C) ratio of 0.40 and 0.31 in each mix. When it comes to materials, these concrete strengths use various batching and mixing techniques. ACI 211.4R-08 (2008) [21] provides the mixture proportions for M30, M30RC, M60, and M60RC concrete mixes.

Zone III contains the fine aggregate, which has a specific gravity of 2.65 [22], as per IS- 383:2016. Flexural testing uses a 20 mm coarse aggregate. The coarse aggregate characteristics are defined by IS 2386: 1963 part III, with a particular gravity of 2.62. For flexural testing, 20 mm is considered coarse aggregate. The use of 0.11 μm-sized silica fume improves the density of packing and strength of high-strength concrete. For high-strength concretes of M60 grade, silica fume is used at a 10% cement replacement rate. In this investigation, concrete contains 7% more devulcanized rubber in place of fine aggregate. Table 1 displays the mix proportion for each of the different concrete mixes.

Specimen Preparation

This experimental study examines the flexural behavior of pre-coated 5D steel fiber SFRC beams. Rubber concrete, fibre chemical treatment, and concrete strength are among the many variables that are taken into account. Contrary to flexural behavior, which involves the same number of concrete batches but the addition of steel fibers, flexural behavior involves four different types of concrete batches, each with a different material composition. These include standard concrete with and without devulcanized rubber and high-strength concrete with and without devulcanized rubber. The laboratory pan mixer was used to dry mix the aggregates after they were placed in batches and given a few turns. Super-plasticizer is introduced to the roller together with aggregates at the specified % after being premixed with water. For studying the flexural behaviour of the beam, the beam of size 1 m × 0.15 m × 0.2 m was cast with cubes of 150 × 150 mm and cylinders of 150 mm diameter and 300 mm length. The coating process for 5D steel fibers with zinc phosphate involves surface cleaning of the fibers followed by submersion in a zinc phosphate (ZnPh) solution. This process enhances the fibres' frictional resistance and contact with the concrete matrix, improving overall performance. In the specimen preparation process, curing conditions typically involve maintaining a constant temperature and humidity for a specified period. Vibration techniques are used to ensure proper compaction of the concrete mix, while quality

Table 1. Mix proportion of Concrete Specimens [29].

Mix Designation	Cement (kg/m^3)	w/C ratio	F.A (kg/m^3)	C.A (kg/m^3)	Steel Fiber (1%) (kg/m^3)	Super Plasticizer (kg/m^3)	Silica fume (kg/m^3)
M30 CC	389.4	0.4	676.3	1063.5	78.5	-	-
M30 RC	389.4	0.4	628.7	1063.5	78.5	-	-
M60 CC	480	0.31	520.8	1107.8	78.5	4.64	48
M60 RC	480	0.31	484.5	1107.8	78.5	4.64	48

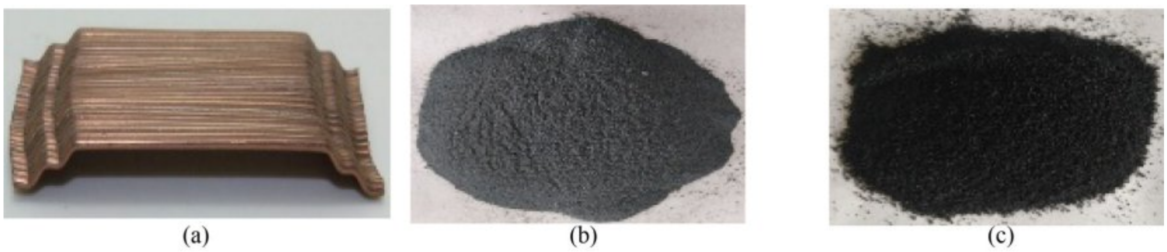


Fig. 1. (a) Type of Fiber, (b) Silica Fume, (c) Rubber Powder.

control measures include regular monitoring of mix proportions and casting procedures.

Flexural test on SFRC beams comprises 12 specimens that are cast with and without 5D fiber of the volume fraction of 1% for M30, M30 rubber concrete, M60 and M60 rubber concrete. Before concreting, the strain gauge is attached to the reinforcement. After 28 days of curing, the outer surface of the test sample was also pasted with the strain gauge. The same concrete mixes are utilized to identify the compressive strengths and the split tensile strengths. When compared to untreated fibers, the inclusion of pre-coated fibers greatly improved the ultimate load and general behavior of the concrete, indicating the impact of treated 5D steel fibers on concrete performance. The pre-coating of zinc phosphate significantly improved the fiber-to-concrete matrix contact and frictional resistance. This improvement led to considerable enhancements in compressive strengths and split tensile strengths for CCM60-treated fiber specimens compared to untreated ones. Additionally, in flexural behavior, CCM60-treated fibers positively impacted the ultimate load over untreated fibers. Moreover, the treated fibers demonstrated a more controlled failure mode, displaying superior energy absorption and anti-cracking capabilities. This underscores the beneficial effect of surface treatment on optimizing the interaction between fibers and concrete, resulting in improved concrete performance overall. Fig. 1 represents the type of steel fiber with silica fume and rubber powder.

Flexural Testing of SFRC Beams

The experimental test setup for the flexural behaviour of the SFRC beams is shown in Fig. 2 illustrates the test setup of flexural testing of SFRC Beams used in this research. The beam is supported symmetrically over a span and load was employed at the middle third of the span which load is distributed equally. Before testing, each specimen was checked for alignment within the testing apparatus. LVDT is placed in the bottom face at mid-section to note the deflection. The deflection readings of the specimen were tested at different loading intervals, and the measurements were made using the LVDT. The load in the first, and last crack and crack pattern were also captured. The beam was loaded to the failure and taken as the maximum load (P). The automatic data acquisition technique is used to record load and deflections. Concrete cubes and cylinders were tested according to IS 516 (2006) to evaluate compressive strengths and split tensile strengths in the same flexural testing [23].

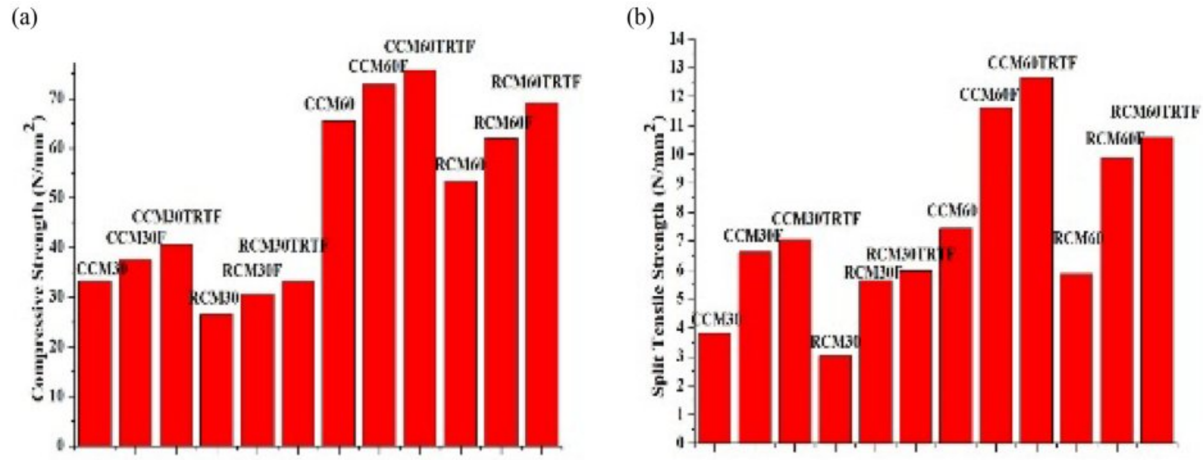
Fig. 2. Test Setup of Flexural Testing of SFRC Beams.

Results and Discussion

Compression and Split Tensile Strength

The split tensile and compressive strengths of the cube and cylindrical SFRC specimens are presented in Fig. 3 (a) and Fig. 3(b), as a failure of the specimen without fiber. Figures demonstrate that cubes and cylinders with CCM60-treated fiber specimens possessed the greatest strength with a higher load-bearing capacity [10, 11]. The failure pattern of the treated fibre-treated cylinders also demonstrates that specimens experienced only multiple cracks throughout their length, resisting the failure of the specimen.

The compressive strengths of CCM30-treated fiber samples and CCM60-treated fiber specimens increased to 21.7 and 15.54% when compared to the conventional specimens CCM30 and CCM60. The compressive strengths of RCM30 treated fiber specimens and RCM60 treated fiber specimens increased up to 25.45 and 29.45% when compared to RCM30 and RCM60 conventional



*CCM30-M30 Conventional concrete CCM30F- M30 Untreated fiber concrete CCM30TRTF-M30 Treated fiber concrete RCM30-M30 Rubber concrete RCM30F- M30 Untreated fiber rubber concrete RCM30TRTF-M30 Treated fiber rubber concrete CCM60-M60 Conventional concrete, CCM60F- M60 Untreated fiber concrete CCM60TRTF-M60 Treated fiber concrete RCM60-M60 Rubber concrete RCM60F- M60 Untreated fiber rubber concrete RCM60TRTF-M60 Treated fiber rubber concrete.

Fig. 3. (a) Compressive Strength, (b) Split Tensile Strength.

specimens. The split tensile strength of CCM30 treated fiber specimens and CCM60 treated fiber specimens increased to 85.53 and 69.7% when compared to CCM30 and CCM60 the conventional sample, the split tensile strength of RCM30 treated fiber specimens and RCM60 treated fiber specimens increased up to 97.68 and 81% compared to RCM30 and RCM60 conventional specimen respectively. In the case of specimens prepared with rubber concrete of high grade, the addition of fibers tends to possess higher compression and split tensile strengths when contrasted to the conventional devulcanized rubber concrete but the overall strength is reduced due to the addition of rubber powder [24]. The devulcanization process of rubber typically involves high temperatures ranging from 150°C to 220°C and durations of 1 to 4 hours, depending on the specific rubber material and desired properties.

Modulus of Elasticity

Figure 4 depicts the modulus of the elasticity test setup, and Fig. 5 shows the associated failure. Fig. 6(a), (b), (c), and (d) depict the stress-strain curves for standard concrete of grade M30, standard concrete of grade M60, rubber concrete of grade M30, and rubber concrete of grade M60, respectively, based on the results of the concrete modulus of elasticity test. The effect of the addition of 5D treated steel fiber had a linear variation in the stress-strain pattern when contrasted to the standard concrete. In contrast to the other specimens, the concrete containing devulcanized rubber exhibited a marginal reduction in its modulus of elasticity. This result is consistent with the concrete's split tensile strength and compression strengths [25]. The modulus of elasticity of reduced by up to 20.28 and 12.26% for RCM30 and RCM60 specimens when compared to CCM30 and CCM60.The modulus of elasticity of reduced by up to 23.6 and 15.2% for the RCM30 treated

Fig. 4. Test Setup of Modulus of Elasticity test.

Fig. 5. Failure of Specimens due to Modulus of Elasticity test.

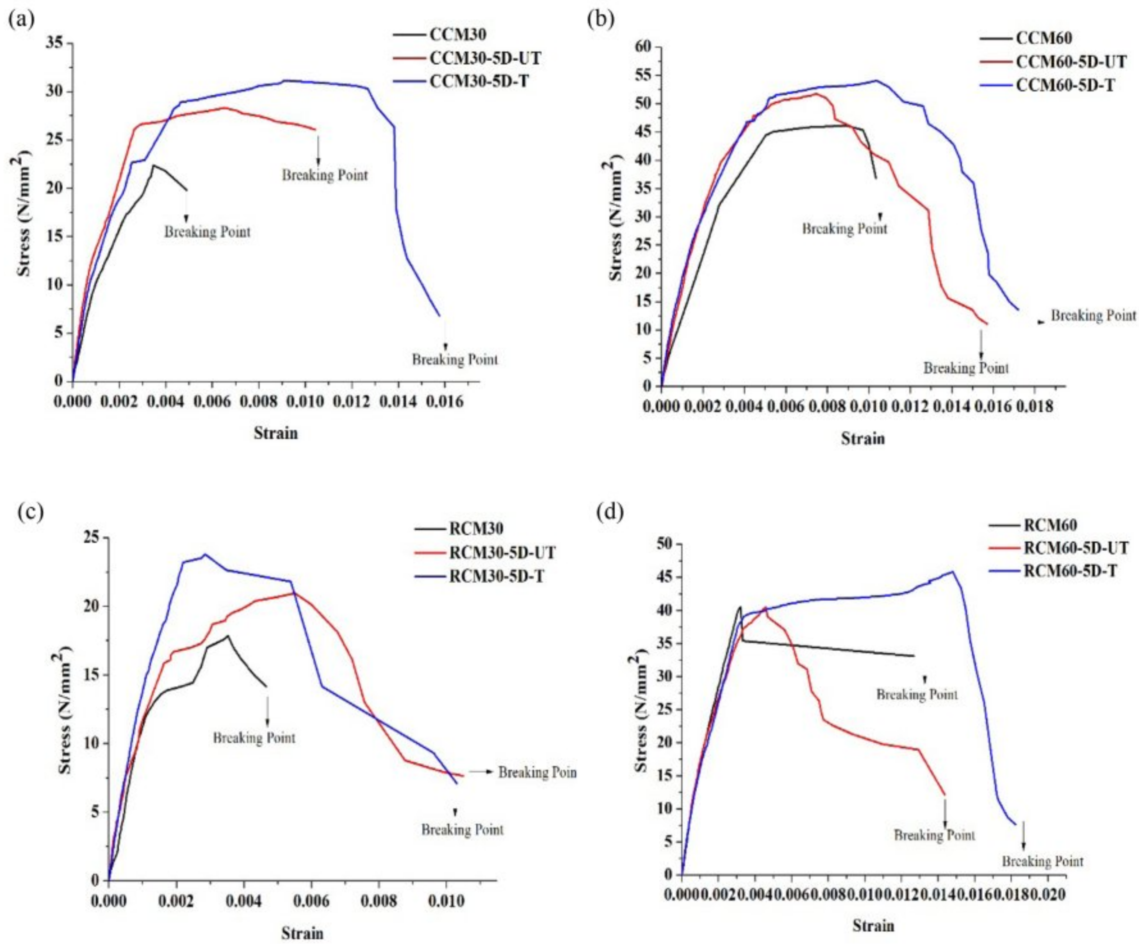


Fig. 6. Stress-strain curves for (a) CCM30, (b) CCM60, (c) RCM30 & (d) RCM60.

fiber specimen and RCM60 treated fiber specimen when compared to the CCM30 treated fiber specimen and the CCM60 treated fiber specimen. The results of the current experiment indicate that devulcanized rubber could be used as replacement material and are similar to the results of previous research [26]. The significance of achieving a balance between the modulus of elasticity and flexural strengths in the concretes, through the combined inclusion of steel fiber and devulcanized rubber powder, lies in its consequential impact on sustainability. This equilibrium fosters a composite material that, despite a slight reduction in elasticity, augments its flexural strength and ductility. The incorporation of steel fiber enhances flexural strength while devulcanized rubber powder contributes to increased crack resistance and energy absorption. This balanced composition extends the structure's durability, minimizing maintenance needs, and fortifies its ability to withstand natural stresses and cyclic loading, thus promoting sustainability in construction practices.

Flexural Behavior of SFRC Beams

Failure modes

The failure modes of beams under a two-point bending load are shown in Fig. 7. Samples with 5D steel fibers underwent a similar failure process in both high and normal-strength concretes rather than conventional concrete. The initial crack was found at the bottom of the mid-range on all vertically developed specimens until the ultimate failure load. whereas when comparing the specimens with devulcanized rubber concrete, the initial and main cracking intensity was lower compared to the conventional concrete [27]. Even though the beams did not undergo ultimate load as CCM60 treated fibers, the crack initiation and the intensity of the crack were lesser, this suggests that the addition of rubber powder might augment the concrete's ability to absorb energy and enhance anti-cracking performance. Additionally, the incorporation of 5D steel fibers with devulcanized rubber concrete appeared to be a beneficial substitution as it not only restrained cracking but also provided significant post-peak strength [28]. The combination of treated fibers and rubber powder, while impacting the maximum load at failure, appears to contribute positively to the concrete's overall behavior by improving its resistance to crack propagation and potentially enhancing its energy-absorbing capabilities. The choice of 5D steel fibers with a length of 60 mm, diameter of 0.9 mm, and

Fig. 7. a) Failure of Conventional Beam under Flexural Testing b) Failure of all Beams Under Flexural Testing.

aspect ratio of 65 is based on their ability to enhance the flexural behavior of concrete by providing effective reinforcement and improving the bond with the concrete matrix due to their specific dimensions and aspect ratio.

Load-Deflection Curves

Load vs. Deflection curves obtained from flexural testing of concrete are illustrated in Fig. 8(a), (b), (c) and (d) for conventional concrete of grade M30, conventional concrete of grade M60, rubber concrete of grade M30 and rubber concrete of grade M60 respectively. The replacement of rubber powder resulted in a decrease in ultimate load when compared to the conventional concrete. The low tensile strength of devulcanized rubber cement may help to explain this. Rubber powder enhances concrete's water absorption, which causes the interfacial transition zone between the powder of rubber

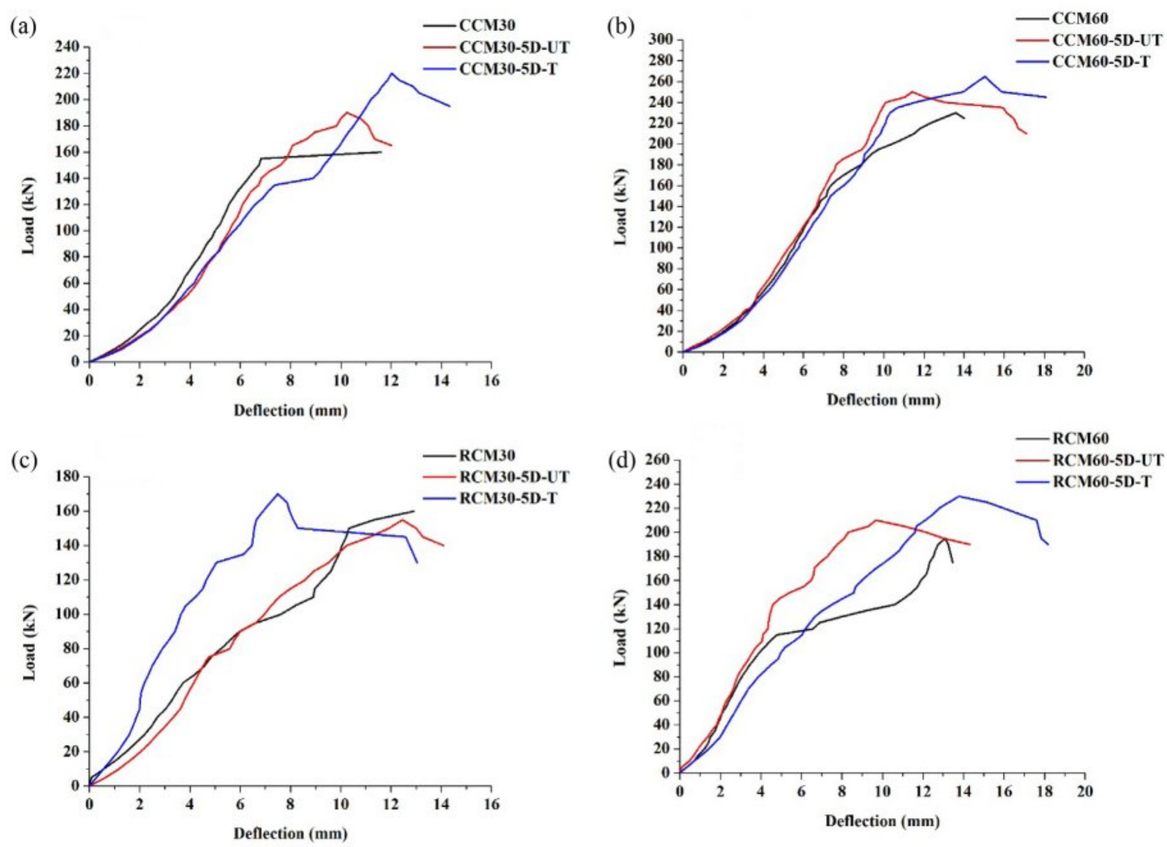


Fig. 8. Load vs. Deflection Curves for (a) CCM30, (b) CCM60, (c) RCM30 & (d) RCM60.

and cement paste to weaken. This lowers the specimen's final strength and raises the risk of failure. In the case of devulcanized rubber concrete, the addition of steel fibers influences only the peak strength and ultimate load rather than enhancing the performance of beams in the post-peak behaviour [24]. The ultimate load of the beam specimen prepared with CCM30 concrete mix with untreated fiber and CCM30 concrete mix with treated fiber is 18.7 and 37.5% higher than that of the CCM30 without fiber respectively. The ultimate load of the beam sample prepared with the CCM60 concrete mix with untreated fiber and the CCM60 concrete mix with treated fiber is 6.52 and 13.04% higher than that of the CCM60 without fiber, respectively.

The conventional concrete beams fail abruptly at cracking load without any further noticeable deflection warning, but the fibrous concrete fails progressively after cracking and it gives appreciable deflection with higher energy absorption capacity. Furthermore, the addition of steel fibers to the concrete mixture inhibits the propagation of cracks. Thus, the load-bearing capacity of the specimen was increased.

The deflection at the ultimate load due found to be low mainly due to the presence of steel fibres that interlock the cracks by bridging the gap. The ultimate load of beam specimen prepared with RCM30 concrete mix with untreated fiber and RCM30 concrete mix with treated fiber is 19.23 and 30.76% higher than that of the RCM30 without fiber respectively. The ultimate load of beam specimen prepared with RCM60 concrete mix with untreated fiber and RCM60 concrete mix with treated fiber is 7.69 and 17.94% higher than that of the RCM60 without fiber respectively. The addition of fibers to concrete and rubber concrete increases the maximum load [26, 28]. The figure shows that concrete beams with steel fibers (RCM30 and RCM60) exhibit higher load-bearing capacity and less deflection compared to beams without fibers (CCM30 and CCM60). The curves indicate that the addition of steel fibers improves the structural performance of the beams, resulting in a more controlled failure mode and enhanced energy absorption capabilities. Inflection points in the curves represent changes in the beam's behavior, such as the onset of cracking or failure, highlighting the effectiveness of steel fibers in improving the beams' overall performance.

Strain in Concrete

The load vs. strain graph for conventional and rubber concrete is shown in Fig. 9. The concrete strain was in

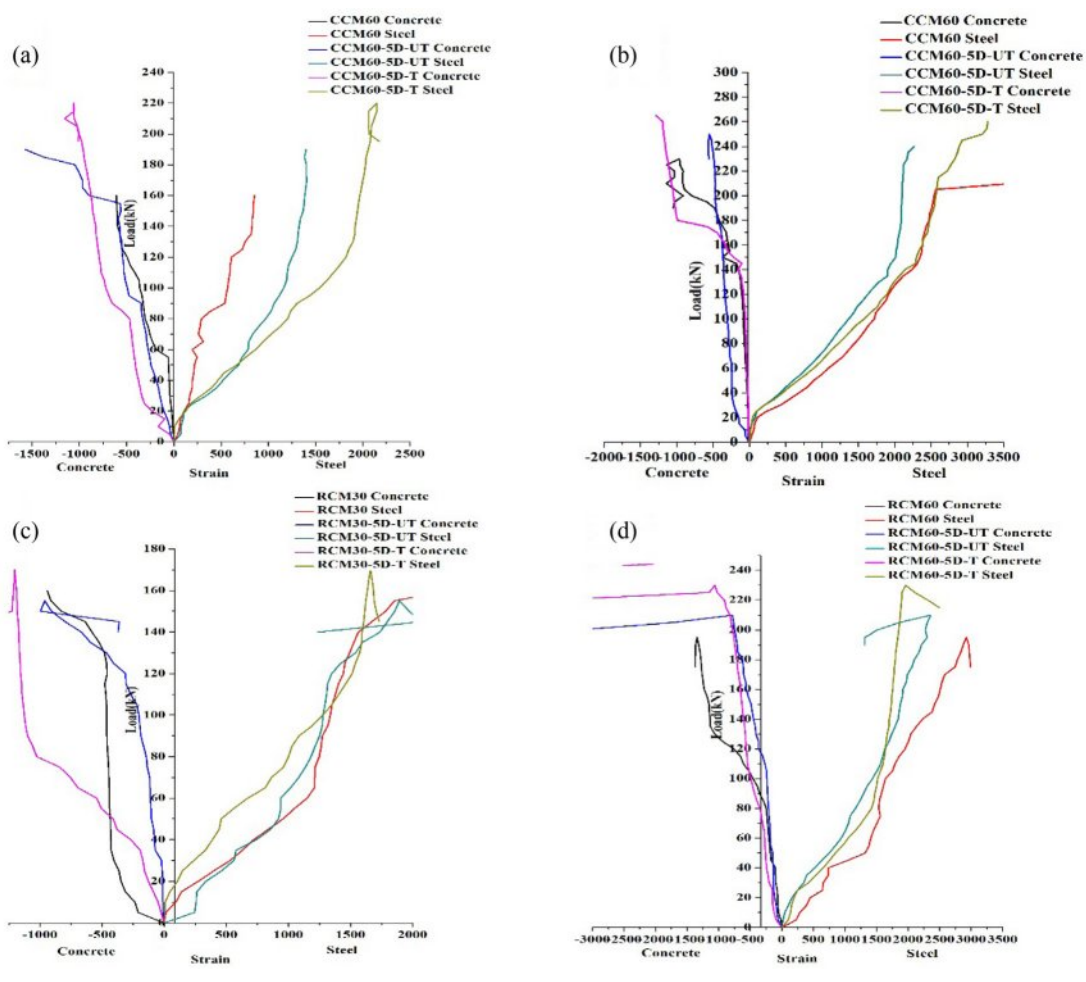


Fig. 9. Load vs. Strain Curves for (a) CCM30, (b) CCM60, (c) RCM30 & (d) RCM60.

the range of 0.000562 to 0.001577. There was very little rise in compressive strain in the concrete at the mid-span of the beams until the initial crack appeared. After the formation of the first crack, the concrete strain was found to increase and reach the maximum value. The sudden increase in concrete stress was due to the formation of a flexural crack at the mid-span or a diagonal tension crack near the support that leads to the failure of beams.

Strain in Steel Bar

The maximum strains of the steel bars were in range of 0.000851 to 0.005984. The increase in tensile strain in longitudinal steel reinforcement at the mid-span of beams till the formation of the first crack is minimal. After this stage, the strain value was found to increase and reached the peak value. The occurrence of diagonal tension cracks in RC beams leads to the failure of beams, resulting in an increase in strain in steel rebars. Larger strains occurred because of the transfer of stress in the concrete reinforcement.

The strain gauges are attached to the reinforcement before concreting and on the outer surface of the test sample after curing to measure strain at different loading intervals. Failure modes in SFRC beams include multiple cracks along the length, indicating enhanced crack resistance and energy absorption, with steel fibers bridging cracks to inhibit further propagation. The proposed method of using pre-coated 5D steel fibers with devulcanized rubber in concrete offers potential applications in infrastructure projects where high strength, crack resistance, and sustainability are key requirements. This method could lead to the development of more durable and sustainable concrete structures, particularly in environments with high loading or potential for cracking.

Conclusions

The study provides the flexural response of environmentally sustainable concrete made with recycled devulcanized rubber powder with 5D steel fiber. The addition of treated 5D steel fiber gives an increased ultimate load than the untreated fiber. The addition of rubber powder with the treated fiber tends to decrease the maximum load at failure. Hence addition of rubber powder does not show notified performance. Overall, the effectiveness of the 5D fibre was better due to the presence of additional hooks. The utilization of the devulcanized rubber powder was a reasonable replacement material for the normal crumb rubber. The ultimate load-to-the-failure ratio was enhanced due to the combined incorporation of steel fiber with devulcanized rubber powder, although this blend does not influence the post-peak of the load-deflection curve. This maintains an excellent balance between the modulus of elasticity and flexural strength. This proves that recycled devulcanized rubber powder is an environmentally sustainable material for recycling and reusing concrete.

Author Contributions All authors contributed to the study's conception and design. Material preparation, data collection and testing were performed by [Thiagarajan Kumanavallal]. The first draft of the manuscript was written by [Thiagarajan Kumanavallal] and conceptualisation and supervision, comments, writing, editing, corrections, checking results and discussions by [Umamaheswari. N]. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

Availability of data and materials The data will be available on request.

References

1. B.S. Thomas, R.C Gupta, and V.J. Panicker, J. Clean. Prod. 112 (2016) 504-513.
2. B.S. Mohammed, A.B. Awang, S. Wong, and C.P. Nhavene, J. Clean. Prod. 119 (2016) 66-75.
3. H. Liu, X. Wang, Y. Jiao, and T. Sha, Materials 9 (2016) 1-12.
4. G.K. Jana and C.K. Das, Polym. Plast. Technol. Eng. 44 (2005) 1399-1412.
5. M. Hassan, O. Raouf, Aly, Aal SEA, M. Ahmed, El Masry, and E.S. Fathy, J. Ind. Eng. Chem. 19 (2013) 1729-19.
6. J.I. Daniel, V.S. Gopalaratnam, M.A. Galinat, S.H. Ahmad, G.C. Hoff, M. Schupack, M. Arockiasamy, R.L. Jindal, S.P. Shah, and P.N. Balaguru, ACI Mater. J. (2002) 544.
7. K. Thiagarajan and N. Umamheswari, Constr. Build. Mater. 359 (2022) 129517.
8. K. Thiagarajan, and N. Umamheswari, J. Environ. Prot. Ecol. 22[3] (2022) 1151-116.
9. N. Banthia, Report on the Phy. Prop. and Dura of Fiber-Rein Con. (2010).
10. S. Tokgoz, C. Dundar, and A.K. Tanrikulu, J. Constr. Steel. Res. 74 (2012) 98-107.
11. P.S. Song and S. Hwang, Constr. Build. Mater. 18 (2004) 669-673.
12. T. Sugama, N. Carciello, and L.E. Kukacka, J. Mater. Sci. 27 (1992) 2863-2872.
13. D.V. Soulioti, N.M. Barkoula, F. Koutsianopoulos, N. Charalambakis, and T.E. Matikas, Const. Build. Mater. 40 (2013) 77-83.
14. M. Sun, D.J. Wen, and H.W. Wang. Mater. Corros 63 (2012) 67-72.
15. D.G. Aggelis, D.V. Soulioti, N.M. Barkoula, A.S. Paipetis, and T.E. Matikas, Cement. Concrete. Comps. 34 (2012) 62-67.
16. A. Imam, V. Kumar, and V. Srivastava, Adv. Concr. Constr. 6[2] (2018) 145.
17. K. Perumal and R. Sundararajan, Conf. Our World Con. Struct (2004).
18. B.M Hanumesh, B.K. Varun, and B.A. Harish, Int. J.

Emerg. Technol. Adv. Eng. 5 (2015) 270-275.
19. H. Katkhuda, B. Hanayneh, and N. Shatarat, J. Constr. Steel. Res. 34 (2009) 781-788.
20. P. Chakraborty, Int. Res. J. Eng. Technol. 4 (2017) 1722-1726.
21. ACI 211.4R-08. ACI Mater. J. (2008).
22. R. Singh, D. Nayak, A. Pandey, R. Kumar, and V. Kumar, J. Build. Eng. (1970).
23. C. Ozyildirim and N.J. Carino, J. Mater. Civ. Eng. (2006).
24. J.Z. Xiao, W.G. Li, Y.H. Fan, and X. Huang, Constr. Build. Mater. 31 (2012) 364-383.
25. N. Fonseca, J. Brito, and L. Evangelista, Cement. Concrete. Compos. 33 (2011) 637-643.
26. C. Naito, J. States, C. Jackson, and B.J. Bewick, J. Mater. Civ. Eng. 26 (2014) 1-8.
27. M.M. Al-Tayeb, B.H. Abu Bakar, H.M. Akil, and H. Ismail, Polymer-Plast. Technol. Eng. 51 (2012) 583-589.
28. T.H. Nguyen, A. Toumi, and A. Turatsinze, Mater. Design 31 (2010) 641-647.
29. IS, BIS, Indian Standard. (2009).
30. S. Anandaraj, A.R. Krishnaraja, P. Kulanthaivel, and P.C. Murugan, J. Ceram. Process. Res. 25[1] (2024) 41-47.
31. Kalyani Gurram and Pannirselvam, N. J. Ceram. Process. Res. 24[3] (2023) 560-568.
32. Xiafei Li, Junzong Feng, Guozhu Zhao, and Xingyu Wu, J. Ceram. Process. Res. 24[5] (2023) 816-826.
33. Xiaohui Guo, Xiaojing Yuan, Guangyong Liu, Hefang Qiu, and Fanfan Cui, J. Ceram. Process. Res. 24[1] (2023) 69-77.
34. K. Sabarinathan and G. Arunkumar, J. Ceram. Process. Res. 24[2] (2023) 390-396.
35. M. Qureshi, J. Li, C. Wu, and D. Sheng, Constr. and Build. Mater. 444 (2024) 137868.
36. M. Zakrzewski and J. Domski, Mater. 16[10] (2023) 3622.
37. S.H. Helmy, A.M. Tahwia, M.G. Mahdy, M. Abd Elrahman, M.A. Abed, and O. Youssf, Sustainability-Basel 15[13] (2023) 10060.