STM JOURNALS

Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 4, 2026
January–December
DOI (Journal): 10.37591/JoPC

Research JoPC

Development of Environmentally Friendly Concrete by Incorporating Rubber and Leather Waste

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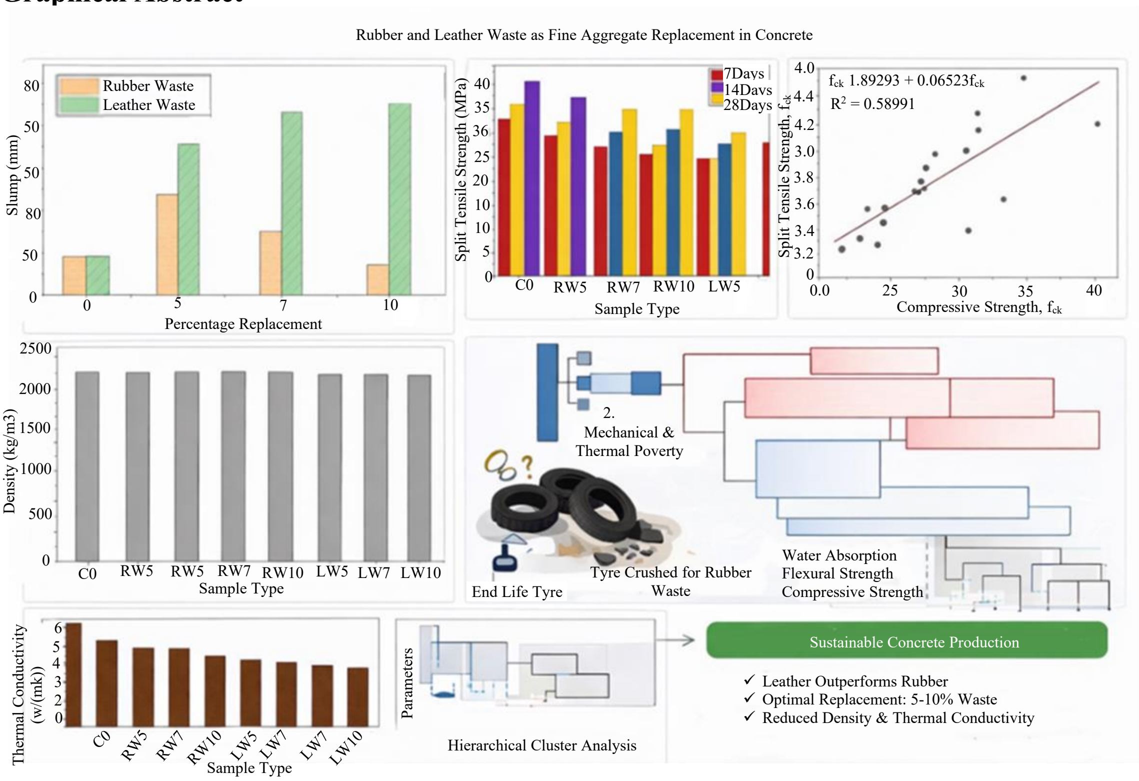
Abstract

The valorization of post-consumer polymeric waste into high-performance composite materials offers a sustainable strategy for advancing circular economy principles and reducing environmental impacts.

Graphical Abstract



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Received Date: July 29, 2026
Accepted Date: August 20, 2026
Published Date: August 22, 2026

Citation: Amit Daiya, Mohit Verma, Deepak Kumar Tiwari. Development of Environmentally Friendly Concrete by Incorporating Rubber and Leather Waste. Journal of Polymer & Composites. 2026; 14(Special Issue 4): S547–S563p.

This study investigates the feasibility of utilizing recycled crumb rubber from end-of-life tires and leather-derived polymeric waste from the footwear industry as sustainable fillers in polymer-modified cementitious composites. Crumb rubber and processed leather waste were incorporated as partial replacements for natural fine aggregate at replacement levels of 0%, 5%, 7%, and 10% in M30 concrete. The effects of polymeric inclusions on fresh properties, mechanical performance, density, water absorption, and thermal conductivity were systematically evaluated. The incorporation of recycled polymeric materials significantly influenced the structure–property relationship of the cementitious composites. Compressive strength was *maintained up to a 5% replacement level, beyond which a gradual reduction occurred, with leather-derived polymeric waste exhibiting superior mechanical performance compared to crumb rubber. Split tensile strength improved at lower replacement levels but declined with increasing polymer content due to weaker polymer–cement interfacial bonding and increased porosity. Conversely, flexural strength benefited from the elastomeric characteristics of the polymeric inclusions, reaching optimum values at 10% crumb rubber and 7% leather waste through enhanced crack resistance and energy absorption. Increasing polymer content reduced composite density and thermal conductivity, producing lightweight composites with improved thermal insulation, although water absorption increased, particularly in leather-modified mixtures. Correlation and hierarchical cluster analyses further revealed distinct relationships among mechanical, thermal, and durability-related properties. Overall, the findings demonstrate that recycled elastomeric and leather-derived polymeric materials can be effectively utilized to develop sustainable polymer–cement composites, contributing to green polymer engineering, recycled polymer composites, and environmentally responsible construction materials.*

Keywords: Sustainable polymeric concrete, polymeric waste, rubber waste, leather waste, thermal conductivity

INTRODUCTION

The disposal of discarded tires has become an important environmental problem in India, attributed to the rapid expansion of the automobile industry and rising vehicle ownership. India is expected to produce approximately 100–150 million discarded tires every year, fueled by the growth of road transport, industrial activities, and urbanization. A considerable amount of these discarded tires is either openly disposed of, unlawfully accumulated, or incorrectly incinerated, resulting in soil degradation, fire risks, and air pollution. Tires in landfills make up a lot of solid garbage. Stockpiled tyres pollute the air, water, and soil, causing health, environmental, and economic issues. The tires retain water for an extended duration due to their specific shape and impermeable characteristics, creating a breeding environment for mosquitoes and other pests [1–3]. Natural fiber-reinforced polymer composites have attracted considerable attention owing to their sustainability, biodegradability, and excellent strength-to-weight ratio [4]. In recent years, numerous supplementary materials have been employed to decrease the sand consumption and, thus, mitigate the natural resource consumption [5]. Secondly, although discarded tires are challenging to ignite, the risk remains ever-present. When tires begin to degrade, high temperatures from unintended causes ensue, resulting in the emission of poisonous fumes [6]. The composite fabrication process involves the collection, grinding, and subsequent sterilization of the biomass [7].

The potential of hybridizing natural fibers for the development of eco-friendly fiber–metal laminates has been extensively investigated over the past several decades [8].

Fiber reinforced concrete is commonly seen as a substitute for ordinary concrete due to its reduced brittleness [9]. Research suggests that tyre waste concrete is ideal for structures in earthquake-prone areas and uses like railway sleepers. This material is also suitable for non-load-bearing applications like noise reduction barriers. Research indicates that the performance of rubber waste concrete is highly influenced by waste aggregates [10]. Although crumb tires diminish compressive strength, they can nonetheless meet the strength requirements of light-weight concrete. Crumb rubber does not significantly reduce the workability of combinations [11]. In today's world, the management and utilization of garbage have evolved into a significant economic challenge. The operations of the economy have a detrimental impact on the natural world. As a result, it is of utmost significance to investigate the potential applications of waste products from households and technological applications, including but not limited to furnace slag, agloporite, perlite, wood chippings and sawdust, crushed glass, shredded tire rubber, zeolites, small polystyrene granules (ranging from one to three millimeters), polypropylene fibers, and other similar materials [12–17]. The decomposition of tires in the natural environment is protracted due to their weather-resistant and non-biodegradable properties. The use of leftover tire rubber will continue to provide challenges in the future. Tires are the primary product of

ISSN: 2321-2810 (Online) ISSN: 2321-8525 (Print)

the rubber business. Recycling used tires requires the segregation of metal, cloth, and rubber for potential reuse as reclaimed raw materials in the production of other products [18]. For instance, structural health monitoring in such environments facilitates the early detection of material deterioration, thereby reducing potential risks and improving overall safety [19].

Venezuelan researchers examined concrete materials using non-destructive techniques. The ultrasonic pulse velocity was evaluated in concrete specimens both with and without rubber admixture. It was observed that in specimens with 5 wt% of fine aggregate substituted by 0.59 mm fraction rubber admixture, the ultrasonic pulse velocity decreased by 19%, while in specimens with 10 wt% of the same rubber admixture, the ultrasonic pulse velocity decreased by 41% relative to the control specimen. In experiments utilizing a rubber admixture of a smaller percentage, specifically 0.29 mm, the ultrasonic pulse velocity decreased by 23% and 56% in samples containing 5 wt% and 10 wt% rubber admixture, respectively [20]. Polymeric garbage, such as plastics and rubber that have been used by consumers, makes up a large part of solid waste. This is bad for the environment since these materials do not break down. Plastic waste, mostly from single-use packaging and construction materials that are thrown away, has reached more than 12 million tons [21]. Plastic waste is often employed as fine or coarse aggregate and fiber, whereas rubber waste is predominantly utilized as fine or coarse material, with occasional applications as fiber and binder. The incorporation of recycled plastic and rubber has been investigated as an effective method for enhancing the characteristics of concrete and mortar for particular applications [22, 23].

Recently, the incorporation of nano-sized fiber particles as reinforcing agents has emerged as a promising approach for overcoming the inherent limitations of natural fibers [24]. An investigation was conducted to utilize ultrasonic analysis through the ultrasonic echo method to examine sound absorption and the ultrasonic modulus of tire–rubber concrete. The findings indicate that RC is a proficient absorber of acoustic and vibrational energy [25]. The studies were carried out on combinations of reinforced concrete incorporating 5%, 7.5%, and 10% water treatment residuals in place of cement and aggregate. The results showed that the addition of WTR reduced the modulus of elasticity, compressive, tensile, and flexural strengths. Additionally, water permeability increased with increasing WTR aggregate proportions but decreased when WTR was used in place of cement [26]. The integration of chromium-tanned leather waste into cementitious and gypsum-based composites presents dual advantages: it offers a novel resolution to the environmental challenge of leather waste disposal and concurrently improves the mechanical and physical characteristics of the resultant composites [27]. Chromium ions in leather residues may function as a catalyst in the hydration of cement. Chromium compounds may affect the production of hydration products, such as calcium silicate hydrates (C–S–H), which enhance the composite’s strength. Chromium may react with calcium hydroxide to create stable complexes, potentially decreasing the free lime content and improving the durability and strength of the composite [28]. Previous studies have shown that adding industrial waste to building materials can make them stronger, better at conducting heat, last longer, and better at resisting weather [29, 30]. The integration of specific organic waste elements has demonstrated enhancement of the thermal insulating capabilities of concrete [31]. However, this research did not address environmental concerns or mechanical qualities of composites manufactured from chromium-tanned leather wastes. A recent study by Canhada et al. found that using leather dust in concrete improved compressive strength, but did not consider thermal characteristics or long-term durability [32]. García et al. investigate the sustainable use of waste wood ash (WWA) in construction, concentrating on its potential as a partial cement replacement [33]. Workability and porosity are improved by the WWA, solving mechanical strength issues at greater substitution levels [34]. The study suggests greater research to maximize WWA’s eco-efficient construction use. In their study, Çelik et al. investigate substituting fine and coarse concrete particles with broken waste glass. Research shows that waste glass increases tensile and flexural strength at appropriate levels but diminishes strength at higher proportions due to vacancies [35].

SCOPE OF STUDY

The present study investigates the utilization of recycled polymeric wastes, namely crumb rubber obtained from end-of-life vehicle tires and processed shoe leather waste generated by the footwear industry, as sustainable fillers in cementitious composite materials through the partial replacement of natural fine aggregate. The research focuses on developing environmentally responsible polymer-modified cementitious composites that contribute to circular economy principles by valorizing industrial polymer waste.

The investigation evaluates the influence of polymeric waste incorporation on the fresh and hardened properties of concrete composites, including workability, density, compressive strength, split tensile strength, and flexural strength. The study further examines the structure–property relationship between the incorporation of elastomeric rubber particles and leather-based polymeric fibers within the cement matrix and their influence on the mechanical behavior of the resulting composite.

From a polymer composites perspective, the research explores the feasibility of integrating recycled elastomeric and leather-derived polymeric materials into conventional concrete to produce sustainable construction composites with reduced environmental impact while maintaining acceptable structural performance. The study also identifies the optimum replacement level that balances mechanical performance with resource conservation and waste management objectives. The work contributes to the fields of polymer composites, recycled polymer materials, green composite technology, sustainable construction materials, and circular polymer science by demonstrating an alternative pathway for the high-value utilization of polymeric industrial waste in cement-based composite systems.

The present investigation is limited to the evaluation of fresh properties, density, and mechanical performance under laboratory conditions. Long-term durability, microstructural characterization, interfacial polymer–cement interactions, chemical resistance, thermal and fire behavior, weathering performance, and large-scale field applications are beyond the scope of the current study and are recommended for future research.

MATERIALS AND METHODS

In this experimental investigation, raw materials comprising cement, fine aggregate, coarse aggregate, water, and polymeric waste were batched in specified proportions. The resulting concrete mixtures were cast into specimens, cured under controlled conditions, and subjected to mechanical testing.

Materials

The experimental study utilized cement, sand and coarse aggregate with rubber and leather waste to prepare the concrete. The properties of these materials were also calculated.

Table 1. Physical properties of cement.

S. N.	Property	Test results	Standard
1	Specific gravity	3.11	IS 4031 (Part 11)
2	Standard consistency (%)	32	IS 4031 (Part 4)
3	Initial setting time (min)	42	IS 4031 (Part 5)
4	Final setting time (min)	460	IS 4031 (Part 5)
5	Fineness (Blaine) (m^2/kg)	312	IS 4031 (Part 2)

Cement

The investigation used 53-grade Ordinary Portland Cement (OPC) that met the standards of IS 12269:2013. It was fresh, did not have any lumps, and had been stored dry. We used Indian Standards to help us when we looked at the physical qualities. Table 1 displays the physical properties of cement.

Fine Aggregate

Fine aggregate was made from natural river sand that met the Zone II grading standards set by IS 383:2016. The physical properties of fine aggregate are shown in Table 2. The sand was pure, well-graded, and free of any organic matter, silt, or harmful substances. Standard testing methods were used to find the specific gravity and fineness modulus.

Table 2. Physical properties of fine aggregate (Zone II Sand).

S. N.	Property	Test results	Standard
1	Specific gravity	2.62	IS 2386 (Part 3)
2	Fineness modulus	2.71	IS 2386 (Part 1)
3	Water absorption (%)	1.22	IS 2386 (Part 3)
4	Bulk density (kg/m^3)	1660	IS 2386 (Part 3)
5	Grading zone	Zone II	IS 383:2016

Table 3. Physical properties of coarse aggregate (20 mm).

S. N.	Property	Test results	Standard
1	Specific gravity	2.70	IS 2386 (Part 3)
2	Aggregate impact value (%)	18.5	IS 2386 (Part 4)
3	Water absorption (%)	0.6	IS 2386 (Part 3)
4	Aggregate crushing value (%)	22.0	IS 2386 (Part 4)
5	Maximum nominal size (mm)	20 mm	IS 383:2016

Coarse Aggregate

We used crushed angular coarse materials that were no bigger than 20 mm, which is what IS 383:2016 says. The aggregates were taken from a nearby quarry and had no dust, clay, or biological materials in them. Before use, the material's specific gravity, water absorption, and aggregate impact value were all measured and are tabulated in Table 3.

Water

Potable water free of toxic salts, oils, acids, and organic matter was used to mix and cure concrete in accordance with IS 456:2000.

Rubber Waste

The crumb rubber utilized in this investigation was sourced from waste automobile tires using a mechanical shredding and grinding procedure. The rubber particles were treated to attain a size range comparable to that of natural fine aggregate, hence assuring improved gradation and homogeneous distribution within the concrete matrix. Before utilization, the crumb rubber had been cleaned to eliminate dust, steel wires, and other contaminants, and subsequently air-dried at ambient temperature. The physical parameters of crumb rubber, including particle size distribution, specific gravity, and water absorption, were assessed in line with applicable Indian Standards and compared to those of traditional fine aggregate. Crumb rubber was used as a partial substitute for fine aggregate by weight since it has a lower density and is hydrophobic. Different levels of replacement were chosen to see how it affected the fresh and hardened properties of concrete. The incorporation of crumb rubber aimed to improve sustainability by reusing waste material while preserving the concrete's ability to perform. Figure 1(a) and (b) shows the rubber and leather waste in concrete.

Leather Waste

The shoe leather scrap used in this study came from factories that make shoes in Agra, Uttar Pradesh, India, which is a major leather industry hub. The waste predominantly comprised leather trimmings and cuttings produced during the manufacture of footwear. The leather waste was cleaned to get rid of dust, glue, and other impurities on the surface before it was mixed with concrete. It was then dried in an oven until it had a regular weight. The dry leather scraps were ground up and sifted by machines to make particles about the same size as natural fine aggregate. The physical parameters of the processed leather waste, such as particle size distribution, specific gravity, and water absorption, were assessed according to applicable Indian Standards. Shoe leather waste, which is low-density and fibrous, was used as a partial substitute for fine aggregate by weight in concrete. It is to improve sustainability by using industrial waste efficiently while maintaining mechanical performance.

(a) (b)

Figure 1. (a) Rubber waste in concrete, (b) Leather waste in concrete.

Mix Designation

Table 4 shows the mix designation as the percentage replacement of fine aggregate with rubber and leather waste in concrete production.

Table 4. Concrete mix sample designation.

Sample designation	Rubber waste (%)	Leather waste (%)
C0	0	0
RW5	5	0
RW7	7	0
RW10	10	0
LW5	0	5
LW7	0	7
LW10	0	10

Methods

A mix proportion was prepared for M30 grade of concrete. The mixed concrete was then cast and tested for 7, 14, and 28 days of testing.

Mix Proportions

Concrete mixes for M30 grade were made using IS 10262:2019 specifications, with a target mean strength depending on standard deviation and exposure conditions.

Table 5. Mix proportions for M30 grade concrete.

S. N.	Material	Quantity (kg/m^3)
1	Cement (OPC 53)	380
2	Fine aggregate (Zone II)	680
3	Coarse aggregate (20 mm)	1200
4	Water	170
5	Water–cement ratio	0.45

The water–cement ratio was chosen to ensure the necessary strength and workability. The amounts of cement, fine aggregate, coarse aggregate, and water were determined per cubic meter of concrete. The mix proportion of concrete is given in Table 5.

Mixing and Casting

To maintain homogeneity, all concrete mixtures were made with a mechanical mixer. Dry components were well blended before gradually adding water. The fresh concrete was layered into

ISSN: 2321-2810 (Online) ISSN: 2321-8525 (Print)

standard steel molds and crushed with a table vibrator to remove any trapped air. After casting, the specimens were covered to minimize moisture loss and demolded 24 hours later.

Table 6. Mix proportion with control concrete, rubber waste, leather waste as fine aggregate replacement.

Mix ID	Replacement (%)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Rubber waste (kg/m^3)	Leather waste (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
C0	0	380	680	0	0	1200	170
RW5	5	380	646	34	–	1200	170
RW7	7	380	632	48	–	1200	170
RW10	10	380	612	68	–	1200	170
LW5	5	380	646	–	34	1200	170
LW7	7	380	632	–	48	1200	170
LW10	10	380	612	–	68	1200	170

The demolded specimens were then cured in clean water at room temperature until tested. Table 6 shows the mix proportion of concrete with control mix, rubber waste, leather Waste as fine aggregate replacement.

Testing for Fresh and Hardened Concrete

The slump test, as specified in IS 1199:2018, was used to examine the workability of fresh concrete. Compressive strength tests were performed on cube specimens after 7, 28, and 56 days of curing, in line with IS 516 (Part 1):2018. The specimens were evaluated on calibrated compression testing equipment, and the average strength of three specimens was calculated for each age group.

TEST RESULTS AND DISCUSSION

Fresh concrete workability was measured using the standard slump test. To assess mechanical performance, hardened specimens were subjected to compressive strength, split tensile strength, and flexural strength testing, enabling the development of a correlation between compressive and split tensile strengths. Further testing was conducted to characterize the density, water absorption, and thermal conductivity of concrete mixtures incorporating rubber and leather waste.

Slump

The workability of concrete using rubber waste and leather waste as partial substitutes for fine aggregate was assessed through the slump test. Replacement amounts of 0%, 5%, 7%, and 10% by weight of fine aggregate were evaluated. The recorded slump values are illustrated in Figure 2. The control mix had a slump of 50 mm, which means it was medium-workability and could be used for normal reinforced concrete work. At 5% replacement, the slump of concrete mixed with rubber waste increased up to 110 mm. It then dropped down to 75 mm at 7% replacement and finally to 40 mm at 10% replacement. Conversely, concrete modified leather waste exhibited a consistent rise in slump with higher replacement levels, measuring 160 mm at 5%, 180 mm at 7%, and 200 mm at 10% replacement.

The findings clearly demonstrate that rubber waste and leather waste affect the fresh properties of concrete in significantly distinct manners. A 5% replacement of rubber waste causes the initial rise in slump. This is because the rubber particles' smooth surface and lower ability to absorb water make the mix easier to move. Still, a big drop in slump was seen when replacement values were raised to 7% and 10%.

Conversely, leather waste demonstrated a significant and steady improvement in workability as the replacement % increased. The fibrous composition and relatively greater water absorption capacity of leather waste may have enhanced lubrication within the concrete matrix, leading to elevated slump values. The big increase in slump at 10% replacement means excellent workability, which is good for situations that need excellent flowability. But it can also cause problems with segregation and bleeding if it is not handled properly. The findings indicate that rubber waste is appropriate for minimal substitution levels (up to approximately 5%) when an advantage in workability is sought without compromising mix stability. Leather waste significantly enhances workability, even at elevated replacement levels, suggesting its possible application in highly workable or self-compacting mixtures, pending further assessment of strength and durability characteristics.

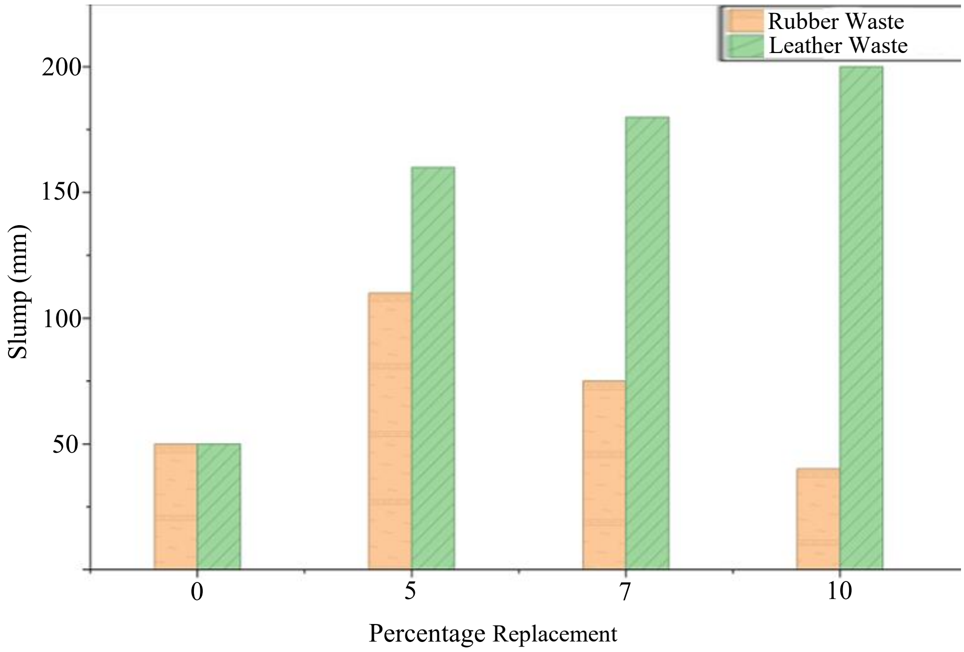

Figure 2. Slump value for rubber and leather waste concrete.

Compressive Strength

Figure 3 shows the compressive strength findings for M30 grade concrete that used rubber and leather waste as a partial replacement for fine aggregate at 0%, 5%, 7%, and 10%. Tests have been conducted on days 7, 14, and 28 of the curing process. At 7, 14, and 28 days, the control mix (C0) showed compressive strengths of 31.7 MPa, 34.8 MPa, and 41.2 MPa, respectively. This shows that the strength was becoming improved and can be used as a standard for comparison. A systematic decline in compressive strength was noted in rubber waste concrete as the replacement level increased. At 5% rubber waste (RW5), the 28-day compressive strength diminished to 35 MPa, reflecting a drop of nearly 15% relative to the control mix. The strength continued to drop when more rubber was added. After 28 days, RW7 and RW10 reached 32.5 MPa and 28 MPa, respectively. As the percentage of leather waste in the concrete increased, the compressive strength of the concrete decreased. But leather waste mixes often had better compressive strength than rubber waste mixtures at the same replacement level. At 5% leather waste (LW5), the 28-day compressive strength was 32.4 MPa, whereas LW7 and LW10 exhibited values of 31.6 MPa and 27.3 MPa, respectively. In all mixtures, compressive strength improved with curing age, suggesting that the inclusion of rubber and leather waste did not hinder cement hydration but affected the overall strength progression.

There are a few reasons why compressive strength decreases when the amount of rubber and leather waste increases. Rubber waste particles are flexible, stretchy, and water-repelling, which makes the cement paste-aggregate interfacial transition zone weaker. This weak bonding reduces concrete load-carrying capacity, especially at higher replacement levels. Leather waste, although also organic in nature, exhibited better strength performance than rubber waste at equivalent replacement percentages. Its rough surface texture and higher stiffness may improve mechanical interlocking and bonding with the cement matrix. Thus, leather waste concrete lost less strength than rubber waste concrete.

Journal of Polymer & Composites
Volume 14, Special Issue 4
ISSN: 2321-2810 (Online) ISSN: 2321-8525 (Print)

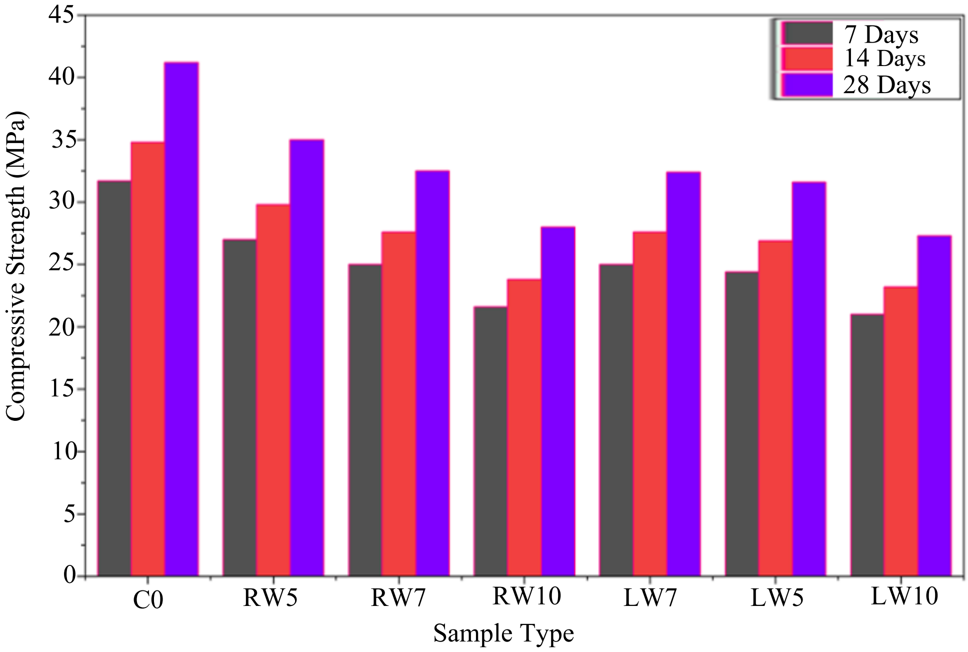

Figure 3. Compressive strength of rubber and leather waste concrete.

Split Tensile Strength

Figure 4 shows the split tensile strength findings of M30 grade concrete integrating rubber waste and leather waste at replacement levels of 0%, 5%, 7%, and 10% for curing durations of 7, 14, and 28 days. The control mix (C0) exhibited split tensile strengths of 3.38 MPa, 3.7 MPa, and 4.2 MPa at 7, 14, and 28 days, respectively, indicating typical tensile strength progression with curing duration. In rubber waste concrete, the 5% replacement level (RW5) had the maximum split tensile strength of 4.6 MPa at 28 days, surpassing the control mix.

This enhancement can be related to superior crack-bridging effects and optimized stress redistribution resulting from the elastic properties of rubber particles. However, a decline in split tensile strength was noted beyond a 5% replacement. The RW7 and RW10 mixtures exhibited 28-day strengths of 4.4 MPa and 4.0 MPa, respectively, suggesting that excessive rubber content negatively impacts tensile performance due to inadequate bonding and increasing voids.

A similar trend was observed with leather waste concrete. The LW5 mix attained a 28-day split tensile strength of 4.3 MPa, which was somewhat higher than the control mix. Increasing the replacement level to 7% and 10% resulted in a gradual decrease in tensile strength, with LW10 having the lowest value of 3.7 MPa at 28 days. In all mixtures, split tensile strength improved with curing age, indicating that the addition of rubber and leather waste did not impede cement hydration. Rubber waste mixtures had somewhat superior split tensile strength compared to leather waste mixes at equivalent replacement levels, especially at lower percentages.

The energy-absorbing and crack-arresting properties of rubber and the fibrous nature of leather waste inhibit crack start and propagation under tensile stress, improving split tensile strength at lower replacement levels (5%). These waste materials micro-reinforce the cement matrix, improving ductility and post-cracking. Weaker interfacial transition zones, paste–aggregate bonding, and porosity lower tensile strength at 7% and 10% replacement levels. Excess waste affects concrete matrix uniformity, causing premature cracking. Up to 5% fine aggregate replacement with rubber or leather waste improves split tensile strength, while larger replacement levels decrease it. These findings suggest using such wastes in sustainable concrete applications that require enhanced ductility and moderate tensile strength.

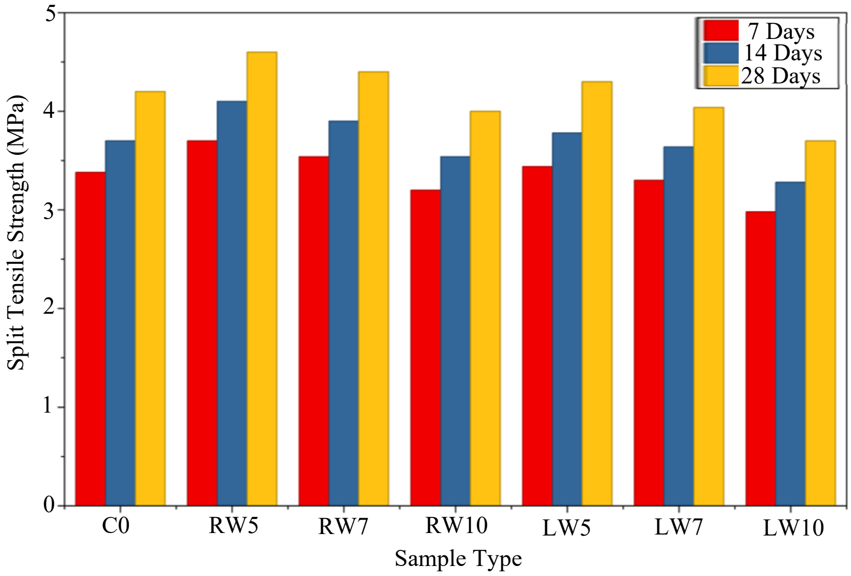

Figure 4. Split tensile strength of rubber and leather waste concrete.

Flexural Strength

Figure 5 shows the flexural strength of M30 grade concrete, incorporating partial substitution of fine aggregate with rubber waste and leather waste at 0%, 5%, 7%, and 10% levels. The tests were conducted on 7, 14, and 28 days of curing. The control mix (C0) showed flexural strengths of 4.06 MPa, 4.5 MPa, and 5.0 MPa at 7, 14, and 28 days, respectively, reflecting typical strength development with curing duration. Concrete mixtures containing rubber waste exhibited a gradual enhancement in flexural strength as the replacement % increased. At 28 days, flexural strength measurements of 5.8 MPa, 6.1 MPa, and 6.4 MPa were documented for RW5, RW7, and RW10, respectively. When compared to the control mix, this shows an improvement of about 16–28%, showing that rubber waste improves bending performance. In the same way, concrete that had leather waste mixed in showed better flexural strength at moderate substitution amounts. The bending strength of the LW7 mix was 6.2 MPa after 28 days, which was higher than the control mix. At LW10, a slight decrease in flexural strength was noted relative to LW7; however, the value continued to exceed that of the control concrete. In all mixtures, flexural strength steadily improved with curing age, indicating that the addition of rubber and leather waste did not negatively impact cement hydration or long-term strength progression.

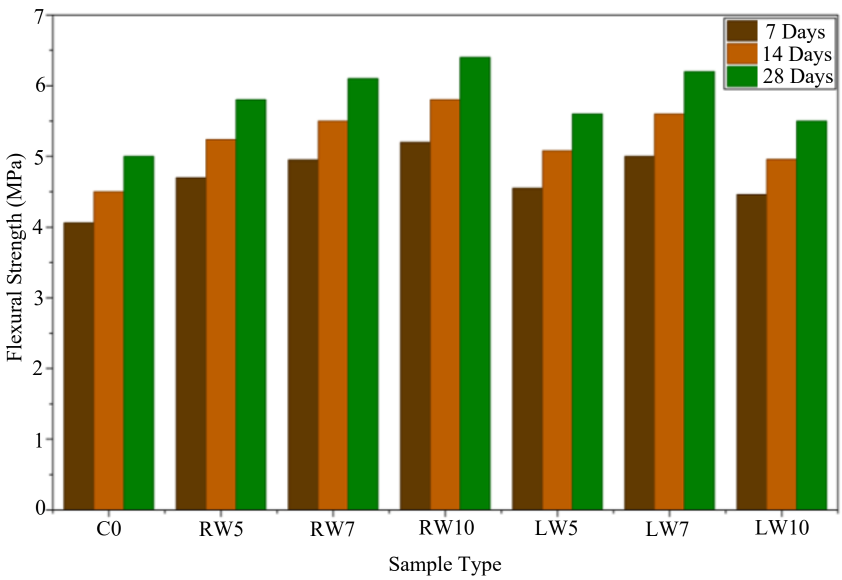

Figure 5. Flexural strength of rubber and leather waste concrete.

Crack-bridging and energy absorption properties of rubber and leather waste increase flexural strength. Due to their elasticity, rubber particles improve concrete ductility and delay fracture propagation under bending forces, increasing flexural strength.

Correlation Between Compressive Strength and Split Tensile Strength

The correlation between compressive strength (f_{ck}) and split tensile strength (f_{ct}) incorporating concrete mixes utilizing rubber and leather waste as a partial substitute for fine aggregate are shown in Figure 6. A linear regression analysis was conducted utilizing the experimental data derived from all mixed proportions and curing periods.

The derived regression equation is:

$$f_{ct} = 1.89293 + 0.06523 f_{ck}$$

Having a coefficient of determination $R^2 = 0.5899$.

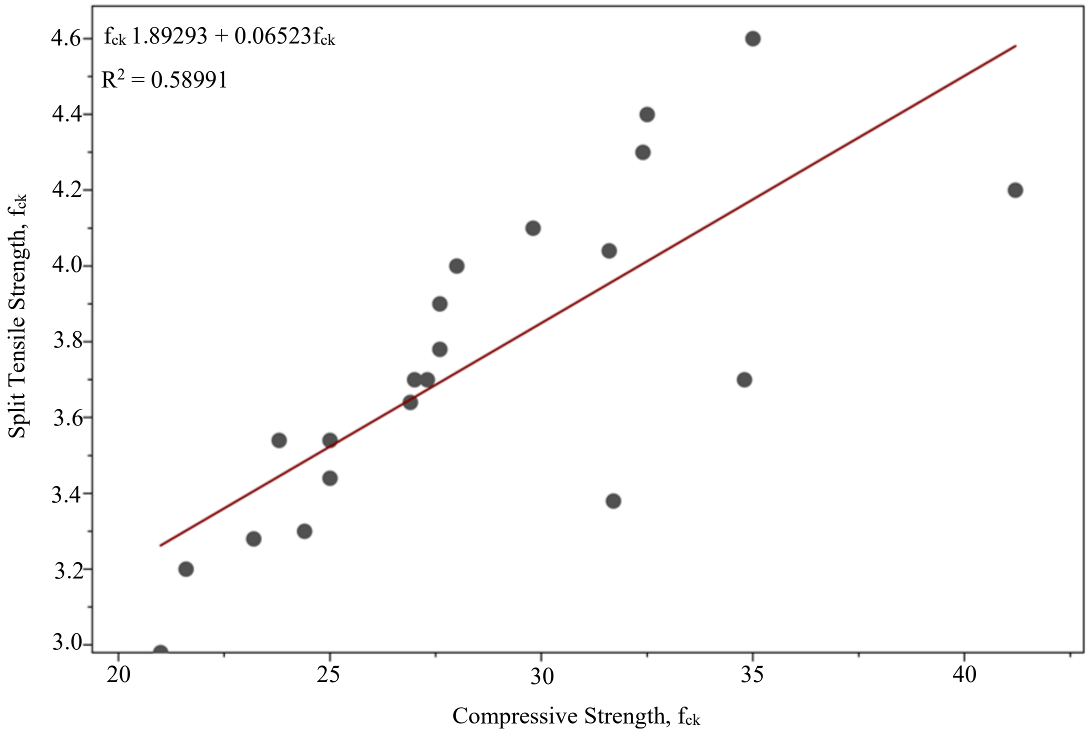

Figure 6. Linear regression between compressive and split tensile strength.

The findings revealed a slightly positive relationship between compressive strength and split tensile strength. All combinations, including control mix, rubber waste, and leather waste concretes, show an increase in split tensile strength at the same time as the increase in compressive strength. Based on this trend, it appears that the compressive strength of waste-modified concrete is a good indicator of tensile strength of concrete. The observed scatter in the data points indicates that the incorporation of rubber and leather waste affects tensile behavior beyond predictions based simply on compressive strength. This difference is caused by differences in how the waste materials connect to each together, how elastic the materials are, and how they bridge cracks. These factors have a much bigger effect on tensile strength than on compressive strength.

The R^2 result shows that while compressive strength has significant impact on the increase of tensile strength, other factors including the type of waste, the level of replacement, and the age of curing are also important. Rubber waste, owing to its elastic properties, improves post-cracking performance, while leather waste facilitates enhanced stress transmission through superior surface interlocking.

Water Absorption of Rubber and Leather Waste Mix Concrete

The water absorption of concrete utilizing rubber waste and leather waste as partial replacement for fine aggregate at 0%, 5%, 7%, and 10% levels, are illustrated in Figure 7. The control mix showed a water absorption value of 4.22%, indicating a dense and well-compacted concrete matrix. The addition of rubber waste resulted in rise in water absorption. The mix RW5, RW7, and RW10 mixtures exhibited water absorption of 5.26%, 5.72%, and 5.9%, respectively. A significant rise in water absorption was seen in concrete including leather waste. The LW5 mix showed a water absorption of 6.8%, which subsequently rose to 7.1% and 7.4% for LW7 and LW10, respectively. The data clearly illustrate that when you replace more rubber and leather waste, the water absorption increased. The leather waste mixed with concrete showed more absorption value as compared to rubber waste concrete at same replacement levels.

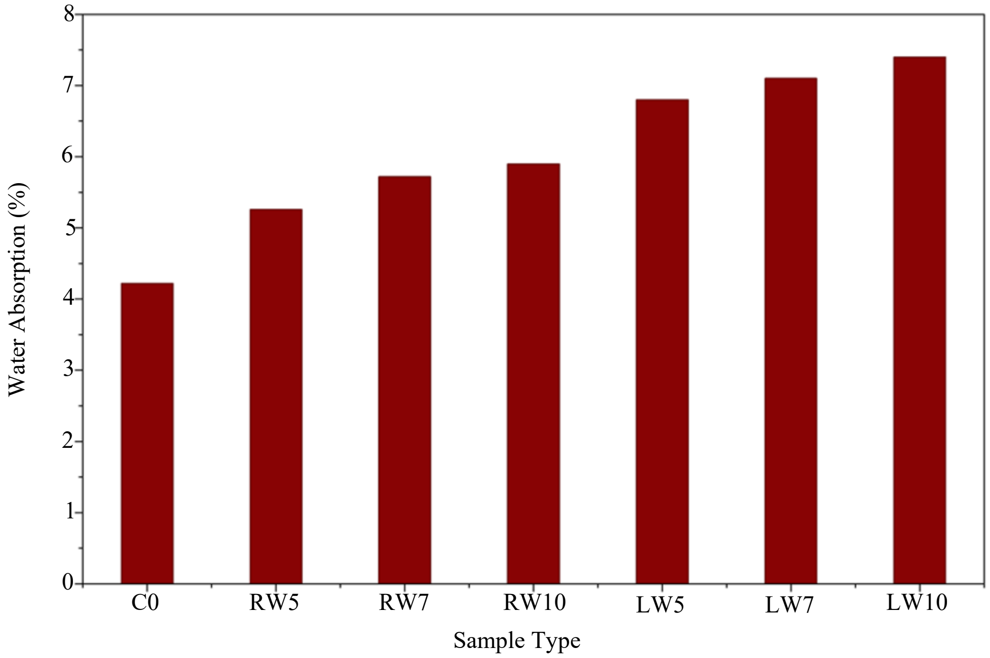

Figure 7. Water absorption of rubber and leather waste concrete.

Rubber and leather waste increase concrete matrix porosity and reduce interfacial transition zones, increasing water absorption. Rubber particles form micro-voids due to their hydrophobicity and irregular shape. This increases permeability compared to concrete. Due to its fibrous and semi-porous nature, leather waste absorbs more water and forms more concrete matrix capillaries.

Density of Rubber and Leather Waste Mixed Concrete

Figure 8 shows the density of concrete incorporating rubber waste and leather waste as partial replacement of fine aggregate at 0, 5, 7, and 10% levels. The control mix showed the maximum density 2390 kg/m³ which indicate the concrete of standard normal-weight concrete. The addition of rubber waste resulted in a gradual reduction in density. Leather waste mixed concrete exhibited a declining trend in density as the replacement level increased. Of all the mixtures, LW10 showed the lowest density. The findings clearly indicate that density decreases as the proportion of rubber and leather waste increases. Leather waste concrete showed less density as compared to rubber waste concrete at comparable replacement levels.

Rubber and leather waste have a lower specific gravity than natural fine aggregate, hence density drops as waste content increases. Leather waste, which is fibrous and porous, reduces concrete matrix density while increasing air entrapment. The reduction in density aids in the production of lightweight concrete, hence reducing structural dead loads. Rubber waste is lighter than sand yet compact, reducing density moderately.

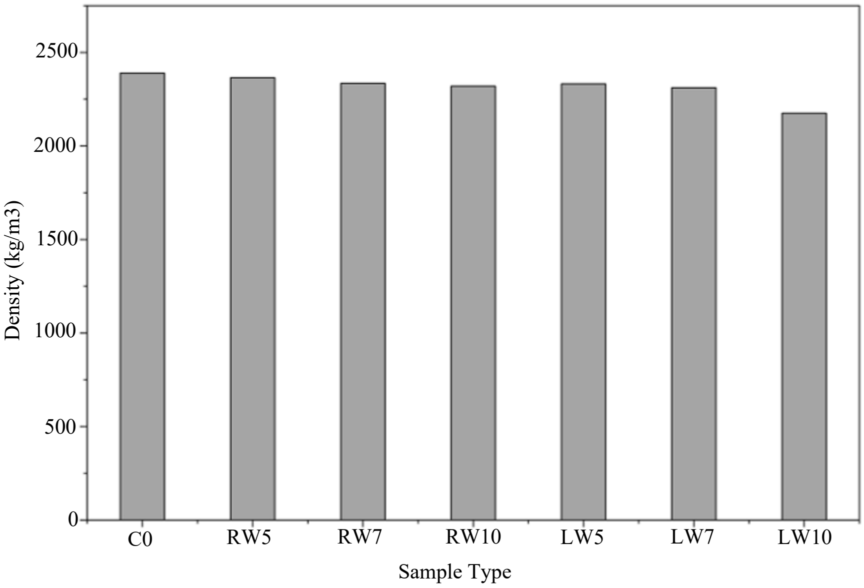

Figure 8. Density of rubber and leather waste concrete.

Thermal Conductivity of Rubber and Leather Waste Concrete

The thermal conductivity of concrete, containing rubber and leather waste as partial replacements for fine aggregate at 0%, 5%, 7%, and 10%, was assessed to evaluate the thermal insulation efficacy of the waste modified concrete as shown in Figure 9. The control mix (C0) reflects the greatest thermal conductivity, primarily to its dense microstructure and enhanced density. A steady decline in thermal conductivity was noted with the increasing of rubber waste replacement from 5 to 10%. The lowest thermal conductivity in rubber waste mixtures was observed in RW10, signifying enhanced thermal insulation properties.

A comparable yet more significant decrease in heat conductivity was noted for leather waste concrete. At comparable replacement levels, leather waste mixtures consistently demonstrated lower thermal conductivity than rubber waste mixtures, with LW10 displaying the lowest thermal conductivity of all mixtures. The findings indicate a distinct inverse correlation between waste content and thermal conductivity, which aligns with the noted decrease in density and rise in porosity of waste-modified concrete.

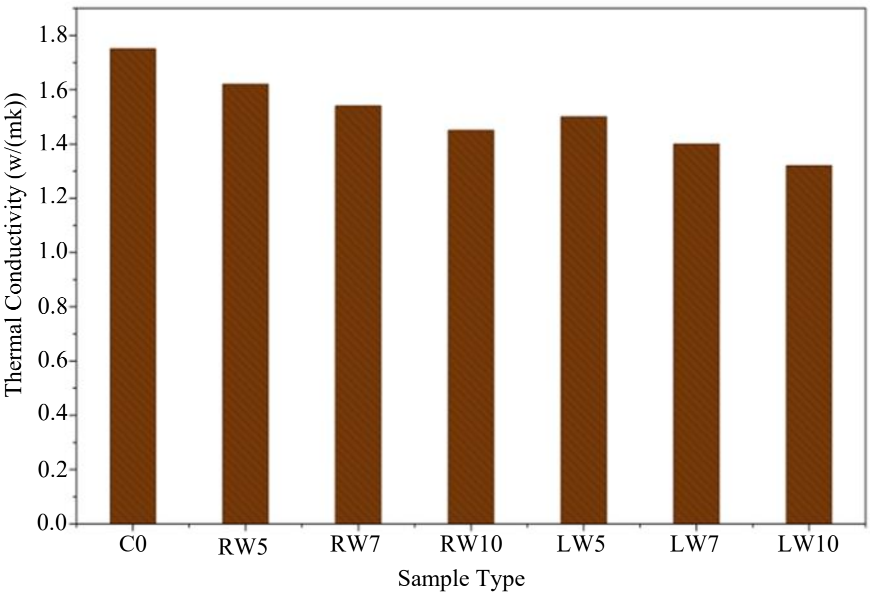

Figure 9. Thermal conductivity of rubber and leather waste concrete.

The low thermal conductivity of rubber and leather waste materials and larger air gaps in the concrete matrix reduce thermal conductivity with increasing waste content. Elastic and non-conductive rubber granules reduce concrete heat transmission by acting as thermal barriers. Leather waste, which is fibrous and porous, traps more air and creates heat transmission discontinuities, making it better insulation than rubber waste concrete. This explains leather waste mixes' reduced heat conductivity at replacement levels.

Hierarchical Cluster Analysis

Hierarchical Cluster Analysis (HCA) was conducted to examine the interrelationships among the parameters of concrete that incorporates rubber and leather waste as a partial substitute for fine aggregate.

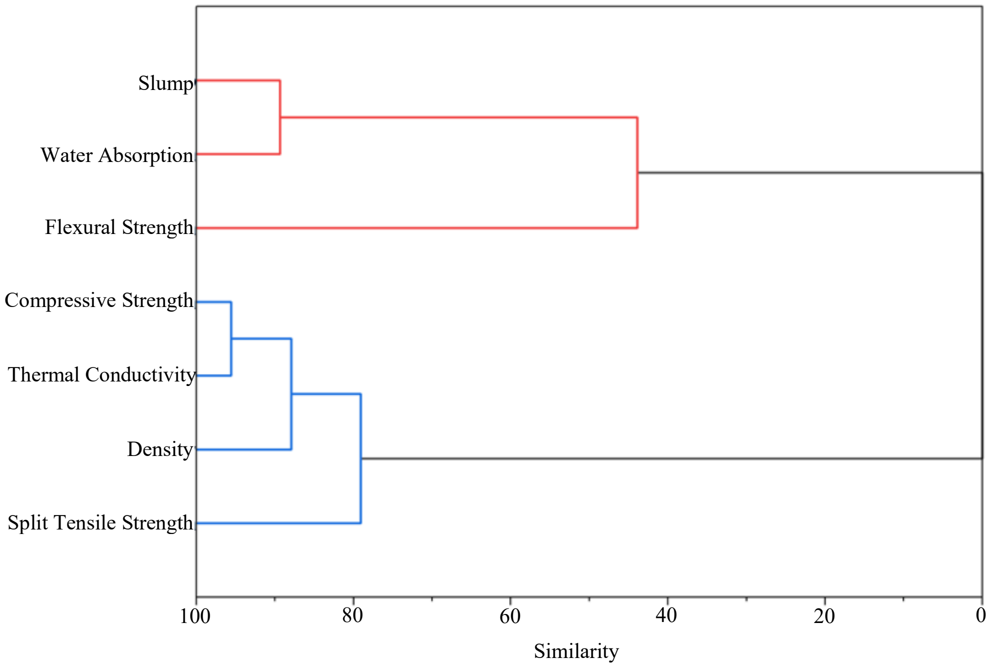

Figure 10. Dendrogram from hierarchical cluster analysis.

Table 7. Descriptive statistics.

Factors	N analysis	N missing	Mean	Standard deviation	Sum	Minimum	Median	Maximum
Slump	7	0	116.42857	64.46668	815	40	110	200
Compressive strength	7	0	32.57143	4.655	228	27.3	32.4	41.2
Split tensile strength	7	0	4.17714	0.29494	29.24	3.7	4.2	4.6
Flexural strength	7	0	5.8	0.47958	40.6	5	5.8	6.4
Water absorption	7	0	6.05714	1.12484	42.4	4.22	5.9	7.4
Density	7	0	2318.42857	68.75768	16229	2175	2332	2390
Thermal conductivity	7	0	1.51143	0.14288	10.58	1.32	1.5	1.75

The dendrogram derived from similarity-based grouping is shown in Figure 10. The descriptive analysis was also derived from the HCA which is shown in Table 7.

The analysis indicates the emergence of two primary clusters at a similarity level of roughly 40%, signifying separate behavioral groups among the evaluated attributes. The initial cluster comprises slump and water absorption, which are intricately linked and demonstrate the greatest similarity. This study demonstrates that the workability of fresh concrete is significantly affected by the pore structure and moisture absorption properties imparted by rubber and leather waste. The rise in waste content results in elevated porosity, which concurrently influences both slump and water absorption.

The second cluster includes compressive strength, split tensile strength, flexural strength, density, and thermal conductivity, which are further categorized into significant sub-clusters. In this group, compressive strength and thermal conductivity exhibit a high correlation, indicating their dependence on concrete density and matrix compactness. Density has a close connection with both parameters, confirming its pivotal role in both mechanical strength and thermal conductivity. A separate sub-cluster comprises split tensile strength and flexural strength, suggesting that tensile related parameters exhibit similar responses to the addition of rubber and leather waste. The similarity illustrates the crack-bridging and energy-absorbing properties of waste materials, which impact tensile and flexural performance more significantly than compressive strength.

CONCLUSION

- The experimental results demonstrate that recycled crumb rubber and leather-derived polymeric waste can be successfully incorporated as sustainable polymeric fillers in polymer–cement composites at replacement levels of up to 5% without significant loss of compressive strength. Beyond this level, the increased polymer content adversely affects load transfer within the cementitious matrix, resulting in a noticeable reduction in compressive strength. Among the investigated polymeric materials, leather-derived waste exhibited superior reinforcing efficiency compared with crumb rubber, highlighting its greater potential for the development of sustainable lightweight polymer-modified construction composites.
- The incorporation of recycled polymeric inclusions significantly influenced the tensile behavior of the developed composites. Moderate incorporation levels (up to 5%) enhanced split tensile strength, indicating improved stress redistribution and crack resistance within the polymer–cement composite. However, higher polymer contents resulted in reduced tensile performance because of weaker polymer–cement interfacial bonding and increased pore volume. These observations emphasize the importance of optimizing polymer loading to achieve a favorable structure–property relationship in sustainable polymer-modified cementitious composites.
- The flexural strength results demonstrate that substituting fine aggregate with rubber waste up to 10% and leather waste up to 7% markedly improves bending performance, attributed to enhanced fracture resistance and energy absorption properties of the waste materials.
- The correlation analysis suggests a slight positive correlation between compressive and split tensile strength, implying that compressive strength can accurately predict tensile behavior in concrete with rubber and leather waste incorporation.
- The water absorption data demonstrate that an increase in rubber and leather waste content resulted in higher porosity, with leather waste displaying superior water absorption compared to rubber waste concrete.
- The incorporation of recycled polymeric materials significantly influenced the durability-related behavior of the polymer–cement composites. Water absorption increased with increasing crumb rubber and leather-derived polymer content, indicating the formation of a more porous composite microstructure. Leather-based polymeric inclusions exhibited higher water absorption than elastomeric crumb rubber, reflecting differences in their intrinsic morphology and interfacial interaction with the cementitious matrix. These findings highlight the critical role of polymer type in governing the structure–property relationship and durability performance of sustainable cementitious composites.
- The experimental data of density revealed that when more fine aggregate is replaced with rubber and leather waste, the concrete becomes less dense. This is because leather waste has a lower specific gravity and more porosity, which makes it weigh less.
- The incorporation of recycled elastomeric and leather-derived polymeric fillers progressively reduced the density of the developed polymer–cement composites owing to the lower specific gravity of the polymeric materials compared with natural mineral aggregates. Leather-derived polymeric waste produced a greater reduction in composite density because of its lower density and higher internal porosity. The resulting lightweight composite characteristics, together with improved thermal insulation, demonstrate the potential of recycled polymeric materials for

developing sustainable and multifunctional construction composites suitable for applications where reduced self-weight and enhanced energy efficiency are desirable.

- The thermal conductivity results suggest that increasing rubber and leather waste content markedly reduces heat transmission in concrete. Leather waste concrete offers greater thermal insulation due to its greater porosity and lower density.
- The hierarchical cluster analysis verifies that fresh and durability-related parameters constitute a separate category from mechanical and thermal properties, underscoring divergent regulating mechanisms for rubber- and leather-waste-modified concrete.

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