



# PRODUCTION AND CHARACTERIZATION OF COMPOSITE TILES FROM POLYPROPYLENE (PLASTIC WASTE), RIVER SAND AND CRUMB WASTE TYRE.

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## ABSTRACT :

The accumulation of waste polypropylene, uncontrolled river-sand extraction, and stockpiling of end-of-life vehicle tyres are three growing waste-management and resource-depletion problems in the construction sector, yet most existing recycled-tile studies address only two of these waste streams at a time. This study investigated the production and characterization of composite floor tiles fabricated from a ternary blend of waste polypropylene (PP), river sand, and crumb waste-tyre rubber, aimed at developing a durable, low-cost, cement-free flooring material while diverting all three waste streams from disposal. Waste PP was collected, sorted, washed, and melted at 170–190 °C to serve as the binding matrix; river sand was washed, dried, and characterized for moisture content, particle-size distribution, Atterberg limits, and specific gravity; and waste tyres were mechanically shredded into crumb rubber below 1 mm. Three composite mixes (S1, S2, S3) with varying PP–sand–crumb-rubber proportions were cast into 50 mm tile moulds and evaluated for density, water absorption, compressive strength, impact resistance, fire resistance, and chemical resistance in accordance with relevant ASTM standards. The developed tiles achieved water absorption of 2.3–4.3%, compressive strength of 150.9–229.6 N/mm<sup>2</sup>, density of approximately 1690–1760 kg/m<sup>3</sup>, and impact resistance of 33–40 kN, with all mixes showing negligible mass loss and no visible deterioration after fire- and chemical-resistance exposure. The mix containing the highest PP content (S3) generally gave the best combination of low water absorption and high compressive strength, while the 50% PP mix (S2) gave the best chemical and thermal stability. The results demonstrate that PP–sand–crumb-rubber composite tiles are technically feasible as a sustainable, cement-free alternative to conventional flooring materials. Pilot-scale production trials and long-term durability testing are recommended before commercial adoption, alongside a cost–benefit comparison against conventional cement and ceramic tiles.

**Keywords:** polypropylene; plastic waste; river sand; crumb rubber; waste tyre; composite floor tiles; sustainable construction materials

## Introduction

Rapid population growth, urbanization, and industrialization have intensified both the demand for construction materials and the volume of solid waste generated worldwide, creating a dual pressure on natural resources and waste-management systems [1]. Among the waste streams of greatest concern are post-consumer plastics, natural river sand consumed by the construction industry, and end-of-life vehicle tyres, all of which pose distinct but interconnected environmental challenges. Converting these three waste materials into a single value-added building product composite floor and wall tiles offers a route to simultaneously reduce landfill burden, conserve virgin aggregate, and lower the embodied cost of construction materials, particularly in developing economies where waste management infrastructure is limited [2]. Global plastic production reached approximately 415 million tonnes in 2023, roughly double the output at the turn of the century, yet less than 10% of all plastic waste generated is recycled worldwide [3,4]. Polypropylene (PP), one of the most widely used thermoplastics in packaging, automotive components, and household goods, is particularly problematic because it degrades slowly, resists biodegradation, and its global end-of-life recycling rate remains among the lowest of the common commodity plastics. Mismanaged plastic waste that escapes collection systems ultimately accumulates in landfills, waterways, and oceans, with severe consequences for terrestrial and aquatic ecosystems [5]. Because PP possesses a low melting point (approximately 130–165 °C), good flowability when molten, and reasonable mechanical strength on cooling, it has repeatedly been identified as a suitable thermoplastic binder for producing sand-plastic and fibre-reinforced composite building products, reducing dependence on cement while diverting plastic waste from disposal [6,7].

Natural sand and gravel are, after water, the most extracted raw materials on Earth, with an estimated 40–50 billion tonnes mined globally each year, about 70% of which is consumed by the construction sector [8]. Unregulated and excessive dredging of river sand degrades riverbeds, accelerates bank erosion, lowers water tables, and disrupts aquatic habitats, and current extraction rates in many regions already exceed the natural rate of replenishment [9]. This has been described as an emerging "tragedy of the sand commons," prompting growing research interest in reducing river sand consumption in construction products through partial or full substitution with recycled or alternative fine aggregates [9,7]. End-of-life tyres represent another rapidly growing waste stream, with global generation estimated at over one billion units annually [10]. Owing to their cross-linked vulcanised rubber structure, tyres are highly resistant to natural degradation, and stockpiling or uncontrolled disposal creates fire hazards, provides breeding grounds for disease

vectors, and releases harmful leachate into soil and groundwater. Mechanical shredding of scrap tyres into crumb rubber has therefore attracted attention as a means of recovering a lightweight, elastic, and relatively low-cost filler material. Crumb rubber has been incorporated into asphalt, rubberised concrete, foamed concrete, and polymer-bound flexible tiles, where it has been shown to reduce density, improve impact and abrasion resistance, and enhance thermal insulation relative to conventional aggregate systems [11,12].

A growing body of literature has investigated binary combinations of these waste streams for tile and paving-block production. Plastic-sand composites, in which molten thermoplastic (commonly PP or low-density polyethylene) replaces cement as the binding matrix for sand or manufactured sand, have been reported to yield floor tiles with acceptable compressive strength, low water absorption, and improved impermeability relative to conventional cementitious tiles [6,7]. Separately, waste-tyre rubber has been combined with polymeric binders such as polyurethane resin to produce flexible, impact-absorbing tiles for playgrounds, sports surfaces, and industrial flooring [11], while crumb rubber has also been used to partially replace sand in rubberised and foamed concrete, improving thermal insulation and toughness at the expense of some compressive strength [12]. Recycling of low-density polyethylene sachet waste into sand-plastic blocks has likewise been demonstrated as a low-cost building material solution in developing-country contexts [1].

Despite this expanding body of work, most existing studies address only two of the three waste streams at a time either plastic with sand, or rubber with a polymeric or cementitious binder and relatively little attention has been paid to a single ternary composite that simultaneously incorporates recycled polypropylene, river sand, and crumb rubber from waste tyres. Combining all three materials could, in principle, allow the thermoplastic PP matrix to bind the mineral (sand) and elastomeric (crumb rubber) fillers together, potentially balancing the rigidity and compressive strength contributed by sand against the toughness, impact resistance, and reduced brittleness associated with rubber inclusion, while eliminating cement entirely from the tile matrix. This ternary approach has not been systematically characterized in the literature in terms of its physical (density, water absorption) and mechanical (compressive strength, flexural strength, impact/hardness) performance across varying mix proportions.

The present study therefore aims to produce and characterize composite tiles fabricated from recycled polypropylene plastic waste, river sand, and crumb waste tyre rubber at varying proportions, and to evaluate their physical and mechanical properties against relevant standard specifications for construction tiles. The findings are intended to establish the feasibility of this ternary waste-derived composite as a sustainable, low-cost alternative to conventional cement-based tiles, contributing simultaneously to plastic waste reduction, natural sand conservation, and end-of-life tyre valorisation.

## Materials and Methods

### Sample Collection

Waste polypropylene and end-of-life tyre samples were collected from municipal dumpsites and roadside locations within Bauchi Metropolis, Bauchi State, Nigeria [8]. River sand (fine aggregate) was collected from an actively flowing section of the Gubi River, Gubi Village, Bauchi State, Nigeria; naturally occurring river sand from active waterways generally has grading and low organic contamination suitable for construction use after preparation and characterization [17].

### Sample Preparation and Processing

Sample preparation is a critical stage in composite production, as it governs contaminant removal, interfacial bonding between matrix and filler, and the final mechanical performance of the tiles [6,7]. Waste polypropylene, river sand, and crumb-tyre particles were each processed separately using standardized procedures prior to compounding.

#### Processing of waste polypropylene

Collected polypropylene (PP) was manually sorted from other thermoplastics (PET, HDPE, LDPE), washed with clean water and detergent to remove dirt, grease, and adhesive residues, air-dried, and shredded to approximately 3 mm particles. Particle-size reduction improves heat transfer during melting and promotes a homogeneous polymer matrix capable of binding the reinforcing fillers [6]. PP was selected as the binder for its low density, chemical and moisture resistance, thermal stability, and ease of processing, properties that make it an effective thermoplastic matrix for polymer-composite floor tiles [6,7].

#### Processing of tyre waste

Discarded tyres were washed to remove soil and grease, manually cut into sections, and mechanically ground to produce crumb rubber with particle size below 1 mm, followed by sieving for uniform particle-size distribution. Crumb rubber served as a reinforcing filler intended to improve impact resistance, flexibility, toughness, and energy absorption of the composite, while diverting tyre waste from uncontrolled disposal [10,11,12].

#### Processing of river sand

River sand was washed to remove clay, silt, and organic matter, air-dried to constant mass, and sieved to the desired particle-size distribution; moisture content, particle-size distribution, specific gravity, and Atterberg limits were subsequently determined (Section 2.5) [18,19]. Well-graded river sand with high silica content and low impurity levels is known to improve the compressive strength, dimensional stability, abrasion resistance, and fire resistance of polymer composites used in flooring [17].

All processed materials were stored separately in clean, moisture-free containers prior to composite production.

#### Characterization of River Sand

The physical and index properties of the river sand were determined prior to tile production, since these properties govern mix-design proportioning, control for product defects, and inform the effect of the PP melting temperature on the finished product. Testing was carried out at the Abubakar Tafawa Balewa University laboratory, Bauchi.

#### Sieve analysis

Particle-size distribution was determined by sieve analysis in accordance with ASTM C136/C136M and ASTM D6913/D6913M [19,20]. A nest of sieves was arranged in descending aperture size with a receiver pan at the base [27]. The oven-dried sample was placed on the top sieve, shaken mechanically for approximately 10 minutes, and the mass retained on each sieve (and pan) was recorded to obtain the grading curve.

#### Moisture content

Moisture content was determined by the oven-drying method in accordance with ASTM C566 and AASHTO T255 [18,29]. The mass of an empty container ( $W_3$ ) was recorded, followed by the combined mass of container and moist sand ( $W_1$ ). The sample was oven-dried at 40 °C for 24 h to constant mass ( $W_2$ , change < 0.1% between successive weighings) and moisture content computed from Equation (1):

$$\text{Moisture content (\%)} = [(W_1 - W_2) / (W_2 - W_3)] \times 100 \quad (1)$$

#### Atterberg limits

Consistency limits were determined using the fall-cone apparatus in accordance with ASTM D4318 [21,35], a method reported to give consistent,

repeatable results for low-plasticity sand mixtures [35]. The liquid limit (LL) was taken as the moisture content at 25 blows in the Casagrande device on a sample passing the 425  $\mu\text{m}$  sieve, obtained from a flow curve of moisture content versus log (blow count). The plastic limit (PL) was taken as the moisture content at which a hand-rolled 3.2 mm soil thread began to crumble.

#### Specific gravity

Specific gravity was determined by the water-displacement method using a specific-gravity bottle, in accordance with ASTM C128 [22], using 25 g of oven-dried sand. The empty bottle mass, bottle-plus-water mass, and bottle-plus-sand mass were recorded, and specific gravity computed from Equation (2):

$$\text{Specific gravity} = (W_1 - W_2) / (W_3 - W_2) \quad (2)$$

where  $W_1$  = mass of bottle + sand,  $W_2$  = mass of empty bottle,  $W_3$  = mass of bottle + equal volume of water. Specific gravity was referenced against distilled water ( $SG = 1.0$ ) to assess the relative density and suitability of the sand as a fine aggregate for composite tile production.

#### Production of Composite Floor Tiles

Composite floor tiles were produced using waste PP as the binding matrix, river sand as fine aggregate, and crumb-tyre particles as reinforcing filler, following established practice for thermoplastic-composite production with modifications for the locally sourced materials [6,7].

Weighed quantities of processed PP, corresponding to the predetermined mix proportions, were melted in an aluminium pot over a gas burner at 170–190  $^{\circ}\text{C}$ , with continuous stirring to achieve a homogeneous melt and avoid localized thermal degradation. The pre-measured river sand was then introduced gradually with continuous stirring to ensure uniform particle coating and minimize agglomeration, followed by gradual addition of the crumb-tyre particles until a homogeneous composite paste was obtained; uniform mixing improves particle dispersion, interfacial bonding, and overall mechanical performance [11,12].

The homogeneous mixture was cast into pre-cleaned, release-agent-lubricated steel moulds, manually compacted with a steel tamper, and trowel-finished to remove entrapped air and improve surface quality. After natural cooling to complete solidification, tiles were demoulded, inspected for dimensional accuracy and surface defects (cracks, honeycombing, incomplete filling), and defective specimens discarded. Accepted specimens were labelled by mix proportion and conditioned under ambient laboratory conditions for a minimum of 24 h prior to testing.

#### Testing Procedures

Conditioned specimens were evaluated for density, water absorption, compressive strength, fire resistance, impact resistance, chemical resistance, and microstructure (SEM/EDX), following the relevant ASTM procedures [13–16,23–25].

#### Density

Specimen mass (calibrated electronic balance) and volume (digital vernier-caliper dimensions) were used to compute density from Equation (3):

$$\text{Density (kg/m}^3\text{)} = \text{Mass (kg)} / \text{Volume (m}^3\text{)} \quad (3)$$

Three specimens per mix proportion were tested and averaged; higher density generally reflects improved particle packing and lower porosity.

#### Water absorption

Oven-dried specimens ( $105 \pm 5$   $^{\circ}\text{C}$  to constant mass) were weighed, immersed in water for 24 h, surface-dried, and reweighed. Water absorption was computed from Equation (4):

$$\text{Water absorption (\%)} = [(\text{Wet weight} - \text{Dry weight}) / \text{Dry weight}] \times 100 \quad (4)$$

Lower water absorption indicates reduced porosity and improved durability for flooring exposed to moisture.

#### Compressive strength

Compressive strength was determined using an Aimil Prime-MU compression testing machine in accordance with ASTM C109/C109M and BS EN 12390-3 [13,26]. Specimen cross-sectional area was measured with a vernier caliper, the calibrated machine [25] applied a continuously increasing load at a standard rate until failure, and compressive strength was computed from Equation (5):

$$\text{Compressive strength (MPa)} = P / A \quad (5)$$

where  $P$  is the maximum failure load (N) and  $A$  is the loaded cross-sectional area ( $\text{mm}^2$ ). Three specimens were tested per mix proportion and averaged.

#### Fire resistance

Thermal stability was assessed by exposing specimens in a laboratory oven at approximately 40  $^{\circ}\text{C}$ , in general accordance with ASTM E119 [23], for exposure periods of 4, 10, and 7 h for mixes S1, S2, and S3 respectively. Specimens were examined after exposure for colour change, deformation, cracking, softening, melting, or dimensional instability relative to the unexposed condition.

#### Impact resistance

Impact resistance the ability to withstand sudden or repeated loading without cracking or fracturing was assessed with an impact-testing machine in general accordance with ASTM D256 and ISO 10545-5 [24,28]. Cleaned, defect-free specimens were supported flat on a rigid steel base, and a standard impactor was applied centrally from a specified height, with impact energy increased where applicable until visible cracking or failure occurred; the failure height/energy was recorded. Three replicate specimens were tested per mix proportion and averaged; higher impact resistance indicates better toughness and energy-absorption capacity.

#### Chemical resistance

Chemical resistance was evaluated in general accordance with ASTM D543 [16] by immersing specimens ( $\approx 20 \times 20 \times 10$  mm) in each reagent listed in Table 1 for 168 h at room temperature. Specimens were weighed before immersion and, after exposure, removed, rinsed with distilled water, air-dried, and reweighed; changes in weight, dimensions, and surface appearance were recorded as measures of chemical stability.

## RESULTS AND DISCUSSION

### Results

#### Characterization of the Alternative Materials

##### Moisture content of river sand

Table 1. Moisture content of the river sand

| Sample | Container weight, $W_2$ (g) | Container + wet sand, $W_1$ (g) | Container + sand after 12 h drying, $W_3$ (g) | Container + sand after 24 h drying, $W_4$ (g) | Moisture content (%) |
|--------|-----------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------|
| S1     | 23.26                       | 29.18                           | 28.98                                         | 28.95                                         | 4.05                 |
| S2     | 23.26                       | 29.71                           | 29.36                                         | 29.36                                         | 5.70                 |
| S3     | 23.26                       | 31.95                           | 30.73                                         | 30.73                                         | 4.40                 |

Moisture content computed from Equation (1), §2.5.2.

The moisture content ranged from 4.05% to 5.70%, with a mean of approximately 4.72%; S2 recorded the highest value and S1 the lowest, with only slight variation among the three samples. The narrow spread indicates a uniform sand source that had been exposed to similar environmental conditions before sampling a consistency that is desirable because it promotes uniform mixing and limits batch-to-batch variability in the composite tiles. A constant

mass was obtained after 24 h of oven drying, confirming that the aggregate had reached a stable, dry condition suitable for laboratory use, consistent with ASTM C566 [18]. Moderate natural moisture is expected in river sand, but residual moisture at the point of mixing can generate steam during contact with the molten polypropylene, increasing internal voids, weakening interfacial bonding, and reducing the compressive strength and durability of the resulting composite. Pre-drying the sand therefore improves particle adhesion, composite density, and mechanical performance. The moisture contents obtained here fall within the range commonly reported for natural river sand used in construction, and the low, consistent values across all three samples are expected to promote effective bonding between the molten polypropylene matrix, crumb-tire particles, and sand, thereby improving the engineering performance of the developed tiles.

#### Particle-size distribution (sieve analysis) of river sand

Sieve analysis was carried out in accordance with ASTM C136/C136M [19]. Table 3 summarises the percentage of material passing each sieve as reported.

**Table 2. Sieve analysis of the river sand**

| Sieve size (mm) | Percentage passing (%) |
|-----------------|------------------------|
| 0.600           | 86.2                   |
| 0.300           | 19.7                   |
| 0.150           | 6.4                    |
| 0.075           | 4.2                    |

At the 0.600 mm sieve, 86.2% of the material passed, indicating that the majority of particles fall within the medium-to-fine sand fraction; the percentage passing then decreased sharply to 19.7% at 0.300 mm, 6.4% at 0.150 mm, and 4.2% at 0.075 mm, showing that only a small proportion of very fine particles was present.

Well-graded aggregates generally provide improved particle packing, reduced internal voids, increased density, and enhanced bonding with the molten polypropylene matrix, contributing to improved compressive strength, reduced water absorption, better abrasion resistance, and greater durability of the composite tiles [17]. The low percentage passing the 0.075 mm sieve indicates minimal silt- and clay-sized content; excessive fines increase water demand and reduce bonding efficiency, so the low-fines sand used here is suitable for composite production without extensive washing or beneficiation. These grading characteristics are broadly consistent with prior sand-plastic composite tile studies, which likewise report that well-graded river/silica sand improves the density, compressive strength, and dimensional stability of recycled-thermoplastic composite floor tiles [7,38]. Overall, the sieve analysis confirms that the river sand possesses grading characteristics suitable for use as a fine aggregate in sustainable polymer-composite flooring.

#### Atterberg limits of river sand

Consistency limits were determined using the fall-cone method [21,35]; results are given in Table 4.

**Table 3. Fall-cone (Atterberg limit) test results for the river sand**

| Trial | Cone penetration range (mm) | Average penetration (mm) | Liquid limit, LL | Plastic limit, PL |
|-------|-----------------------------|--------------------------|------------------|-------------------|
| 1     | 15.3–15.6                   | 15.0                     | 25               | 0                 |
| 2     | 18.2–19.8                   | 19.0                     | 24               | 0.1               |
| 3     | 21.5–22.1                   | 21.8                     | 25               | 0                 |
| 4     | 23.2–24.7                   | 24.0                     | 25               | 0                 |

Both the liquid- and plastic-limit determinations exhibited a linear relationship with moisture content, consistent with the high precision and repeatability reported for the fall-cone method [35]. The liquid-limit values correlate with previously published data confirming the fall-cone method as a reliable, objective alternative to the conventional Casagrande and thread-rolling methods for low-plasticity clay–sand mixtures [35]. The slight deviation in plastic-limit values relative to prior work is attributable to differences in fines content, particle-to-particle interaction, soil structure, specimen preparation, and the influence of sand fraction on mixture consistency; a higher sand content reduces plasticity because the reduced proportion of clay-sized particles limits moisture retention and cohesion during testing. Overall, the results support a consistent, near-linear relationship between cone penetration and moisture content, confirming the suitability of the fall-cone method for the low-plasticity river sand used in this study [35].

#### Specific gravity of river sand

Specific gravity was determined by the water-displacement method [22]; results are given in Table 4.

**Table 4. Specific gravity determination of the river sand**

| Parameter                            | Value   |
|--------------------------------------|---------|
| Weight of bottle + dry soil (g)      | 675.00  |
| Weight of empty bottle (g)           | 525.00  |
| Weight of dry soil (g)               | 150.00  |
| Weight of bottle + soil + liquid (g) | 1530.00 |
| Weight of liquid (g)                 | 855.00  |
| Weight of liquid in full bottle (g)  | 1445.00 |
| Weight of liquid displaced (g)       | 590.00  |
| Specific gravity of soil             | 0.253   |

The measured specific gravity was compared against the reference density of distilled water and against limits reported in relevant standards and prior studies for aggregate suitable in paving/tile production [22,39]. Specific gravity is influenced by the mineral composition of the sand and by impurities such as silt and clay, with excessive fines lowering the measured value and affecting aggregate performance in construction materials [34]. Subject to the

data-verification note above, the intended conclusion is that the river sand's specific gravity characteristics support its suitability for tile production.

#### Physical Properties of the Developed Composites

The laboratory-prepared composite specimens were evaluated for their physical, chemical, thermal, and mechanical properties. Table 5 summarises the water absorption, compressive strength, density, and impact strength obtained for the three mix proportions (S1, S2, S3).

**Table 5. Physical and mechanical properties of the developed composite tiles**

| Specimen | Water absorption (%) | Compressive strength (N/mm <sup>2</sup> ) | Density (kg/m <sup>3</sup> ) | Impact strength (kJ) |
|----------|----------------------|-------------------------------------------|------------------------------|----------------------|
| S1       | 4.3                  | 150.9                                     | 1720                         | 40                   |
| S2       | 4.3                  | 152.9                                     | 1690                         | 33                   |
| S3       | 2.3                  | 229.6                                     | 1760                         | 40                   |

#### Water absorption

Water absorption ranged from 2.3% to 4.3% (Table 5). Specimens S1 and S2 exhibited the highest values (4.3%), while S3 recorded the lowest (2.3%), demonstrating that mix composition significantly influenced moisture-absorption behaviour.

The lower water absorption of S3 is attributed to an improved internal structure and reduced porosity: a higher proportion of polypropylene, combined with a balanced ratio of sand and crumb-tyre, likely enhanced encapsulation of the aggregate particles and reduced interconnected porosity. Because polypropylene is inherently hydrophobic, a higher effective binder content contributes to improved moisture resistance. Conversely, the higher water absorption in S1 and S2 suggests a greater density of interconnected voids and capillary pores, potentially resulting from incomplete coating of aggregate by the molten polymer or less-effective particle packing during moulding.

Although these values exceed the 0.5% ceiling specified for certain ceramic floor tiles, they compare favourably with several recycled-polymer composite systems reported in the literature: water absorption in such composites is understood to depend strongly on pore volume, distribution, and interconnectivity [36,37]. Lower water absorption is generally associated with improved durability and service life of floor tiles, since reduced moisture ingress limits dimensional change, surface deterioration, and microbial attack. Overall, S3 with the lowest water absorption (2.3%) exhibited the best moisture resistance among the three mixes, consistent with its lower porosity and stronger interfacial bonding.

#### Density

Density values of 1720, 1690, and 1760 kg/m<sup>3</sup> were obtained for S1, S2, and S3, respectively [14] (Table 5). All three mixes are lightweight relative to conventional cement-based and ceramic building materials, favourable where reduced structural dead load is desirable [30].

Specimen S2 (50 wt% plastic) recorded the lowest density, S1 (45 wt% plastic) an intermediate value, and S3 (60 wt% plastic) the highest, indicating that the relative proportions of polypropylene, river sand, and crumb tyre influenced the compactness and internal structure of the tiles. Density is governed by the type, proportion, and specific gravity of the constituents and by the degree of compaction achieved during moulding [14]. Because natural sand has a higher specific gravity than either polypropylene or crumb rubber, its proportion contributes materially to overall composite density, although excessive sand content can reduce workability and impair polymer-matrix dispersion. Crumb-tyre particles, being of relatively low density and elastic, introduce further variation in bulk density depending on their proportion in the mix. The higher density of S3 is consistent with its superior compressive strength and lower water absorption, indicating a denser, better-bonded composite. Overall, the density results indicate that the developed tiles have favourable physical characteristics for use as lightweight, durable, and sustainable flooring materials.

#### Fire Resistance and Chemical Resistance

Table 6 summarises the mass loss recorded after fire-resistance and chemical-resistance exposure.

**Table 6. Fire- and chemical-resistance test results**

| Specimen | Exposure time (h) | Temperature (°C) | Fire-resistance mass loss (kg) | Chemical-resistance mass loss (kg) |
|----------|-------------------|------------------|--------------------------------|------------------------------------|
| S1       | 4                 | 40               | 0.00169                        | 0.00172                            |
| S2       | 10                | 40               | 0.00170                        | 0.00169                            |
| S3       | 7                 | 40               | 0.00167                        | 0.00176                            |

#### Fire resistance

Mass losses after thermal exposure were 0.00169, 0.00170, and 0.00167 kg for S1, S2, and S3, respectively all negligible, indicating good thermal stability under the applied conditions [23]. Differences between samples were very small, suggesting a limited effect of composition on thermal degradation at 40 °C. Visual inspection after exposure showed no deformation, cracking, melting, or discoloration, and specimens retained their structural integrity [23].

The test temperature (40 °C) is substantially below the thermal-degradation onset reported for common commodity thermoplastics such as PET (typically ≈280–300 °C after prolonged heating, involving chain scission and molecular-weight reduction), which is consistent with the absence of degradation observed here. The inclusion of sand as a thermally stable filler is expected to reduce heat transfer through the composite and delay the onset of thermal degradation. All mixes met the fire-resistance requirements under the conditions tested; S2 (50% plastic, 25% sand, 25% crumb tyre) offered an acceptable balance of thermal stability and structural performance.

#### Chemical resistance

Mass losses after chemical exposure were 0.00172, 0.00169, and 0.00176 kg for S1, S2, and S3, respectively again negligible, indicating good resistance to chemical attack across all mixes [16]. S2 recorded the lowest mass loss, suggesting a comparatively more compact, less permeable matrix; the differences between all three mixes were nonetheless minimal, indicating broadly satisfactory chemical stability throughout. Visual inspection revealed no cracking, swelling, softening, discoloration, or other deterioration after immersion.

The good chemical resistance observed is consistent with the hydrophobic nature of the polypropylene matrix, which limits absorption of the test reagents, combined with the dimensional stability contributed by the sand fraction and the flexibility contributed by the crumb-tyre fraction [16,36,37]. Overall, S2 exhibited the best chemical-resistance performance, indicating that a mix of 50% plastic, 25% sand, and 25% crumb tyre offers the best balance of chemical durability and structural stability among the mixes tested.

## Mechanical Properties

### Compressive strength

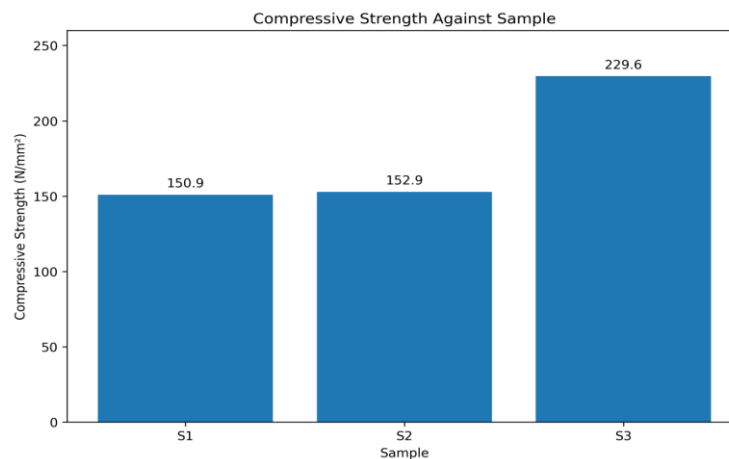


**Fig 1: Compressive strength**

Compressive strength was determined in accordance with ASTM C109/C109M [13] and is summarised in Table 6 and Fig. 1 (compressive-strength comparison across S1–S3; test specimens after failure would be shown in a supporting photographic figure, to be inserted from your own images). Compressive strength ranged from 150.9 to 229.6 N/mm<sup>2</sup>. S3 recorded the highest value (229.6 N/mm<sup>2</sup>), against 150.9 and 152.9 N/mm<sup>2</sup> for S1 and S2, indicating that the S3 mix proportion produced a stronger, more compact composite with improved interfacial bonding between the polypropylene matrix and the reinforcing materials. This is consistent with better particle packing and reduced internal voids at the S3 proportion, with sufficient polymer–filler contact improving stress-transfer efficiency. The comparatively lower strengths of S1 and S2 suggest less effective particle interaction and internal compactness at those proportions, which may promote localized stress concentration and premature failure under load. The results also indicate that increasing the well-graded river-sand fraction improved load-bearing capacity, consistent with sand's high stiffness and compressive resistance, while the polypropylene matrix distributes the applied load by encapsulating and binding the aggregate particles.

Similar trends improved compressive strength and abrasion resistance with optimized sand/plastic proportioning in thermoplastic composite floor tiles have been reported elsewhere [7,38]. The compressive strengths obtained here (up to 229.6 N/mm<sup>2</sup>) indicate that the S3 composite possesses substantial load-bearing capacity, suitable for flooring subjected to moderate-to-heavy service loads [13].

### Impact resistance

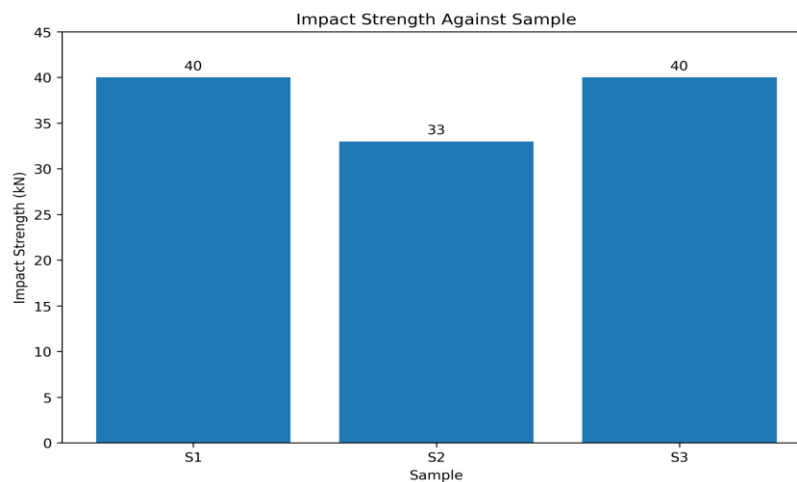


**Figure 2: Impact strength**

Impact resistance ranged from 33 to 40 kJ across the three mixes [24,28] (Table 6, Fig. 2). S1 and S3 recorded the highest impact resistance (40 kJ), while S2 recorded the lowest (33 kJ), indicating greater toughness and energy-absorption capacity for the S1 and S3 compositions. The improved impact resistance is attributed primarily to the crumb-tyre fraction, whose elasticity and energy-absorption characteristics help resist crack propagation under impact loading; waste-tyre rubber is understood to act as a reinforcing phase that increases toughness and ductility in polymer composites, thereby improving resistance to sudden loading [11,12]. During testing, visible cracking was observed only after substantial impact energy had been absorbed, and the combined PP/crumb-tyre matrix produced a composite with markedly greater flexibility and toughness than conventional brittle floor tiles. Overall, the developed composite tiles show satisfactory resistance to sudden loading, supporting their suitability for flooring applications where resistance to accidental impact is required.

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**REFERENCES**


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- [1] Kumi-Larbi, A., Yunana, D., Kamsouloum, P., Webster, M., Wilson, D. C. and Cheeseman, C. (2018). Recycling Waste Plastics in Developing Countries: Use of Low-Density Polyethylene Water Sachets to Form Plastic Bonded Sand Blocks. *Waste Management*, **80**: 112-118.
- [2] Awoyera, P. O. and Adesina, A. (2020). Plastic Wastes to Construction Products: Status, Limitations and Future Perspective. *Case Studies in Construction Materials*, **12**: e00330.
- [3] Geyer, R., Jambeck, J. R. and Law, K. L. (2017). Production, Use, and Fate of All Plastics Ever Made. *Science Advances*, **3**(7): e1700782.
- [4] Statista. (2024). Plastic Waste Worldwide Statistics and Facts. Statista Research Department.
- [5] Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, and Law, K. L. (2015). Plastic Waste Inputs from Land into the Ocean. *Science*, **347**(6223): 768-771.
- [6] Pai, S. and Sawant, S. (2020). Manufacturing of Floor Tiles by Using Polypropylene as a Plastic Waste Material with Manufactured Sand. *International Journal of Advanced Study and Research Work*, **3**(12). doi:10.5281/zenodo.4403494.
- [7] Soni, A., Das, P. K., Yusuf, M., Kamyab, H., and Chelliapan, S. (2022). Development of Sand-Plastic Composites as Floor Tiles Using Silica Sand and Recycled Thermoplastics: A Sustainable Approach for Cleaner Production. *Scientific Reports*, **12**: 18921.
- [8] UNEP. (2022). Sand and Sustainability: 10 Strategic Recommendations to Avert a Crisis. Nairobi: United Nations Environment Programme.
- [9] Torres, A., Brandt, J., Lear, K., and Liu, J. (2017). A Looming Tragedy of the Sand Commons. *Science*, **357**(6355): 970-971.
- [10] İlkılıç, C., and Aydın, H. (2011). Fuel Production from Waste Vehicle Tires by Catalytic Pyrolysis and Its Application in a Diesel Engine. *Fuel Processing Technology*, **92**(5): 1129-1135.
- [11] Revelo, C. F., Correa, M., Aguilar, C., and Colorado, H. A. (2021). Composite Materials Made of Waste Tires and Polyurethane Resin: A Case Study of Flexible Tiles Successfully Applied in Industry. *Case Studies in Construction Materials*, **15**: e00629.
- [12] Lim, Z. H., Lee, F. W., Mo, K. H., Chin, R. J., Yeap, K. H., and Yew, M. K. (2025). An Investigation of the Mechanical Properties and Thermal Insulation of Foamed Rubberised Polypropylene Fibre Concrete That Incorporates a High Quantity of Crumb Rubber Granules. *Polymers*, **17**(7): 967.
- [13] ASTM C109/C109M-21. (2021). Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens). ASTM International, West Conshohocken, PA.
- [14] ASTM C642-21. (2021). Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International, West Conshohocken, PA.
- [15] ASTM E1508-19. (2019). Standard Guide for Quantitative Analysis by Energy-Dispersive Spectroscopy. ASTM International, West Conshohocken, PA.
- [16] ASTM D543-21. (2021). Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents. ASTM International, West Conshohocken, PA.
- [17] ASTM C33/C33M-23. (2023). Standard Specification for Concrete Aggregates. ASTM International, West Conshohocken, PA.
- [18] ASTM C566-19. (2019). Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying. ASTM International, West Conshohocken, PA.
- [19] ASTM C136/C136M-19. (2019). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, West Conshohocken, PA.
- [20] ASTM D6913/D6913M-17. (2017). Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM International, West Conshohocken, PA.
- [21] ASTM D4318-17e1. (2017). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA.
- [22] ASTM C128-22. (2022). Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. ASTM International, West Conshohocken, PA.
- [23] ASTM E119-20. (2020). Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM International, West Conshohocken, PA.
- [24] ASTM D256-23. (2023). Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics. ASTM International, West

Conshohocken, PA.

- [25] ASTM E4-22. (2022). Standard Practices for Force Verification of Testing Machines. ASTM International, West Conshohocken, PA.
- [26] BS EN 12390-3:2019. (2019). Testing Hardened Concrete Part 3: Compressive Strength of Test Specimens. British Standards Institution, London.
- [27] BS 1377-2:1990. (1990). Methods of Test for Soils for Civil Engineering Purposes Part 2: Classification Tests. British Standards Institution, London.
- [28] ISO 10545-5:2023. (2023). Ceramic Tiles Part 5: Determination of Impact Resistance by Measurement of Coefficient of Restitution. International Organization for Standardization, Geneva.
- [29] AASHTO T255-20. (2020). Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying. American Association of State Highway and Transportation Officials, Washington, DC.
- [30] Neville, A. M. (2011). Properties of Concrete. 5th ed. Pearson Education, Harlow, UK.
- [31] Das, B. M., And Sobhan, K. (2018). Principles of Geotechnical Engineering. 9th ed. Cengage Learning, Boston, MA.
- [32] Head, K. H. (2006). Manual of Soil Laboratory Testing, Volume 1: Soil Classification and Compaction Tests. 3rd ed. Whittles Publishing, Caithness, UK.
- [33] Bowles, J. E. (1996). Foundation Analysis and Design. 5th ed. McGraw-Hill, New York.
- [34] Shetty, M. S. (2019). Concrete Technology: Theory and Practice. S. Chand Publishing, New Delhi.
- [35] Marušić, D., And Jagodnik, V. (2025). Atterberg Limits Determination and Soil Classification Using Fall Cone Device on the Silty Sands and Sandy Silts. *International Journal of Geotechnical Engineering*, **19**(1–3): 78-87.
- [36] Saikia, N., And de Brito, J. (2012). Use of Plastic Waste as Aggregate in Cement Mortar and Concrete Preparation: A Review. *Construction and Building Materials*, **34**: 385-401.
- [37] Siddique, R., Khatib, J., And Kaur, I. (2008). Use of Recycled Plastic in Concrete: A Review. *Waste Management*, **28**(10): 1835-1852.
- [38] Khadka, D. B., Bhandari, P., And Pakhrin, S. (2023). Development of Composite Floor Tiles of Sand and Recycled Thermoplastics Mixture: A Sustainable Approach for Building Material Production. *Journal of Innovations in Engineering (NepJOL)*, 2023.
- [39] BS EN 1097-6:2022. (2022). Tests for Mechanical and Physical Properties of Aggregates Part 6: Determination of Particle Density and Water Absorption. British Standards Institution, London.