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Strength Compensation in Rubberized Concrete through Steel Fiber Reinforcement: Experimental Evaluation and Predictive Correlation Models

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Abstract:

The current research problem is the mechanical and predictive ability of steel-fiber-reinforced rubberized concrete, utilizing shredded (chipped) tire rubber as a partial substitute for coarse aggregate, with the dual aim of increasing sustainability without compromising structural integrity. In contrast to most studies conducted to date, which predominantly utilize crumb rubber mixed with steel fibers, the present study presents a relatively unexplored combination of chipped rubber and steel fiber hybridization, thereby filling a significant gap in the existing literature and demonstrating the novelty of the study.

Blends of chipped rubber replacement of 0-30% of the concrete mixes of M30 and M40 grades, and substitution with 1% steel fibers were hybridized. Experiment findings show that the compressive strength decreases gradually with the addition of rubber, and the losses were approximately 8-15 percent at a 10 percent replacement, 18-25 percent at a 20 percent replacement, and more than 30 percent at a 30 percent replacement after 28 days. Nevertheless, tensile-related characteristics were significantly improved, along with flexural strength. Split tensile strength increased by 12-18 percent and 10-16 percent, respectively, compared to non-fiber rubberized mixes, especially at an ideal 20 percent replacement ratio. This has been enhanced by the efficient system of crack-bridging and stress redistribution offered by the fibers.

In addition, predictive modelling using regression showed that compressive, flexural, and tensile strengths were strongly correlated ($R2 = 0.974\text{-}0.982$) and therefore could be used with confidence to estimate mechanical properties. The analysis of the surfaces in 3D showed that compressive strength does reduce with added rubber content, but to some extent, it can be restored by hybridizing the fibers and optimizing the grades. The comprehensive method of the combination of the use of chipped rubber, steel fiber reinforcement, regression modelling, and the 3D interaction analysis is an integrated framework for determining the performance thresholds.

The best replacement with 10-20% chipped rubber, which contains 1% steel fibers, is an optimum range of 10-20 percent based on mechanical efficiency and sustainability factors. The results indicate that hybrid rubberized concrete using chipped rubber can reach a balanced performance in terms of mechanical actions, which facilitates the feasibility of the material as a construction material that is environmentally friendly.

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. ***Keywords***: Chipped Rubber, Design mix, Mechanical Properties, Weak Bonding, Impact Resistance, Cantabro Abrasion test, Surface Abrasion Test.

1. INTRODUCTION

Due to the high rate of development in the automobile industry, wastes like metals, nuts, bolts, and even discarded rubber tires have been generated in a relatively high rate (A. A. Beiram & Al-Mutairee, 2022), (Hasan et al., 2024). End-of-Life tyres are one of the primary environmental issues facing the country as they have a long life and are non-biodegradable, hence resulting in fire hazards, the release of toxic gases, and the mass disposal of landfills (Sanjaya et al., 2023), (A. A. H. Beiram & Al-Mutairee, 2022). Even though a number of disposal and recycling techniques exist (including energy recovery (Tire-Derived Fuel), retreading, reuse, and even pyrolysis), they are usually constrained by cost, technology, or scale. The inclusion of the waste tire rubber in the concrete has thus been a viable and environmentally friendly solution. Rubberized concrete (RubCrete) concept does not only solve the waste tire disposal problem but it also provides greater toughness, flexibility, and impact resistance than conventional concrete (Chandran, 2017), (Jeevana et al., 2023). Nevertheless, it has been mentioned that many studies observed compressive and tensile strength decrease were caused by the bad interfacial bondage of rubber aggregates and the cementitious matrix (Parung et al., 2020), (Etefa & Mosisa, 2020). To address this drawback, fibre and additional cementitious have been added to augment the mechanical and structural viability execution of rubberized concrete permitting its application to the pavement and structural construction where toughness and ductile properties are important (Roknuzzaman et al., 2021), (Su, 2015).

In this experiment a test mix on M30 and M40 grade concrete mixes using waste tire rubber (non-fibered) that was shredded into 20 mm chips was conducted at the proportion of 10, 20 and 30 percent of the coarse aggregate by volume. The mechanical properties used compressive, flexural and split tensile strengths were calculated at each replacement level and put against the control mix to determine the best rubber content. The findings indicated that rubber replacement of 20 percent gave the most optimal strength-ductility balance. Addition of 10% silica fume and 1% steel fibres was done to enhance the performance of the optimum mix. Silica fume was added to enhance the interfacial bond and microstructural density as it is pozzolanic and steel fibres increased the post-cracking, tensile capacity and impact resistance. Both M30 and M40 blends with such additions were reported to have significant enhancement of strength and durability over plain rubberized concrete. The additional testing using impact resistance, Cantabro loss, and surface abrasion tests identified that the adjusted mixes had sufficient toughness, and wear resistance to be used in pavement and in high-impact applications. In this manner, the use of waste rubber, silica fume, and steel fibres combined, not only helps in environmental sustainability but also produces a ductile, energy absorptive and durable concrete material that can satisfy the construction needs of both M30 and M40 grade concretes that would meet the contemporary construction needs.

The current research was done to experimentally investigate the performance of rubberized concrete through the partial utilization of shredded waste tyre chips as natural coarse aggregates in different proportions (Muyen et al., 2019). The main aim was to examine the mechanical behaviour of rubberized concrete, find the correlations between various strength parameters and the appropriate percentage of rubber substitution that does not affect the loss of strength and increases ductility, energy absorption and other advantageous properties (Wakili et al., 2018). In addition, this optimum rubberized mix and the control mix were compared and used to test the parameters relating to durability in terms of Impact Resistance, Cantabro Abrasion Loss, and Surface Abrasion Loss tests (Al & Al-Khafaji, 2025). The purpose of the study was also to understand how the rubberized concrete can be used as a light and sustainable alternative material that can be used in pavement and non-structural applications as part of waste management and green construction procedures (Raulkar et al., 2020), (Wani & Shimla, 2020).

In order to achieve these goals, an experimental program was developed and conducted in M30 and M40 grade concretes. The Ordinary Portland Cement (OPC), natural river sand (fine aggregate), and crushed stone (coarse aggregate) were used to prepare the control mixes. The modified mixes were three winters of the natural coarse aggregates with three equal volumes of non-fibered waste tyre rubber chips that were shredded to an approximate size of 20 mm (Kamel et al., 2022). Specimens were cast and evaluated at each replacement level and respective control mix with compressive strength, flexural strength, and split tensile strength with 7-day and 28-day curing test (Bušić et al., 2018), (Ocholi et al., 2018). The experimental findings were compared afterwards to assess the effect of rubber replacement on the mechanical performance and to come up with correlation models between compressive, flexural and tensile strengths (Medina et al., 2016), (Dhivya & Priyadharshini, 2022). Such models are also very useful because in this way it is possible to predict different mechanical properties and not to use the extensive experiment testing, so, the practical using of rubberized concrete will be increased.

Based on the experimental results, it was observed that when rubber aggregates were included, compressive and tensile strengths were usually lower because of the poor bonding at the interface between rubber and cementitious matrix. Nevertheless, there was a significant enhancement in ductility, impact energy absorption and workability (Khan & Singh, 2015). Of the three replacement levels, 20% replacement in rubber was determined as the most appropriate content as it has the best proportion of strength retention and enhanced ductile. In order to further improve the mechanical and durability properties of this optimum mix, 1% steel fibres and 10% silica fume were added (Luong et al., 2017). The silica fume, which is a very reactive pozzolanic substance, enhanced bond strength and densified the microstructure which decreased porosity and increased compressive strength (Thomas & Gupta, 2016).

1.1 Experimental Procedure:

The mechanical performance of rubberized concrete using shredded waste tyre rubber as a partial replacement of the natural coarse aggregate was to be investigated in an experimental program. M30 and M40 concrete mixes were chosen as the concrete of medium and high strength, typical of structural concrete applied in the engineering sphere. The rubber particles were added at the replacement levels of 0 per cent, 10 per cent, 20 per cent, and 30 per cent of the volume of the coarse aggregate of 20 mm size. Moreover, according to the mix design framework, the hybrid modification was made with 1% of steel fibres (volume of concrete) and 10 percent of silica fume (weight of cement) in the chosen mixes to check the possibility of enhancing mechanical performance. The experimental matrix was created to test the effect of rubber replacement and hybrid reinforcement on the strength properties predictively and to develop predictive relationships among mechanical properties.

The main binder was ordinary Portland Cement (OPC) that met the requirements of the relevant standards. The fine aggregate was made up of natural river sand, and the conventional coarse aggregate was made up of crushed stone. The replacement coarse aggregate was in the form of shredded waste tyre rubber chips of homogenized gradation. The supplementary cementitious material (silica fume) was utilized to increase densification of the matrix, and crimped steel fibres were employed to promote resistance to cracks. The preparation, casting, and compacting of concrete specimens were done by standard laboratory procedures. Demoulding was done after casting, and specimens were cured under controlled conditions of curing water for 24 hours until the ages of testing, 7 and 28 days. The standard test methods, such as compressive strength, flexural strength, and split tensile strength tests, were used to assess mechanical properties in line with the relevant standards in IS and ASTM.

Alongside experimental tests, theoretical and analytical modelling was done to measure the relationship between mechanical properties. Empirical correlation was established between compressive strength, flexural strength and split tensile strength by the use of regression analysis. Interdependence between various parameters of strength was measured using correlation matrix analysis. More, the combined effect of rubber replacement percentage and concrete grade on compressive strength has been investigated using surface modelling which was done in three dimensions. Such a combined experimental-statistical solution is a major methodological input of the research, which allows it to model predictive strengths and optimize hybrid rubberized concrete mixes to ensure sustainable engineering use.

1.2 Materials and their Properties:

The right choice of materials is the basis of the desired performance, durability, and workability of concrete. In this experiment, the traditional materials, including Ordinary Portland Cement (OPC), fine and coarse aggregates, and potable mixing water, were used, along with alternative materials such as shredded tire chips to increase sustainability. All materials have been described in accordance with the standard material properties in order to be uniform and reliable in the experimental program. The next section provides the physical and mechanical properties of all materials utilized in the research in more detail.

Table 1: Material Specifications and Standard Properties for Experimental Program

Material	**Property**	**Value**
Ordinary Portland Cement (OPC 53 Grade)	Specific Gravity	3.15
	Initial Setting Time	30 minutes
	Final Setting Time	600 minutes
Fine Aggregate (Zone-III Sand)	Specific Gravity	2.60
	Fineness Modulus	2.69
	Bulk Density	1.58 g/cc
	Compacted Density	1.68 g/cc
Coarse Aggregate	Specific Gravity	2.65
	Shape	Angular
	Bulk Density	1.454 g/cc
	Compacted Density	1.58 g/cc
	Nominal Maximum Size	20 mm
	Water Absorption	< 1%
Potable Water	Suitability	Conforms to IS 456:2000 requirements; free from harmful salts, acids, oils, and organic matter
Shredded Tire Chips	Specific Gravity	1.178
	Shape	Angular
	Nominal Maximum Size	20 mm
	Water Absorption	< 1%

Table 1 of the material properties was developed by a combination of experimental laboratory tests, specifications provided by the manufacturer, and code provisions. In the laboratory, the physical properties of the fine aggregate and the coarse aggregate, such as specific gravity, fineness modulus, bulk density, compacted density, and water absorption, were experimentally established according to the relevant Indian Standard specifications, including IS 2386 (Part I) and IS 2386 (Part III). Likewise, the experimentally measured specific gravity and water absorption of shredded tire rubber chips were determined through the application of standard testing using modified levels of methods of lightweight aggregates. Specific gravity and setting times of Ordinary Portland Cement (OPC 53 Grade) were found in the test certificate provided by the manufacturer and were checked according to the requirements of the standard IS 12269:2013. The concrete mixing and curing used was done in a manner that was compliant with the provisions of IS 456:2000 on the suitability of potable water. Besides this, the measured values were validated with standard ranges provided by the relevant codes of IS and published literature.

The materials used in this paper were well chosen to have consistency and reliability of the concrete mixes presented in the table 1. Ordinary Portland cement of 53 grade was adopted since it has a better early strength with good performance attributes with specific gravity of 3.15 and regular setting times which favour controlled hydration. The fine aggregate, which is a Zone-III aggregate based on sieve analysis, had specific gravity of 2.60 and sufficient fineness and density parameters, and thus would be applicable to the accomplishment of workability, as well as proper particle packing. Angular-shaped coarse aggregates were selected to increase their interlocking and mechanical properties, and the nominal maximum size of coarse aggregates was 20 mm, as well as the absence of more than 10 water absorption to guarantee minimum variation in the context of moisture. Potable water that met the requirements of IS 456: 2000 was used to eliminate any deleterious effects of chemical on the concrete properties. Further, re thread tires chips acquired during re threading industry were also used as alternative material, thus, characterized by low specific gravity and angular shape with a maximum size of 20 mm and minimum absorption of water. All these material properties work together to achieve preferred mechanical properties and resistance of the concrete mixtures discussed in this paper.

The Behavior of recycled aggregates and rubber-modified concrete has been studied previously on physical and mechanical behaviour to get insight into their behaviour under the moisture exposures and structural loads. Recycled aggregates and waste tyre steel fibres were found to have varying specific gravity, water absorption and bonding properties than natural aggregates, which affect the general concrete behaviour. The report on the absorption of the water of the shredded tire rubber particles in this study (< 1%) was established after 24 hours of submersion in water under laboratory conditions, which aligned with the standard practice in the aggregate test. As rubber is hydrophobic, it usually absorbs little water at the beginning as opposed to natural aggregates. Nonetheless, it has been reported in previous research that increasing apparent water absorption with time through surface discontinuity and irregularities on microstructural level can occur when subjected to prolonged submersion. Thus the value reported reflects short-term absorption behaviour and in this respect proper references have been provided to recognize time dependent absorption nature of tire based aggregates (Sanjaya et al., 2024).

1.3 Mix Design and Proportions:

Based on the concrete mix proportioning guidelines of the comprehensive guidelines described in the Bureau of Indian Standards IS 10262:2019, with the durability and exposure conditions of plain concrete described in the ISO 456:2000 guideline in place, we created a design mix of an M30 and M40 grade concrete. To verify the proper operation of the mix design under controlled conditions and to get final proof-checking, accelerated curing test was performed, which proved the proper functioning of the mix design.

Table 2: Mix Design Details and Accelerated Curing Parameters

Parameter	**M30 Mix**	**M40 Mix**
Design Mix Grade	M30	M40
Target Compressive Strength (Normal Curing)	38.25 N/mm²	48.25 N/mm²
Water–Cement Ratio (W/C)	0.48	0.40
Mix Proportion (C : FA : CA)	1 : 1.64 : 3.02	1 : 1.32 : 2.69
Accelerated Curing Method	Boiling Water Method	Boiling Water Method
Curing Duration	3.5 hours at 100°C + 30 min cooling	3.5 hours at 100°C + 30 min cooling
Sample Size	150 × 150 × 150 mm	150 × 150 × 150 mm
Number of Samples	3	3
Target Compressive Strength (Accelerated Curing)	42.84 MPa	49.46 MPa

The mix design parameters and accelerated curing conditions applied in the present experimental study of the rubberized and hybrid fibre-reinforced concrete mixes in the current study are presented in table 2, respectively. These parameters ensure the correct prognosis of the 28-day strength and make it possible to assess the performance of the accelerated conditions at the earlier age.

Table-3: Rubberized Concrete Proportions for 1m^3 mix for M30 and M40.

mix grade	**Rubber Tire chip as Replacement by Volume of Coarse Aggregate**	**Cement (Kgs)**	**Water (Kgs)**	**Coarse Aggregate (Kgs)**	**Fine Aggregate (Kgs)**	**Rubber (Kgs)**
M30	**0%**	388	186	1170	635	-
	10%	388	186	1054	635	52
	20%	388	186	937	635	104
	30%	388	186	820	635	156
M40	**0%**	440	176	1187.57	582.582	0
	10%	440.00	176.00	1053.70	582.58	52.01
	20%	440.00	176.00	936.06	582.58	104.02
	30%	440.00	176.00	819.05	582.58	156.04

The mix proportions evidence in the table 3 clearly depicts the systematic difference in materials as the content of rubber goes up in both the M30 and M40 of concrete. The more the portion of rubber tire chips that are used in place of coarse aggregate, the lesser the amount of coarse aggregate that will be used, and at the same time the cement and water content will be maintained the same in order to ensure consistency in the mix. In the case of M30 concrete, the coarse aggregate decreases to 820kg and the rubber content is increased to 156kg. Equally in M40 the coarse aggregate reduces to 819.05 kg compared to the 1187.57 kg and the rubber increases to 156.04 kg. Also, in hybrid mixes (20% rubber + 1% steel fibre), addition of steel fibres (approximately 1% weight of cement) increases tensile and flexural strength, which overcomes the weakening of strength due to rubber. Fine aggregate is nearly fixed, and cement (388 kg M30, 440 kg M40) and water (186 kg M30, 176 kg M40) are adjusted to meet the required workability and strength. These ratios offer a moderating structure to examine the impact of rubber and steel fibre on the mechanical and structural features of concrete. Figure 1 shows different pictures related to the experimental program. Chipped rubber and steel fibers in the concrete is shown in the figure 2.

Figure1 (a)- Beam specimen

Figure1 (b)- Casting of Beam and cylinder specimen

Figure1 (c)- Testing of beam samples

Figure 2-a: chipped rubber

Figure 2-b: Steel fibers inside the concrete

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1 Mechanical Properties of Rubberized Concrete:

The outcomes of the experiment are a full assessment of the effect of shredded rubber and steel fibres on the mechanical behaviour of concrete. The results show that the flexural and split tensile strength have shown a steady rise with optimum rubber content and steel fibres, especially at 28 days. Correlation tests indicate that there exist strong correlations among compressive strength, flexural strength, and tensile strength, which depict predictable material behaviour. Regression models also verify the stability of these tendencies with a high R 2. The surface analysis in 3D indicates that as the rubber content increases, compressive strength goes down, with the effect being more pronounced as the replacement level increases. Overall, the findings show that the use of rubberized fibre-reinforced concrete is possible, but it is necessary to maximise replacement percentages in order to induce a balance between strength and sustainability.

The optimum level of rubber replacement was established after making a comparative analysis of the compressive strength, flexural strength, and split tensile strength values obtained on mixes with 0, 10, 20, and 30 percent rubber replacement. Out of the explored mixes, the 20% replacement level proved to be the most suitable balance between the strength retention and enhanced ductility, and the greater the replacement level, the greater the decrease in strength. Hence, 20 percent replacement with rubber was chosen as the ideal percentage, and it was later mixed with 1 percent steel fibres to increase the crack resistance and regain the mechanical performance by using hybrid reinforcement.

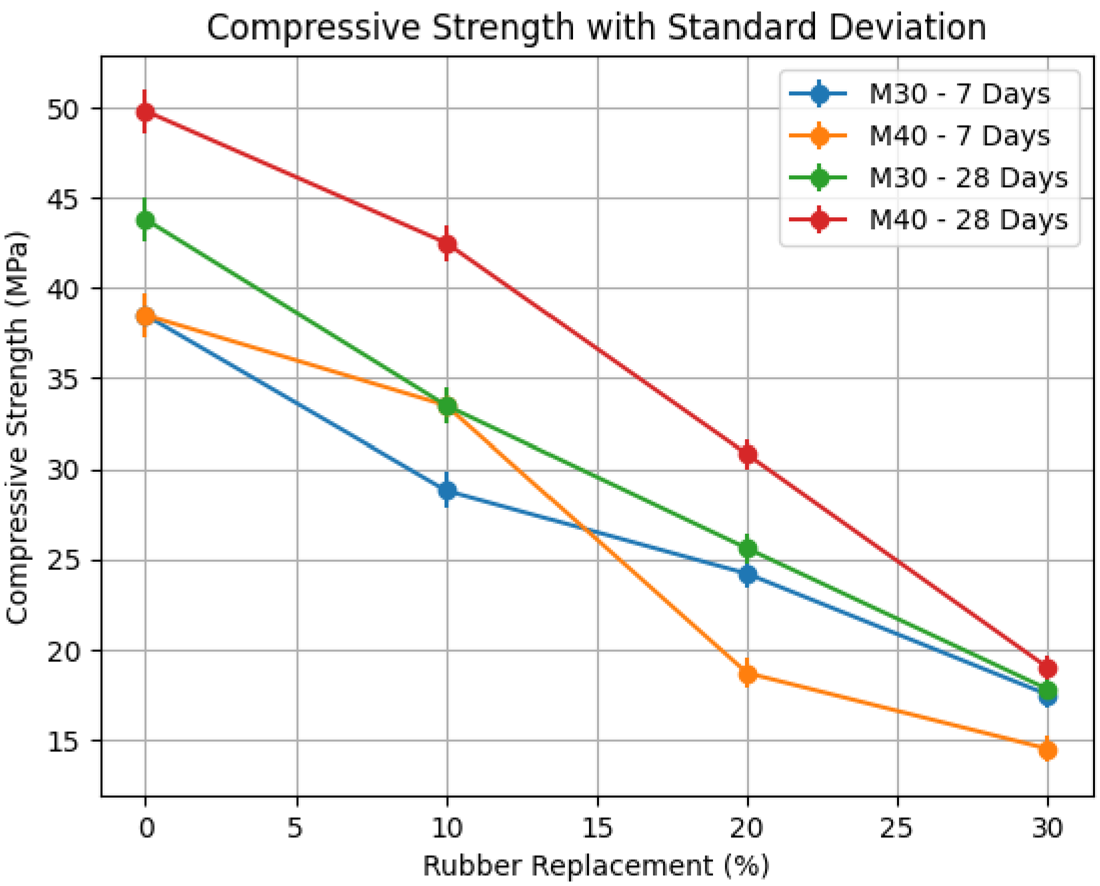

Figure 3: Variation of Compressive Strength with Rubber Replacement for M30 and M40 Grades at 7 and 28 Days

Figure 3 shows how replacing the rubber tire chips (0-30% by volume) affected the compressive strength of M30 and M40 grade concretes at 7 and 28 days of curing. Both grades show a steady decrease in strength with an increase in rubber content, which is due to lower bonding and more voids in the matrix. Compared to all the levels of replacement, M40 concrete has relatively high strength retention. The 20 percent replacement level demonstrates a significant decrease yet satisfactory functionality, in accordance with the described maximum in the research.

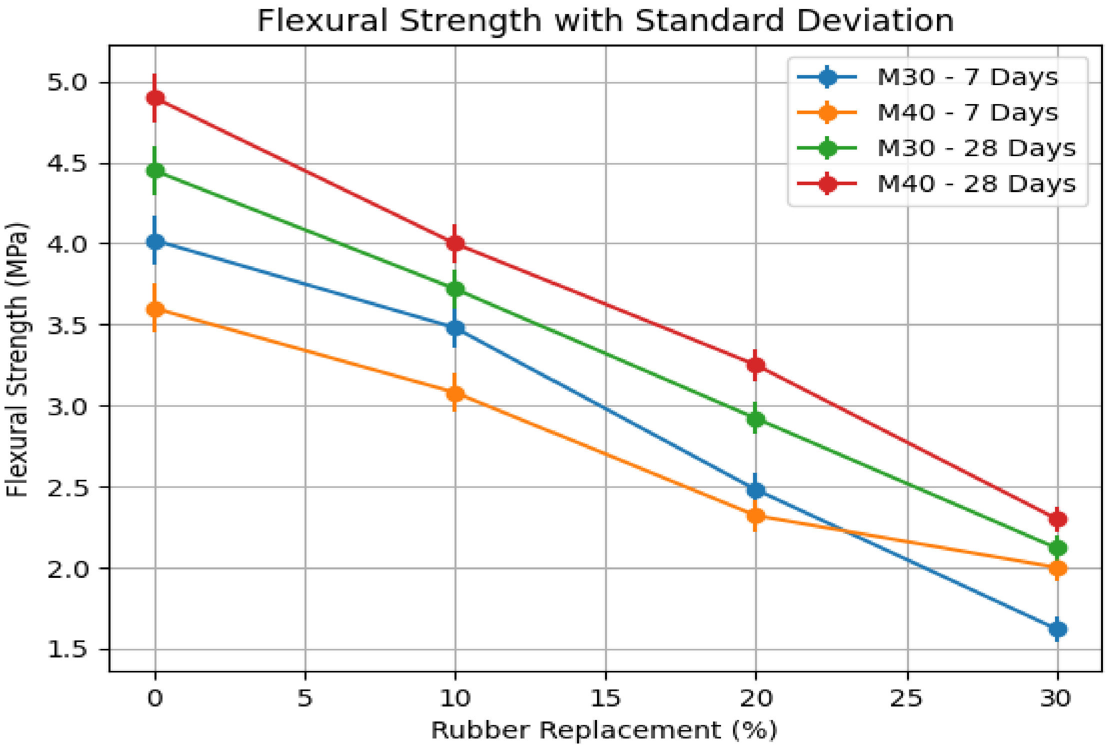

Figure 4: Variation of Flexural Strength of Rubberized Concrete with Rubber Replacement at 7 and 28 Days

Figure 4 demonstrates the effect(s) of waste rubber replacement (0-30%) on flexural strength (fcr) of M30 and M40 grade concrete at 7 and 28 days of curing. There is a steady decreasing tendency of both grades with an increase in rubber content, which depicts a loss of body of the rubber and the degree of bonding because of the softer rubber aggregates. The strengths of 28 days are still more than the strength of 7 days, indicating the normality in the strength development. It is also shown that M40 concrete has a better flexural behaviour at all levels of replacement, which indicates a positive role of the increased matrix strength in reducing the negative effect of rubber inclusion.

3. CONCLUSION

Depending on the conducted experimental study and the analytical model of steel fibre-reinforced rubberized concrete, the following conclusions can be made:

1. Impact of replacement of rubber on compressive strength: The compressive strength reduced gradually as the rubber replacement was increased because the interfacial bonding was weaker, and also because of the lesser stiffness of rubber particles. Compression strength was found to be reduced by 20 percent of the replacement but was still within an acceptable range in structural applications, and had a large decrease in compression strength at 30 percent of replacement.
2. Enhancement by incorporation of steel fibre: The inclusion of 1% of steel fibres contributed greatly to mechanical performance by alleviating the loss in strength due to the inclusion of rubber. Hybrid reinforcement was effective because steel fibre-reinforced rubberised concrete displayed observable strength recovery in comparison to plain rubberised concrete.
3. Improvement in flexural strength under fibre strength: The flexural strength was also enhanced through the addition of steel fibre because it increased crack-bridging and post-cracking resistance. E.g., flexural strength rose between 5.16 MPa and 6.05 MPa at 7 days and 28 days, respectively, for M30 concrete and M40 concrete in the optimum rubber-fibre mix (20% rubber + 1% steel fibre).
4. Split tensile strength improved with hybrid modification: Split tensile strength that declined with the rise of rubber in the plain rubberized concrete was also measurably improved by the addition of steel fibres. This proves that steel fibres increase tensile load transfer as well as improve post-cracking behaviour.
5. Determination of the optimal level of replacement of rubber: Due to the strength retention, ductility, and structural performance, it was found that 20% rubber replacement was the best level when there was a mixture of 1% steel fibre that gave the best balance between the mechanical performance and the sustainability.
6. High predictive correlations between mechanical properties: Regression analysis indicated that compressive strength and flexural strength (R2 = 0.982) and compressive strength and split tensile strength (R2 = 0.974) had strong correlations, indicating good predictive relationships to hybrid rubberized concrete.
7. Mechanical consistency: Correlation matrix assures. The positive interdependence of compressive, flexural, and tensile strengths as depicted by the correlation matrix was very strong, indicating the consistency in mechanical behaviour and structural reliability of hybrid rubber-fibre concrete.
8. Influence of rubber content proved by 3D surface analysis: Surface analysis in three dimensions showed that compressive strength is reduced as rubber is progressively replaced, and also a high grade of concrete and the addition of steel fibre reduce the effect of strength loss.
9. Fibre concrete with rubber makes concrete more efficient: The incorporation of steel fibres resulted in resistance to cracks, ductile behaviour, and distribution of stress, which resulted in the structural behaviour of the rubberised concrete in comparison to plain rubberised mixes.
10. Appropriateness to the use of sustainable building: The application of waste tyre rubber, shredded waste, and steel fibre helps in sustainable construction due to their use of natural later aggregate and the use of waste materials at a relatively acceptable mechanical performance.
11. Mechanical properties are also predictably correlated regardless of the inclusion of rubber: But even though the absolute values of the strength decrease as the content of rubber increases, the relative relationships between compressive, flexural, and tensile strength are the same, allowing one to predict strength reliably.
12. New input of hybrid alteration with prediction modelling: The combination of replacement with rubber aggregate, steel fibre hybrid reinforcement, regression modelling, and interaction analysis in 3D offers a quantitative model in optimization of sustainable rubberized concrete mixes.

13.Optimal mix (that has been recommended) in structural applications: According to the quantitative experimental and analytical results, a concrete mix with 10-20 percent replacement of rubber with 1 percent of steel fibre can be suggested as the best range to provide a balanced strength, ductility, and sustainability.

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