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Original Article

Performance Evaluation of Multi-Size Chemically and Mechanically Treated Waste Tyre Rubber as Coarse Aggregate Replacement in Concrete

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Abstract - *Sustainable reuse of waste tyre rubber in construction material is an effective path to alleviate environmental impact and landfill quantity. This research considered the performance of concrete mixes that partially replaced coarse aggregates with Chemically and Mechanically Treated (CMT) and Cement-Coated chemically and Mechanically Treated (CCMT) waste tyre rubber of varying sizes and volume replacement ratios. Sixty concrete mixes were produced using rubber sizes of 10, 12, 16, and 20 mm, to provide volumetric replacements of 5%, 10%, 15%, and 20%, respectively. In a separate production to optimize the 15% level, 24 blended multi-size mixes were developed using macro-to-micro aggregate gradation. The best blend of all mixes (M62) produced the highest compressive strength of 36.67 MPa, which was approximately 16.2% improved from the control mix (31.56 MPa). The flexural strength of the rubber blends was also favorable. Additionally, durability tests, water absorption, and acid attack demonstrated better bonding, as well as lower degradation of the treated rubber concrete compared to the control mix. The outcomes indicate that treated rubber aggregates blended with other aggregates at an optimized replacement level are structurally feasible and able to be environmentally sustainable alternatives to traditional coarse aggregates in concrete.*

Keywords - *Waste tyre rubber, Multi-size aggregates, Chemical-mechanical treatment, Compressive strength, Durability, Sustainable concrete.*

1. Introduction

As a result of the end-of-life tyres around the world, they present an enormous environmental risk. Their durability as multi-composite materials means they consistently produce waste that will ultimately lead to pollution, and consequently require sustainable management options. In addition to disposal and energy recovery, there is an increasingly strong case to work with the end-of-life tyre waste stream. This is borne out of a circular economy (not only as waste) and associated value-added products. The strong descriptions originate from a waste stream.

1.1. Global Context: Waste Tire Disposal Challenge

Over the last few decades, tire manufacture and consumption have steadily been rising throughout the globe, creating millions of tons of End-of-Life Tires (ELTs) every year. Tires are very durable in the environment: they occupy landfill space; they present a fire hazard with toxic emissions; and when they are illegally disposed of or burned, they release pollutants into the air, soil, and water. Landfilling and energy recovery practices (landfilling, incineration, pyrolysis) simply shift the environmental burden or are constrained by economic and regulatory restrictions. As such, there is a strong impetus to divert ELTs into circular, value-added streams - one such potential route is to use them in construction materials, especially concrete, plastic, and asphalt, where tire rubber substitutes natural aggregates, thus diversifying waste management and conserving virgin resources [1].

1.2. Concrete Production and Sustainability Challenges

Concrete is the most used manufactured product in the world, and while it is not feasible to eliminate all cement use, cement does indeed have a role in CO_2 emissions and resource use. The depletion of natural aggregates and negative environmental consequences associated with cement production have sparked conversations around lower carbon alternatives (e.g., geopolymer systems) as well as partial replacements for aggregates through industrial or consumer recycled waste.. Any substitute that can be considered sustainable will need to have sufficient fresh, mechanical, and durability performance for the application

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intended. Rubber from used tyres reduces density and improves toughness or energy absorption, but often decreases compressive and modulus characteristics; thus, a trade-off that requires optimal mix design, surface treatment, and additives to overcome [2].

1.3. Recycling Industrial Waste into Concrete

Quite a lot of literature has investigated the potential of industrial waste products (fly ash, ground granulated blast-furnace slag, and silica fume) and recycled solid wastes (crushed concrete, rubber crumbs, polymeric wastes) as substitutes for cement and/or aggregate in concrete. Geopolymer binders (alkali-activated aluminosilicate systems) can also serve as low-carbon alternatives to Portland cement. They can be used with precursors (recycled aggregates such as crumb rubber) to develop new types of composite mixtures with desired thermal and insulating performance.

While systematic reviews and laboratory studies have shown that recycled rubberized geopolymer and cementitious composites can perform well for the majority of non-structural and some structural applications, the rubber component, rubber particle size, and the specific surface treatments should be considered [1, 2, 5]. By employing either surface treatments, chemical pretreatment (NaOH), or hybrid reinforcement (fibres/steel), improvements can be achieved in terms of the overall strength of the recycled rubberized geopolymer and/or cementitious composites.

1.4. Motivation and Problem Statement

The increasing need for sustainable alternatives related to waste tyre rubber management creates a demand for sustainable concrete materials. Waste tyre rubber has a wide array of disposal methods that contribute substantially to environmental concerns. Although concrete with tyre rubber can be recycled, waste rubber aggregates are typically not treated, significantly reducing the strength and durability of the resulting concrete and limiting applications for structural purposes. Treating the rubber adds motivation to study chemically and mechanically treated (CMT and CCMT) rubber to replace a portion of conventional coarse aggregate. The problem is that there have not been extensive studies involving multi-size treated rubber and optimized blend ratios. Addressing this issue can improve the performance of leachate concrete and meet sustainability goals through construction with eco-friendly materials [3, 4].

Earlier investigations primarily focused on single-size or untreated rubber aggregates and were thus limited in their contribution to understanding the combined effects of rubber size distribution and surface treatment methods on mechanical and durability performance. The current study uniquely examines multi-size (10–20 mm) rubber aggregates treated by chemical-mechanical coating (CMT, CCMT), determines the optimum 15% replacement, and evaluates durability under acid exposure. The systematic investigation offers practical information necessary to evaluate the durability of structural-grade sustainable concretes.

1.5. Objectives and Scope of the Present Study

The primary aim of this study is to assess the performance of concrete containing multi-size chemically and mechanically treated (CMT and CCMT) waste tyre rubber as partial replacements for coarse aggregates. These assessments include 60 concrete mix combinations and a minimum of 60 combinations with various levels of rubber size and replacement, as well as the selection of 15% to optimize replacement mixtures via macro-to-micro blend ratios of aggregate sizes. The performance will be assessed in terms of compressive strength, flexural strength, and a durability property (water absorption and acid resistance) to support the use of treated rubber aggregate as a sustainable structural alternative in concrete applications [1-5].

As a result of the end-of-life tyres around the world, they present an enormous environmental risk. Their durability as multi-composite materials means they consistently produce waste that will ultimately lead to pollution, and consequently require sustainable management options. In addition to disposal and energy recovery, there is an increasingly strong case to work with the end-of-life tyre waste stream. This is borne out of a circular economy (not only as waste) and associated value-added products. The strong descriptions originate from a waste stream.

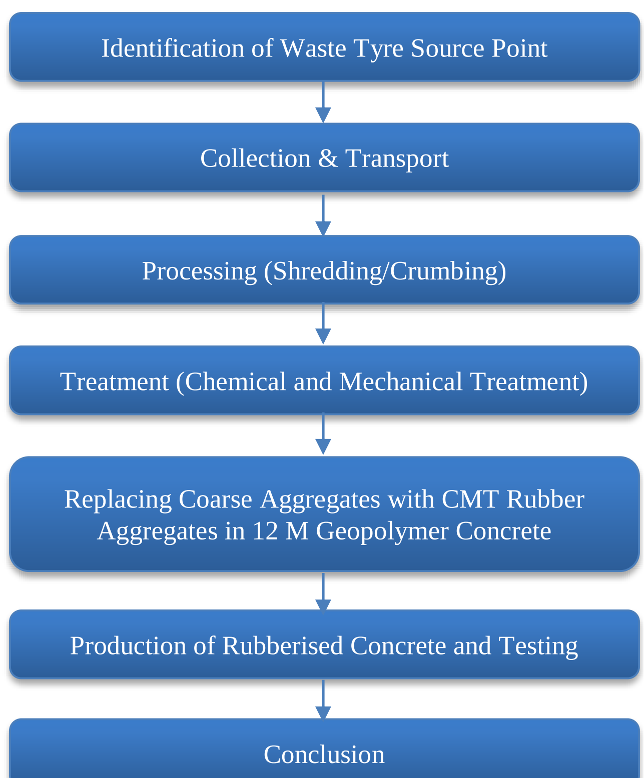

Fig. 1 Flow diagram showing tyre waste to concrete lifecycle

Figure 1 provides a lifecycle of waste tyres that have been converted to concrete. The process starts with tyre sources, collection, and transport. Tyres are shredded and processed before replacing the coarse aggregates in geopolymer concrete with rubber. In the end, rubberised concrete is created, tested, and the performance is assessed, leading to the sustainable use of waste.

Table 1 outlines estimates of waste tyre generation on a regional level in relation to environmental aspects and reuse in concrete. Globally, it is estimated that 1.5 billion tyres are disposed of each year. Case studies from Saudi Arabia, Europe, Egypt, and Iran highlight the potential for cost-effective recycling and reuse of waste tyres (e.g., recovery of steel fiber as a valuable commodity) and the use of waste tyres in sustainable geopolymer concrete. Overall, this information represents an example of effective waste valorisation.

2. Literature Review

To combat environmental problems and reflect sustainability values, the recycling of waste tyres in concrete materials has drawn a lot of attention and research. Studies have examined various methods of tyre rubber incorporation, including untreated, chemically treated, and mechanically modified, and their influence on the mechanical, durability, and structural performance of the concrete product.

Table 1. Global waste tyre generation statistics

Region / Focus	Estimated Waste Tyre Generation	Key Notes	Key References
Global overview	1.5 billion waste tyres are generated annually worldwide	Highlights environmental concerns and potential use in concrete	[1]
Middle East (Saudi Arabia focus)	20 million tyres are discarded annually in Saudi Arabia	Study emphasizes cost-effective treatment for reuse in concrete	[2]
Europe (with recycling emphasis)	3.5 million tonnes of waste tyres annually in the EU	Notes on increasing recycling with steel fiber recovery	[3]
Egypt / MENA region	15 to 20 million tyres annually in Egypt	Suggests potential for reuse in geopolymer and sustainable concretes	[4]
Iran (case study context)	300,000 tonnes annually in Iran	Demonstrates potential valorisation in construction materials	[5]

2.1. Overview of Studies Involving Untreated Rubber in Concrete

Past and recent experimental investigations indicate that incorporating untreated crumb or shredded tyre rubber in concrete generally results in lighter, more flexible mixes with enhanced energy absorption, damping, and impact resistance, yet with compromised compressive strength and stiffness relative to conventional concrete. The majority of investigators indicate that even low-to-moderate volumetric substitution (e.g., 5–20% by volume of fine or coarse aggregate) decreases compressive strength to greater or lesser degrees based on rubber gradation and mix design. These fundamental studies identify the performance trade-offs that drive treatment and hybrid techniques [6, 8].

2.2. Performance limitations of Raw Tyre Aggregates

The fundamental weaknesses of raw tyre aggregates are well established: (a) weak interfacial adhesion owing to the hydrophobic, chemically inert vulcanized rubber surface; (b) stress concentration and Interfacial Transition Zone (ITZ) weakness that compromise peak strength; and (c) particle size/shape variability and contaminant residue that contribute to workability and durability. These effects correspond to decreases in modulus, tensile and compressive strength, and enhanced drying shrinkage or creep in a few mixes. Summaries and long-term investigations consistently point to the ITZ and surface incompatibility as the overarching mechanistic causes of loss of properties [6, 9].

2.3. Review of Investigations into Treated Rubber Aggregates (Chemical, Mechanical)

A variety of surface modification techniques have been tested to enhance rubber–matrix adhesion: chemical treatments (NaOH, KMnO2, oxidative or silane treatments), physical treatments (thermal, microwave, high-shear milling), and thin cement/fly-ash coatings or polymeric primers. Partial regain of compressive/flexural strength, as well as enhanced durability indicators, is commonly reported by many studies.

For instance, alkaline or oxidative conditioning enhances surface roughness and incorporates polar groups that promote wettability and bonding. Cost-effective and scalable treatments (basic alkaline soaking, cement slurries, or low-temperature thermal procedures) have been of specific interest in recent applied research. However, the extent of strength recovery depends strongly on treatment intensity and rubber content [7, 8, 10].

2.4. Effect of the Size of Rubber Particles and the Level of Replacement

Particle size and level of replacement are consistently demonstrated to be major controls on both fresh and hardened performance. Small crumb sizes are usually less detrimental to compressive strength, but enhance packing and decrease slump loss; larger particles enhance deformability and energy absorption but enhance strength penalties. Replacement level interacts with size. At low percentages, the reduction in strength is moderate, but high-volume substitutions (≥30–40%) tend to drive the composite into non-structural application regimes. Current quantitative research gives empirical models and neural-network solutions that forecast strength in terms of particle size and volumetric composition, which assists in practical mix selection [9, 11].

2.5. Gaps Identified

Little work on multi-size treated rubber and micro-to-macro blending. Although waste tyre rubber has been extensively studied in concrete applications, little research exists examining the combined effect of aggregates with wide variability in size and two different types of treatment (i.e., chemically treated mixtures (CMT) and mechanically treated mixtures (CCMT)). The vast majority of studies examining waste tyre rubber bricks as aggregates focus on single-size replacements and do not examine the synergy of blending both micro and macro aggregate size particles. Each study conducted in deeper investigations that get at the heart of how the combined particle sizes co-act and particle treatments co-action simultaneously create properties that affect, such as compressive and flexural strength and durability performance on the micro and macro levels. Addressing this gap can be pivotal to determining acceptable replacement levels and legitimizing the treated rubber mix as a sustainable alternative to traditional coarse aggregate in structural concrete [6, 11].

2.6. Justification for the Present Study

The main aim of this study is to investigate the performance of concrete using multi-size chemically and mechanically treated (CMT and CCMT) waste tyre rubber as a partial coarse aggregate replacement. The study involves producing and testing 60 concrete mixes at different rubber sizes and rubber replacement percentages of 5%, 10%, 15%, and 20%, with additional optimization at 15% rubber replacement using macro-to-micro grades of aggregate in 24 mixes. The study includes compressive strength, flexural strength, water absorption, and acid resistance to demonstrate at the conclusion of the study that treated rubber aggregates are a sustainable and structurally sound substitute for concrete construction [6-11].

Table 2. Summary of recent studies using tyre rubber in concrete

Study Focus	Material/Modification	Key Findings	Key Reference
Dynamic mechanical behaviour and LCA of rubberised solid waste-based geopolymer concrete	Rubber as a partial aggregate in geopolymer concrete	Improved dynamic performance; life cycle assessment showed enhanced sustainability	[6]
Durability and mechanism of modified crumb rubber concrete	Modified crumb rubber	Enhanced durability properties and resistance to environmental effects	[7]
Improving mechanical properties via the pre-mixing technique	Polypropylene and crumb rubber	Polypropylene addition significantly improved the strength and bonding in crumb rubber concrete.	[8]
Sustainable geopolymer foam concrete with dual fibers	Crumb rubber, polypropylene, and glass fibers	Achieved lightweight, durable foam concrete with improved mechanical and thermal properties	[9]
Recycling rubber in impact-resistant composites	Waste tire rubber in engineered cementitious composites	Rubber aggregate improved impact resistance and energy absorption capacity	[10]
Review of untreated vs treated crumb rubber in concrete	Untreated and treated crumb rubber	Treatment methods enhanced interfacial bonding; a comprehensive review of mechanical and durability trends	[11]

Table 1, presented below, outlines important research relevant to rubberised concrete, specifically focusing on mechanical utility, durability properties, and sustainability. Results suggest that rubber used as a partial aggregate improved the dynamic and impact resistance of concrete. Alternative enhancements, such as polypropylene and glass fibre, showed improvements in strength and bond. As well, there are various treatment methods serving to further optimise interfacial properties and potentially offer sustainable, durable, versatile applications in advanced concrete product development.

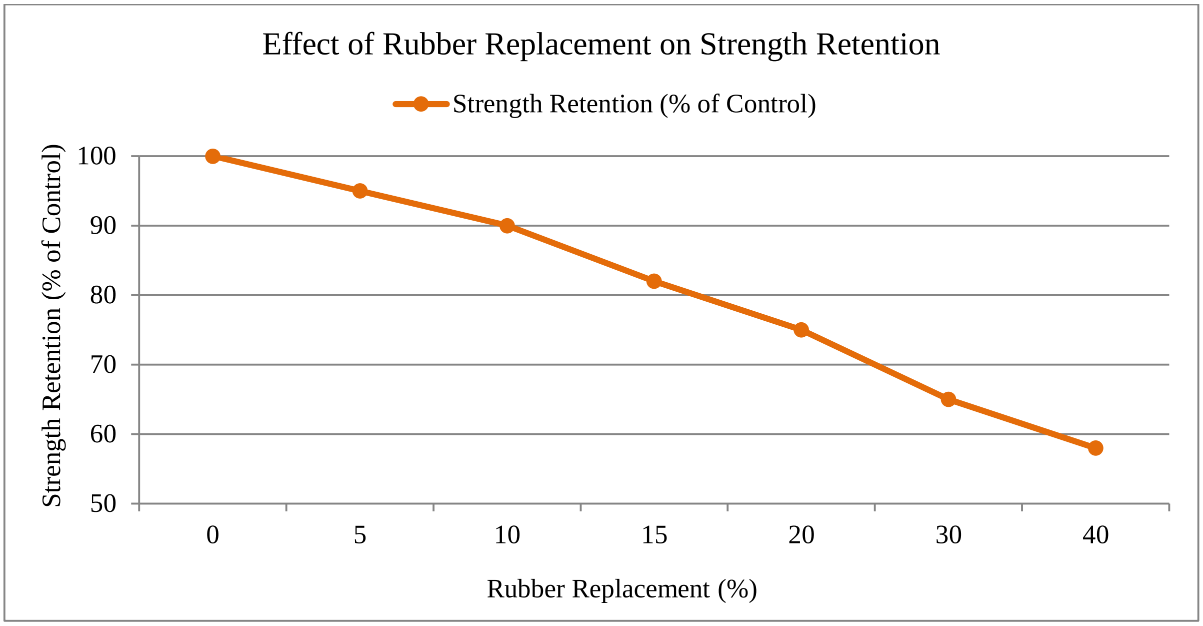

Fig. 2 Strength trend from literature vs rubber replacement % [1-11]

Figure 2 demonstrates how rubber replacement percentage correlates with retention of strength in concrete. This shows that as rubber content increases from 0% to 40%, compressive strength retention decreases from 100% to about 58%. It shows the compromises between sustainability and mechanical performance when using tyre rubber in concrete mixtures.

3. Materials and Methods

3.1. Materials

3.1.1. Resin

Resin is a flexible adhesive obtainable from synthetic or natural sources. Some common types of resin and resin adhesives are epoxy, polyurethane, and polyester resins. Their use on multiple substrates provides strength and durability.

Fig. 3(a) Resin

3.1.2. Hardener

Hardener is an important aspect of resin adhesives like epoxy. The hardener induces the curing action. The hardener and its mixture will create a cure of solid resin when mixed and applied in the correct ratio with resin, mixed correctly, and applied correctly. The correct hardener used for specific resin formulations is very important to ensure proper performance in each application.

Fig. 3(b) Hardener

3.1.3. Cobalt

Cobalt compounds can be useful in resin systems, most notably in catalyzing unsaturated polyester resins. Catalysts promote the polymerization of the resin, so it becomes solid and can form a solid bond. Including impermeant into adhesive formulations may help cure the adhesive and enhance the performance/durability of the adhesive bond.

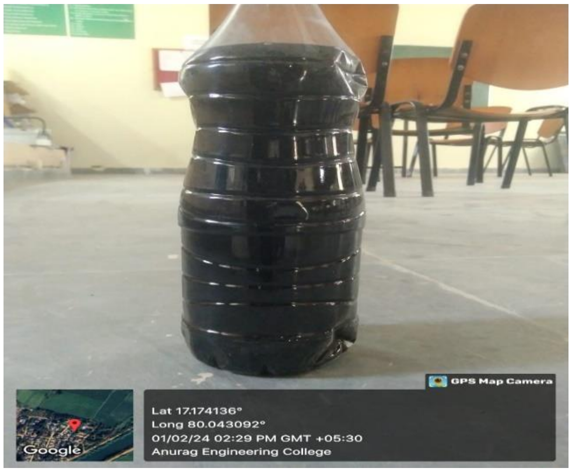

Fig. 4(a) Cobalt

Fig. 4(b) Tyre Rubber

3.1.4. Tyre Rubber

Waste tyre rubber causes environmental issues and is a significant contributor to pollution and landfill issues. Recycling of waste tyre rubber using recycled rubber is a sustainable solution and the recycled rubber is used in construction as Rubberized concrete, where the recycled rubber is used in a construction as a partial replacement of aggregate using 10mm and 20mm size aggregate with a chemical mechanical treatment to improve the properties of elastic behaviour and adhesive bonding but helps to mitigate cracking and improves concrete performance and durability.

3.1.5. Cement

OPC 53 grade cement is generally used due to its superior compressive strength, as the designation 53 Grade refers to the minimum compressive strength of the cement, i.e., 53 MPa after 28 days of curing. OPC 53-grade cement was used in the mix design for M25 grade (IS 10262: 2009).

3.1.6. Natural Aggregate

In the present study, fine aggregates were used as Zone II based on IS: 383-1970. Coarse aggregates of 20 mm and 10 mm with specific gravities of 2.85 and 2.75 were used in a 60:40 ratio.

3.1.7. Fine Aggregate

Fine aggregate refers to the natural sand or crushed stone material that consists of particles that pass through the 4.75 mm sieve and are retained on the 0.075 mm sieve. The particle size distribution of fine aggregates contributes to the workability and strength of concrete.

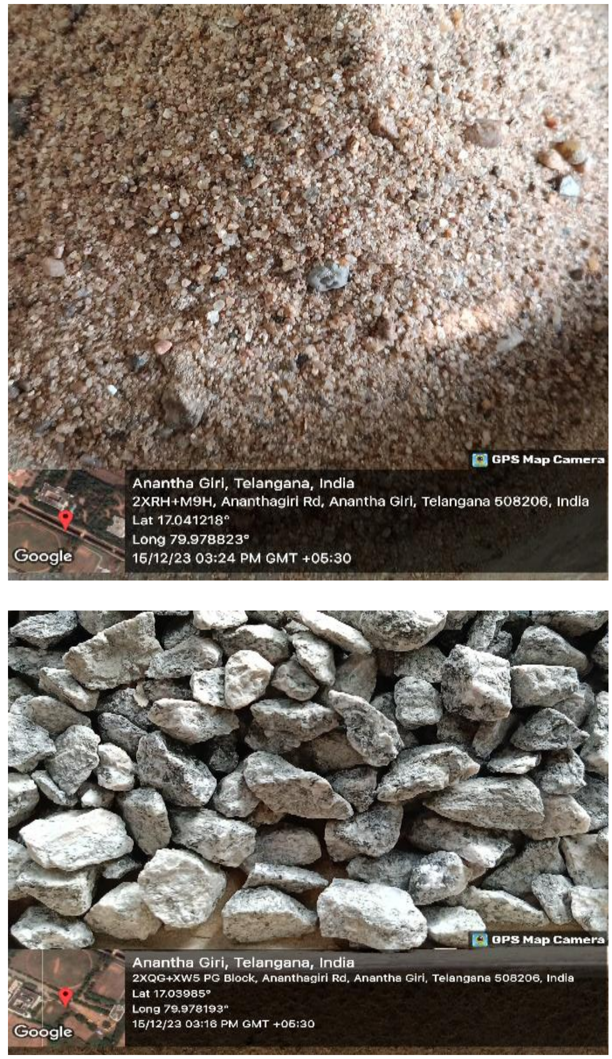

Fig. 5 Coarse and fine aggregates

3.2. Rubber Treatment Processes

In the Chemical Mechanical Treatment (CMT) trial, the mix ratio (Resin - 2 parts, Hardener - 1 part, Cobalt - 0.5 part) produced bonding effective enough to have priority in some of our trials including a water absorption trial where it proved to have a fantastic 0% absorption which validated CMT's success in achieving a well bonded and water resistant rubberized concrete.

In Phase II, we chose about cemented rubberized concrete. We did this by dipping CMT Rubber into a cement slurry to provide greater strength and bonding between the particles. (CCMT)

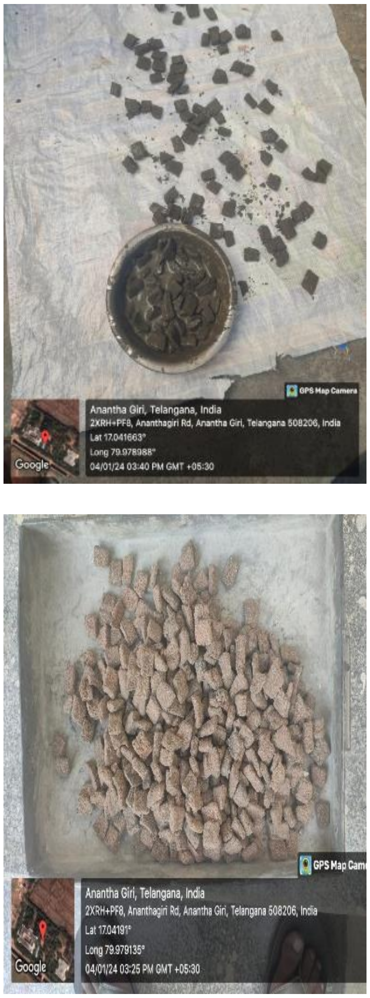

Fig. 6 CMT and CCMT output Image

Waste tyre rubber aggregates were processed via two methods: CMT (Chemical-Mechanical Treatment): Composition ratio of Resin: Hardener: Cobalt = 2: 1: 0.5 (by mass) was prepared. For CMT, rubber was mixed for 2 minutes, coated, and then oven dried at 50 °C for 24h. CCMT (Cement-Coated for Chemical-Mechanical Treatment): CMT rubber was then dipped for 2 minutes into a cement-silica slurry (w/c = 0.35; cement: silica = 1: 0.2 by mass), and cured at 25 °C for 24h. Visual observations were taken, and mass changes were measured to check the treated rubber's water absorption and surface texture.

3.3. Mix Design Details

The mix designs conformed to IS 10262:2019 guidelines for high-strength concrete with a desired compressive strength of 30 to 40 MPa after 28 days. The water-to-binder ratio was kept at 0.58, and polycarboxylate ether-based superplasticizers were incorporated to enhance workability.

3.3.1. CMT Mixes (Chemically Treated Rubber)

Rubberized concrete mixes involving 10 mm and 20 mm CMT particles were made by substituting natural coarse aggregates at 5%, 10%, 15%, and 20% by volume. M7–M22 series allowed for assessment of the stepwise impact of rubber content on compressive, flexural, and impact resistance characteristics.

3.3.2. CCMT Mixes (Coated+ Chemically/Mechanically Treated)

In this set, rubber chemically pretreated was coated additionally with cement silica slurry. Replacements at 5%, 10%, and 15% were tested in concrete mixes M23–M38. It was hoped that the coating would cushion the sharp fall in compressive strength typically associated with rubber addition, while maintaining the toughness and impact resistance advantages.

3.3.3. Multi-Size Blending Strategy

A new strategy was followed in blends M39–M62 in which rubber fractions of different sizes (crumb <4.75 mm, 10 mm chips, and 20 mm chunks) were blended in optimized proportions (e.g., 40:40:20 by weight).

This multi-size blend strategy was meant to enhance packing density, minimize interfacial porosity, and maximize stress distribution under load. The blends were planned to mimic variability in real-world rubber aggregates in investigating micro-to-macro blend effects.

3.4. Experimental Techniques

3.4.1. Fresh Properties

Slump test (IS 1199:2018) and compaction factor tests were performed to evaluate workability. Rubber inclusion tended to decrease the slump, where superplasticizers were needed.

3.4.2. Mechanical Properties

Compressive strength (IS 516:2018): Cube samples (150 mm) tested at 7, 28, and 90 days.

Flexural strength: Prism samples (150×150×700 mm) tested under third-point loading.

3.4.3. Durability Properties

Water absorption (ASTM C642), sorptivity (ASTM C1585), and chloride penetration (ASTM C1202) tests were performed to determine durability performance. These were important to evaluate if surface treatments had the potential to enhance long-term performance [12].

Table 4 below provides 24 concrete mix designs (M39–M62), each with 15% treated rubber as a partial replacement for coarse aggregate. The mixes have the same cement, fine aggregate, and water content, while the distribution of 10–20 mm aggregate sizes and the amount of rubber replacement are varied to examine performance optimization for sustainable concrete applications.

Table 3. Detailed mix proportions for all mixes

Mix Description	Mix No.	Cement (kg/m³)	GGBS (kg/m³)	Fly Ash (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³) 10 mm	Treated Rubber	Water (kg/m³)
CC	M1	349	-	-	675	1199	-	204
12M GPC Made with 50% Fly Ash & 50% GGBS	M4	-	174.5	174.5	675	1199	-	57.83
10mm CMT 5%	M7	349	-	-	675	1139.05	59.95	204
10mm CMT 10%	M8	349	-	-	675	1079.1	119.9	204
10mm CMT 15%	M9	349	-	-	675	1019.15	179.85	204
10mm CMT 20%	M10	349	-	-	675	959.2	239.8	204
12mm CMT 5%	M11	349	-	-	675	1139.05	59.95	204
12mm CMT 10%	M12	349	-	-	675	1079.1	119.9	204
12mm CMT 15%	M13	349	-	-	675	1019.15	179.85	204
12mm CMT 20%	M14	349	-	-	675	959.2	239.8	204
16mm CMT 5%	M15	349	-	-	675	1139.05	59.95	204
16mm CMT 10%	M16	349	-	-	675	1079.1	119.9	204
16mm CMT 15%	M17	349	-	-	675	1019.15	179.85	204
16mm CMT 20%	M18	349	-	-	675	959.2	239.8	204
20mm CMT 5%	M19	349	-	-	675	1139.05	59.95	204
20mm CMT 10%	M20	349	-	-	675	1079.1	119.9	204
20mm CMT 15%	M21	349	-	-	675	1019.15	179.85	204
20mm CMT 20%	M22	349	-	-	675	959.2	239.8	204
10mm CCMT 5%	M23	349	-	-	675	1139.05	59.95	204
10mm CCMT 10%	M24	349	-	-	675	1079.1	119.9	204
10mm CCMT 15%	M25	349	-	-	675	1019.15	179.85	204

10mm CCMT 20%	M26	349	-	-	675	959.2	239.8	204
12mm CCMT 5%	M27	349	-	-	675	1139.05	59.95	204
12mm CCMT 10%	M28	349	-	-	675	1079.1	119.9	204
12mm CCMT 15%	M29	349	-	-	675	1019.15	179.85	204
12mm CCMT 20%	M30	349	-	-	675	959.2	239.8	204
16mm CCMT 5%	M31	349	-	-	675	1139.05	59.95	204
16mm CCMT 10%	M32	349	-	-	675	1079.1	119.9	204
16mm CCMT 15%	M33	349	-	-	675	1019.15	179.85	204
16mm CCMT 20%	M34	349	-	-	675	959.2	239.8	204
20mm CCMT 5%	M35	349	-	-	675	1139.05	59.95	204
20mm CCMT 10%	M36	349	-	-	675	1079.1	119.9	204
20mm CCMT 15%	M37	349	-	-	675	1019.15	179.85	204
20mm CCMT 20%	M38	349	-	-	675	959.2	239.8	204
Blended (multi-size) CMT 15%	M39–M62	349	-	-	675	1019.15	179.85	204

Table 4. Detailed mix proportions for blended CMT(M39-M62)

Mix Description	Mix No.	Cement (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3) 10 mm	Treated Rubber				Water (kg/m^3)
					10 MM	12 MM	16 MM	20 MM	
4321CMT15%	M39	349	675	1019.15	71.94	53.96	35.97	17.99	204
4312CMT15%	M40	349	675	1019.15	71.94	53.95	17.98	35.97	204
4231CMT15%	M41	349	675	1019.15	71.94	35.97	53.95	17.98	204
4213CMT15%	M42	349	675	1019.15	71.94	35.97	17.98	53.95	204
4132CMT15%	M43	349	675	1019.15	71.94	17.98	53.95	35.97	204
4123CMT15%	M44	349	675	1019.15	71.94	17.98	35.97	53.95	204
3421CMT15%	M45	349	675	1019.15	53.95	71.94	35.97	17.98	204
3412CMT15%	M46	349	675	1019.15	53.95	71.94	17.98	35.97	204
3241CMT15%	M47	349	675	1019.15	53.95	35.97	71.94	17.98	204
3214CMT15%	M48	349	675	1019.15	53.95	35.97	17.98	71.94	204
3142CMT15%	M49	349	675	1019.15	53.95	17.98	71.94	35.97	204

3124CMT15%	M50	349	675	1019.15	53.95	17.98	35.97	71.94	204
2431CMT15%	M51	349	675	1019.15	35.97	71.94	53.95	17.98	204
2413CMT15%	M52	349	675	1019.15	35.97	71.94	17.98	53.95	204
2341CMT15%	M53	349	675	1019.15	35.97	53.95	71.94	17.98	204
2314CMT15%	M54	349	675	1019.15	35.97	53.95	17.98	71.94	204
2143CMT15%	M55	349	675	1019.15	35.97	17.98	71.94	53.95	204
2134CMT15%	M56	349	675	1019.15	35.97	17.98	53.95	71.94	204
1432CMT15%	M57	349	675	1019.15	17.98	71.94	53.95	35.97	204
1423CMT15%	M58	349	675	1019.15	17.98	71.94	35.97	53.95	204
1342CMT15%	M59	349	675	1019.15	17.98	53.95	71.94	35.97	204
1324CMT15%	M60	349	675	1019.15	17.98	53.95	35.97	71.94	204
1243CMT15%	M61	349	675	1019.15	17.98	35.97	71.94	53.95	204
1234CMT15%	M62	349	675	1019.15	17.98	35.97	53.95	71.94	204

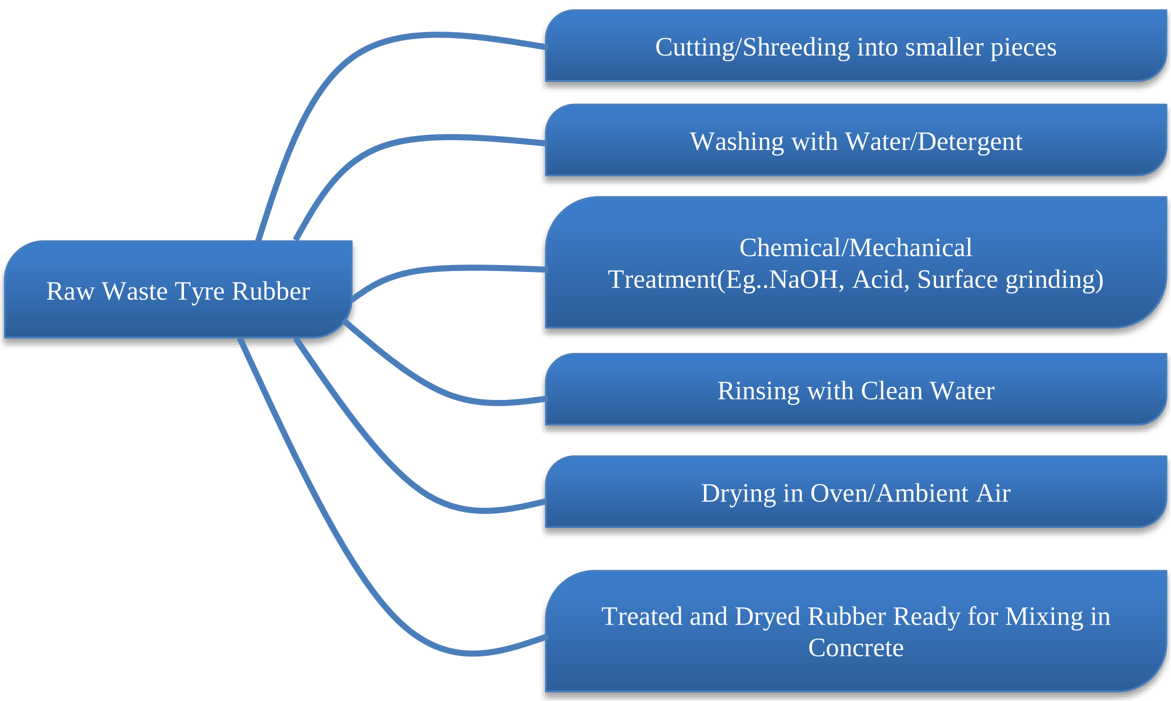

Fig. 7 Tyre rubber treatment and drying process

The presented mind map illustrates the preparation of raw waste tyre rubber for use in concrete. The process begins with the cutting and shredding of the rubber into smaller pieces, followed by washing with water and detergent. The rubber then undergoes the chemical/mechanical treatment of something with NaOH or acid, then surface grinding. Rinse the rubber with clean water and then dry with an oven or ambient air to arrive with treated and dried rubber ready to be mixed in the concrete.

Table 5. Testing standards

Test Type	Standard Code	Description
Compressive Strength	IS 516:2018	Method of tests for the strength of concrete
Flexural Strength	IS 516:2018	Flexural test method for concrete beams

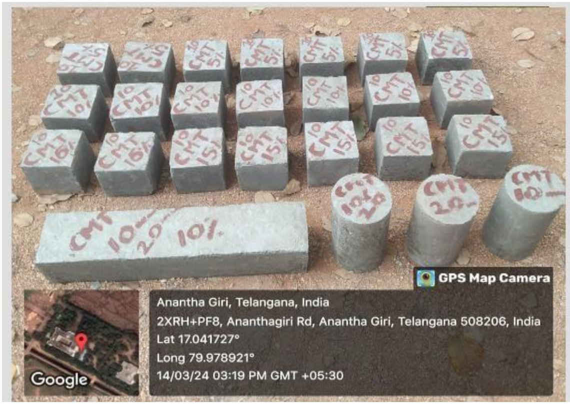

Fig. 8 Concrete cube and beam sample preparation workflow

4. Results

The experimental program comprised 60 concrete mixes that included Chemically Mechanically Treated (CMT) or Combined Chemically Mechanically Treated (CCMT) waste tyre rubber as coarse aggregate replacement with replacement levels of 5%, 10%, 15% and 20% using 10 mm, 12 mm, 16 mm, and 20 mm aggregate. There were a further 24 mixes prepared using multi-size blending approaches at the optimum replacement level of 15%. Performance of concrete mixes was subsequently determined predominantly by their compressive strength. Some mixes also underwent an evaluation of flexural strength, water absorption, and acid resistance.

4.1. Compressive Strength of CMT Replacements

For the 10 mm CMT mixes, compressive strength increased with replacement levels to a maximum of 15% (34 MPa, M9), then decreased (30 MPa, M10). For the 12 mm CMT replacements, compressive strength reached a maximum of 33.33 MPa (M13) at 15% and decreased with further replacements. The 16 mm series produced a maximum compressive strength of 32.44 MPa (M17) at 15%. The 20 mm replacements consistently resulted in reduced compressive strengths. Ultimately, 20% of the aggregate was replaced (M22), and compressive strength was only 27.56 MPa. What is clear is that smaller aggregate sizes and substitution levels of approximately 150% yield more extensive bonding and greater strength retention.

4.2. Compressive Strength of CCMT Replacements

The CCMT mixtures followed a comparable pattern, with a lower overall performance than CMT. Peak compressive strength for 10 mm CCMT aggregates occurred at 15% replacement, with a maximum strength of 32 MPa (M25). The 12 mm and 16 mm CCMT mixtures reached maximums of 31.56 MPa (M29) and 30.89 MPa (M33), respectively, while the 20 mm CCMT replacements showed the least compressive strength of 26.67 MPa at 20% (M38). It can therefore be concluded that CCMT improves workability but has a lesser contribution to slight strength improvements compared to CMT.

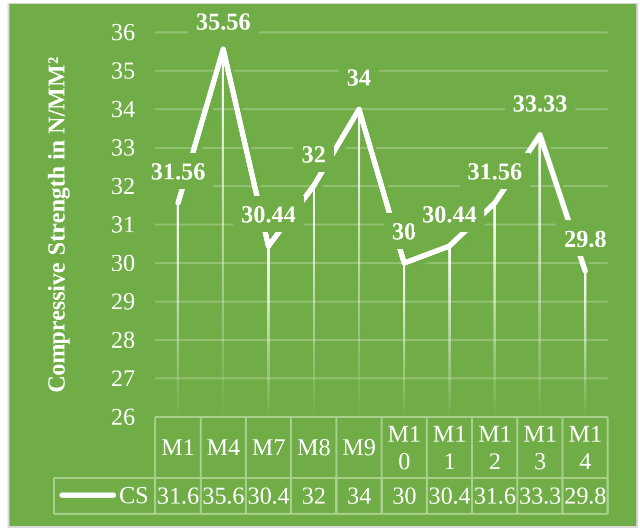

Fig. 9 Compressive strengths of M1, M4, M7 TO M14

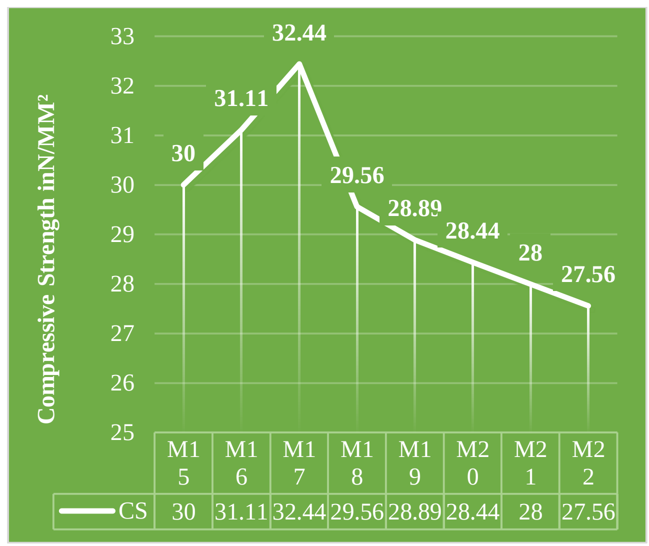

Fig. 10 Compressive strengths of CMT M15 TO M22

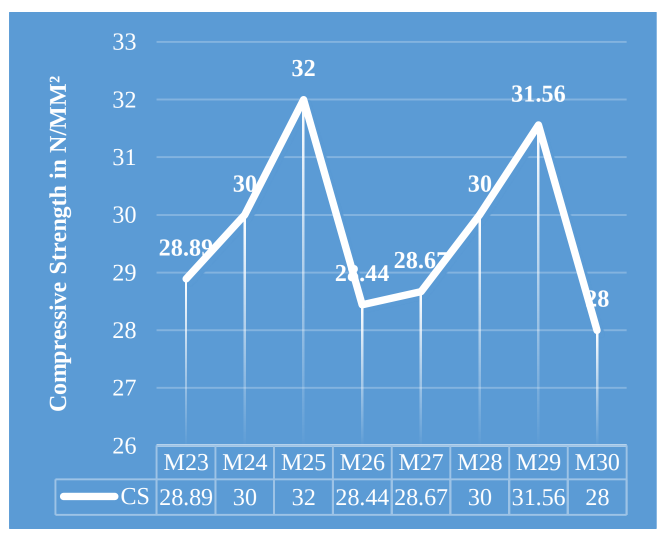

Fig. 11 Compressive strengths of CCMT M23 TO M30

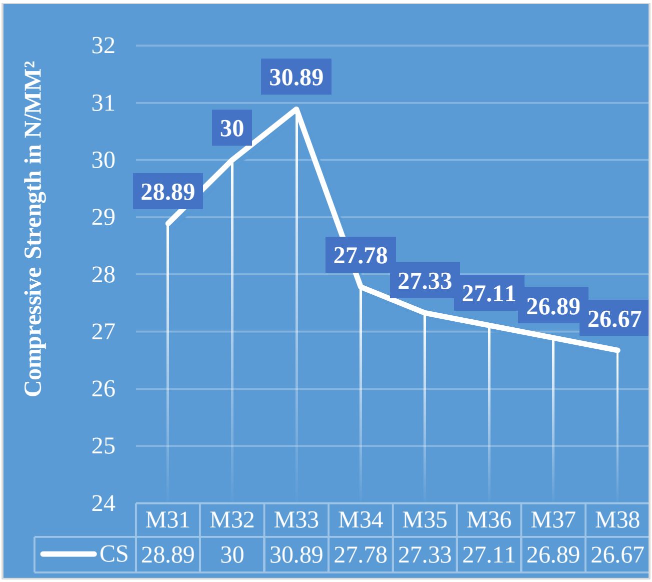

Fig. 12 Compressive strengths of CCMT M30 TO M38

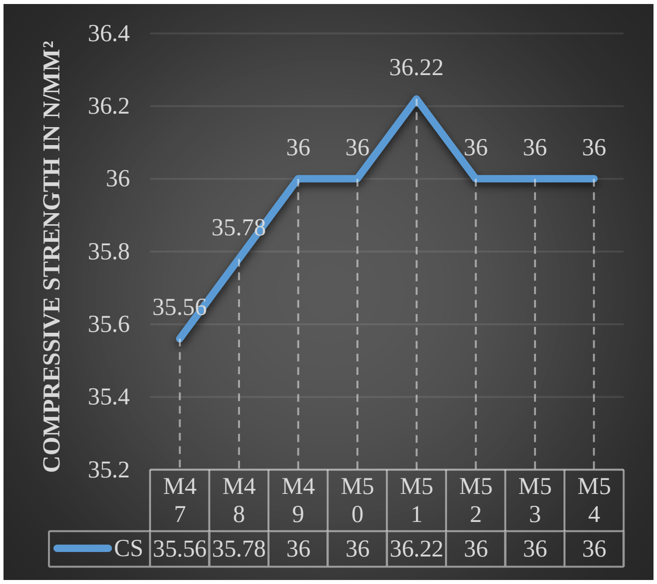

Fig. 14 Compressive strengths of Blended mix M47 TO M54

4.3. Performance of Multi-Size Blended Mixes

In order to examine the performance of rubber aggregate and enhance its performance, we created a macro-to-micro blend at a 15% replacement. All blended series have improved compressive strength over the previous and standard mixes. The values were 34.0 MPa (M39) through to 36.67 MPa (M62). The best mix performing (M62 - 1234CMT15%) was 36.67 MPa, which exceeds both the conventional control mix (31.56 MPa, M1) and the benchmark geopolymer mix (35.56 MPa, M4).

The results have highlighted that within the blended multi-size program, the use of rubber aggregates has improved packing density and interfacial bonding, helping to overcome the loss of strength usually seen when rubber is included in the mix.

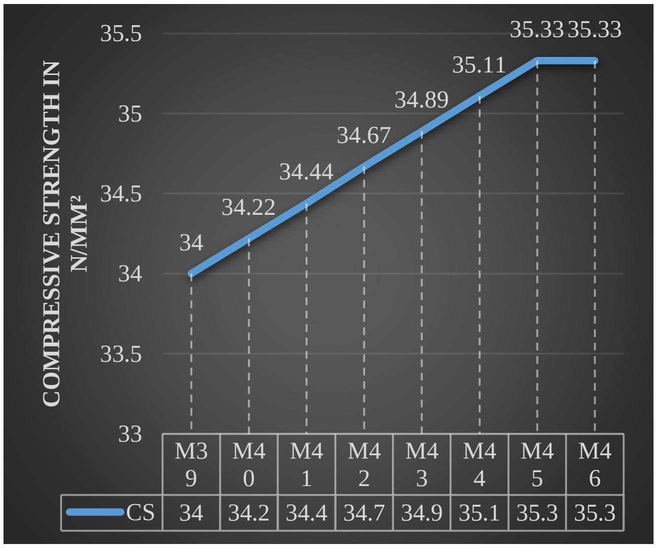

Fig. 13 Compressive strengths of Blended mix M39 TO M46

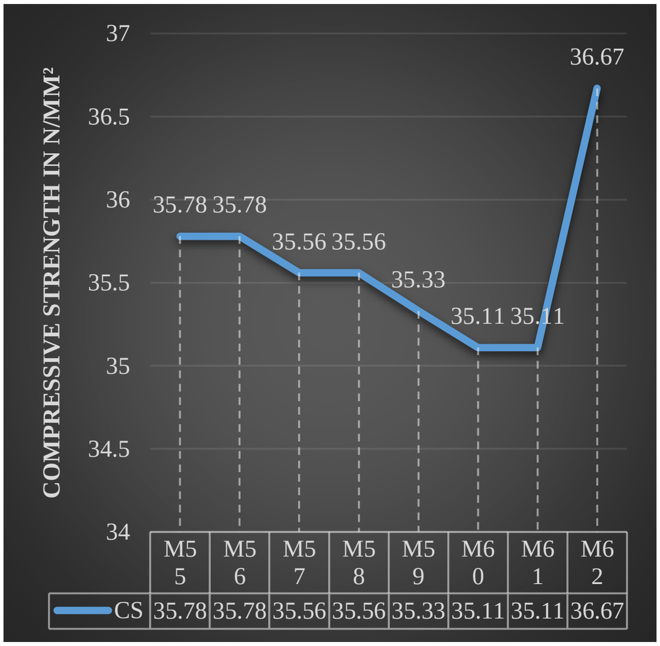

Fig. 15 Compressive strengths of Blended mix M55 TO M62

4.4. Flexural Strength and Durability Evaluations

The best-performing mix (M62) was also evaluated using flexural strength and durability tests. The flexural strength results indicated better load-carrying capacity when compared to the control mix. These results were attributed to the treated rubber aggregates having better energy absorption.

The durability evaluation showed that water absorption was reduced, which could indicate a denser matrix, and the acid resistance tests showed less degradation of strength when exposed to agitated conditions when compared to untreated rubber concretes.

Table 6. Test results for flexural strength at 28 days

Mix ID	Mix Type	Flexural Strength (N/mm²)
M1	CC(Conventional Concrete)	3.93
M62	1234CMT15%	4.24

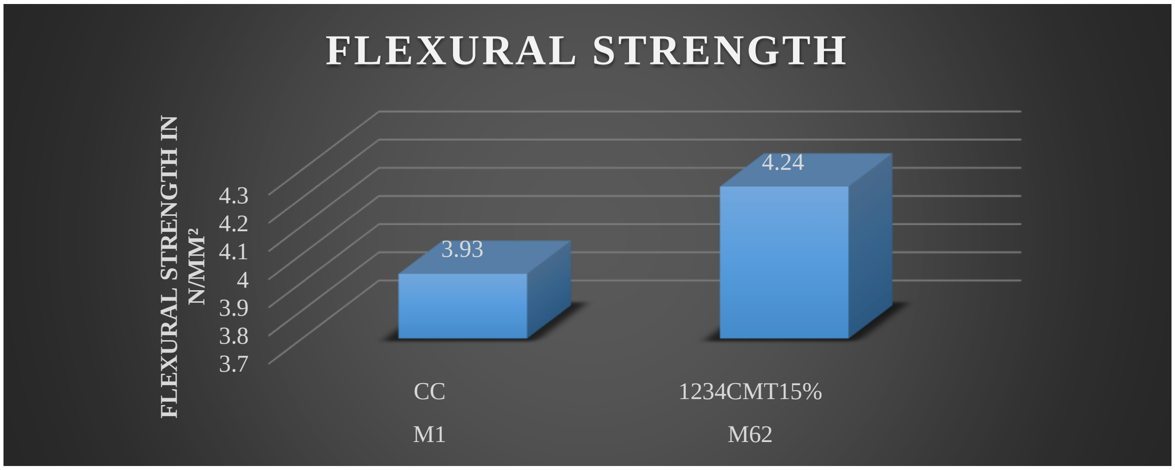

Fig. 16 Flexural strengths of M1 and M62

Table 7. Durability for optimum mix (M62)

Mix	Mix Designation	Initial Compressive Strength at 28 Days (N/mm²)	Residual Strength After HCl at 90 Days (N/mm²)	Mass Loss (%)	Durability Factor (%)
M62	1234CMT15%	36.67	31.65	2.6	85.4

Table 7 demonstrates that the M62 mix shows good durability. After 90 days of HCl exposure, it retains 85.4% of the original strength with a minimal mass loss of 2.6%. This indicates very good resistance to the acid attack for this type of concrete mix.

The ideal blend was reached at 15% replacement with multi-size CMT aggregates. The M62 (1:2:3:4 CMT15%) blend had the greatest compressive strength at 36.67 MPa, representing a 16.2% increase over the control mix (M1 = 31.56 MPa). The flexural strength was 4.24 MPa (11.6% of fc), which is also within IS Code limits and demonstrates compliance with structural and load-bearing adequacy. The strength retention was mainly due to the Improved Interfacial Transition Zone (ITZ) between the rubber that had been treated and the cement paste.

5. Discussions

5.1. Compressive Strength

The compressive strength tests confirmed that the CMT aggregates performed better than the CCMT aggregates with 15% replacement as the preferred level of replacement of both treated rubber systems. The best performing replacement mix, M62, achieved a compressive strength of 36.67 MPa compared to the conventional concrete control with a compressive strength of 31.56 MPa, establishing that treated rubber aggregates provide for the absence of any strength reduction normally associated with rubberized concrete and improve mechanical properties. This is due to the additional strength obtained by combining chemical and mechanical surface treatments for the rubber, due to the enhanced bond strength at the rubber–cement interface, and the blending of macro-to-micro aggregates, which produced an optimized packing density and interfacial transition zones. These additional mechanical properties of treated rubber aggregates allowed for approximately 16% improvement in the compressive strength over conventional concrete and improved durability, confirming that treated waste tyre rubber is a structurally viable and environmentally sustainable replacement for natural coarse aggregates.

5.2. Flexural Strength

According to the results provided, there exists a strong positive correlation between compressive strength (36.67 MPa) and flexural strength (4.24 MPa) of the optimum mix M62. Specifically, the flexural strength value of 4.24 MPa represents approximately 11.6% of its compressive strength, which aligns with the accepted relationships for conventional concrete, where flexural strength is often between 10-15% of the compressive strength. There is evidence to support the notion that the use of treated rubber aggregates at a 15% replacement level does not impact the expected relationship between mechanical performance. The treated rubber would also have undergone chemical and mechanical treatments, which would strengthen the bond with the cement matrix, allowing tensile stresses to be transferred to the composite efficiently. This related correlation supports that the mix continues to structurally perform as expected while under loads, again confirming the structural capabilities of using the full composite, replacing 15% of the concrete.

5.3. Durability

The durability tests indicated that the optimal compressive strength of CMT-treated concrete was 31.65 MPa after 90 days of immersion in a 5% HCl solution, demonstrating a mass loss of 2.6% and a durability of 85.4%. Water absorption was substantially reduced compared to conventional concrete. Results of the study confirm that CMT treatment improves the chemical stability and durability of concrete in a severe environment over a long time.

5.4. Comparative Assessment of CMT and CCMT Treatments

With regard to the aggregate sizes assessed (10-16 mm), the CMT-treated aggregates consistently achieved higher compressive and flexural strength than CCMT mixes. This can be attributed to uniform coating thickness, increased surface energy, and increased densification of the cement matrix in the CMT-treated samples. While CCMT produced additional surface roughness, it also generated micro-voids and weaker interfacial bonding in aggregates with finer rubber fractions.

5.5. Sustainability and Practical Implications

The results indicate that multi-sized CMT-treated rubber aggregates can be employed as structurally reliable and environmentally sustainable alternatives to natural coarse aggregates in concrete. This strategy advances waste tyre recycling while protecting natural resources and reducing environmental pollution; all consistent with the objectives of furthering global sustainability initiatives and a circular economy. The results presented support treating rubber concrete as a viable material for pavement blocks, precast panels, and structurally, amongst moderate loads.

5.6. Limitations and Future Scope

This study has established the success of CMT-treated rubber in the laboratory, but further research should be conducted on the following:

- Long-term durability for chloride ingress, freeze-thaw cycles, and alkali-silica reaction.
- Microstructural analyses using SEM, FTIR, etc., treatment, and matrix interaction.
- Life-Cycle Assessment (LCA) of chemical treatment costs and environmental benefits.
- Field-scale trials to assess the ecological scalability and uniformity of mixing, as well as structural performance in a realistic setting.

6. Conclusion

The experimental study found that waste tire rubber aggregates, which have undergone both Chemical and Mechanical Treatments (CMT), can be used as partial coarse aggregate replacement in concrete without any degradation in performance. A total of 60 single-size mixes and 24 multi-size blended mixes were tested with 5-20% replacement of rubber aggregates with particle sizes of 10, 12, 16, and 20 mm. All CMT treatments provided a better surface bond with lower void content compared to cement-coated (CCMT) aggregates.

The M62 aggregate blend (1:2:3:4 CMT15%) yielded the highest compressive strength of all the blends, with 36.67 MPa representing a 16.2% improvement vs. the control blend (M1 = 31.56 MPa). A flexural strength of 4.24 MPa (11.6% of fc) is demonstrative of adequate structural capacity, based on IS Code correlation. The CMT-treated aggregates outperformed CCMT in blends, where aggregate sizes were in the 10–16 mm size range, primarily due to their superior surface bonding and densification of the cement matrix.

Durability performance results have shown the M62 blend to yield a compressive strength of 31.65 MPa after 90 days of exposure to Hydrochloric acid (HCl) with a 2.6% mass loss and a durability factor of 85.4%. Treated rubber concrete blends also demonstrated a lower level of water absorption and improved chemical resistance compared with conventional control concrete.

Finally, this study provides evidence that multi-size CMT-treated waste tyre rubber aggregates can be recycled as a viable, modern, and sustainable alternative for natural coarse aggregates for durable concrete applications. This method provides a new pathway to recycle waste tyres, consistent with the global sustainability agenda in the construction industry.

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