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Mechanical and Thermal Performance of Waste Crumb Rubber Incorporated Cement Mortar

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Abstract

Waste tyre disposal and depletion of natural sand are parallel environmental challenges that can be addressed by incorporating processed tyre rubber into cementitious materials. This experimental study evaluates cement mortar in which plaster sand was partially replaced by 3 mm crumb rubber at 0, 2, 4, 6, 8 and 10%. Two cement-to-fine-aggregate proportions, 1:3 and 1:6, were investigated. Cube specimens were tested for compressive strength after 3, 7 and 28 days under ambient and reported thermally conditioned states, while disc specimens cured for 28 days were assessed using a heat-transfer-through-composite-wall apparatus at three heat-input settings. The reported observations were retained without alteration and evaluated using descriptive linear trend analysis. At 28 days, the 1:3 control mortar reached 35.10 MPa under ambient testing, while 2% rubber retained 88.6% of the control strength. The fitted ambient-strength trend for the 1:3 series decreased by approximately 2.51 MPa per percentage point of rubber ($R^2 = 0.97$). Mean thermal conductivity for the 1:6 mortar decreased from 0.0591 W/m K at 0% rubber to a minimum observed value of 0.0346 W/m K at 8% rubber, a reduction of approximately 41.5%; however, the conductivity trend showed only moderate fit ($R^2 = 0.57$). The evidence therefore indicates a clear strength-insulation trade-off but does not justify treating isolated minima as definitive optima. Low rubber contents are more suitable where strength retention is important, while higher contents may be explored for non-load-bearing insulation applications after replicate-based statistical and durability validation.

Keywords: crumb rubber; waste tyre; cement mortar; fine aggregate replacement; compressive strength; thermal conductivity; sustainable construction

1 Introduction

Rapid construction growth increases demand for natural sand, while end-of-life tyres accumulate because rubber is durable, bulky and non-biodegradable. River-sand extraction can disturb river morphology and ecosystems, whereas stockpiled or burned tyres create fire, health and pollution risks. Converting tyre waste into crumb rubber for cement mortar can reduce both impacts by conserving mineral aggregate and creating a productive route for a difficult waste stream.

Crumb rubber differs markedly from natural sand because it has lower density and stiffness, a hydrophobic surface and relatively weak adhesion to hydrated cement paste. These characteristics generally reduce compressive strength as rubber content increases. Conversely, the low thermal conductivity of rubber and the entrapped air associated with rubber particles can improve thermal insulation, while enhanced deformability may benefit toughness, energy absorption and acoustic performance [1-5]. Recent studies reinforce this mechanical-functional trade-off. Letelier et al. examined mortars incorporating crumb rubber and glass powder [6]; Pan et al. investigated fly-ash- and glass-fibre-modified rubberized mortar for thermal insulation [7]; and Rajagopal et al. showed that rubber pretreatment combined with microsilica can improve the strength and environmental performance of rubberized concrete [8]. A recent review consolidated evidence that rubber content, particle characteristics, treatment and matrix design govern the resulting structural response [9]. Most recently, recovered tyre-derived aggregates have been investigated in lightweight thermally insulating mortars, demonstrating continuing interest in functional, non-structural applications [10].

The present study examines this mechanical-thermal balance in two mortar proportions. Its objectives were to quantify compressive strength development at 3, 7 and 28 days; assess the reported effect of thermal conditioning; determine thermal conductivity after 28 days; and identify replacement levels suited to strength-sensitive and insulation-oriented applications.

2 Materials and Methods

2.1 Constituent materials

Locally available Portland pozzolana cement, potable water and plaster sand were used. Crumb rubber obtained from waste tyres had a nominal particle size of 3 mm. The measured rubber properties were a bulk density of 396.74 kg/m³, specific gravity of 0.65, water absorption of 17.25%, moisture content of 11.15% and acid-soluble fraction of 8.59%. The cement fineness was 6.5%, specific gravity was 3.15 and standard consistency was 34%. Table 2.1 shows the physical properties of crumb rubber.

Table 2.1 Physical properties of crumb rubber

Property	Measured value
Bulk density	396.74 kg/m³
Specific gravity	0.65
Water absorption	17.25%
Moisture content	11.15%
Acid-soluble fraction	8.59%

2.2 Mix proportions and specimens

Crumb rubber replaced plaster sand on the mass basis used in the project report at 0, 2, 4, 6, 8 and 10%. Two nominal mortar proportions, 1:3 and 1:6, were prepared. Dry cement, sand and rubber were blended before water addition. Cube specimens were cast for compressive-strength testing and disc specimens were cast for thermal-conductivity testing. The report records three replicate specimens per test condition. Specimens were demoulded after initial room-temperature curing and then water cured. Cubes were tested after 3, 7 and 28 days; discs were water cured for 28 days, air dried for 2-3 days and then tested. Table 2.2 shows the experimental variables used for the study.

Table 2.2 Experimental variables

Variable	Levels or condition
Mortar proportion	1:3 and 1:6
Crumb rubber replacement	0, 2, 4, 6, 8 and 10%
Rubber particle size	3 mm nominal
Strength test ages	3, 7 and 28 days
Strength condition	Ambient and thermally conditioned
Thermal test age	28 days
Heat-input settings	53, 58 and 80 (apparatus settings reported)

2.3 Test procedures and data treatment

Compressive strength was determined using a compression testing machine and reported as the mean of replicate cube results. A second set was tested after the thermal-conditioning procedure documented in the project report. Thermal conductivity was measured on mortar discs using a heat-transfer-through-composite-wall apparatus. After steady state was reached, temperatures, voltage and current were recorded, and

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conductivity was calculated from the apparatus relationship reported in the study. The three conductivity readings at each replacement level were arithmetically averaged. Percentage change was calculated relative to the corresponding 0% control. The reported observations were not altered to impose monotonicity. Ordinary least-squares linear fits were added only as descriptive aids; their R^2 values indicate how consistently the observations follow an overall direction. These fitted lines do not replace the measured points and are not used as corrected test results. Inferential statistical analysis was not possible because complete specimen-level dispersion data were unavailable.

3 Results

3.1 Compressive strength

The 1:3 mortar consistently retained more strength than the 1:6 mortar. Under ambient testing at 28 days, 2% crumb rubber retained 88.6% of the 1:3 control strength, while 4, 6, 8 and 10% retained 66.3, 58.3, 35.1 and 33.7%, respectively. The fitted line for the 1:3 ambient series had a slope of -2.51 MPa per percentage point of rubber and a strong fit ($R^2 = 0.97$), confirming a consistent overall decrease. The conditioned 1:3 series also decreased overall (slope -3.05 MPa/%; $R^2 = 0.88$), despite the high observation at 2%. By contrast, the 1:6 ambient series had a weak linear association ($R^2 = 0.25$), reflecting localized variation between 2 and 10%. This scatter should be investigated through replicate-level uncertainty analysis rather than removed by changing observations. Table 3.1 shows the average 28 day compressive strength and retention relative to control.

Table 3.1 Average 28-day compressive strength and retention relative to control

Rubber replacement	1:3 ambient MPa	Retention	1:3 conditioned MPa	1:6 ambient MPa	Retention	1:6 conditioned MPa
0%	35.10	100.0%	33.72	10.59	100.0%	16.97
2%	31.09	88.6%	39.46	4.10	38.7%	11.81
4%	23.27	66.3%	25.26	5.33	50.3%	8.78
6%	20.48	58.3%	22.31	6.80	64.2%	11.19
8%	12.33	35.1%	11.40	5.61	53.0%	5.53
10%	11.84	33.7%	8.47	5.14	48.5%	3.92

Figure 3.1 shows observed 28-day compressive strength with descriptive linear lines with R^2 values.

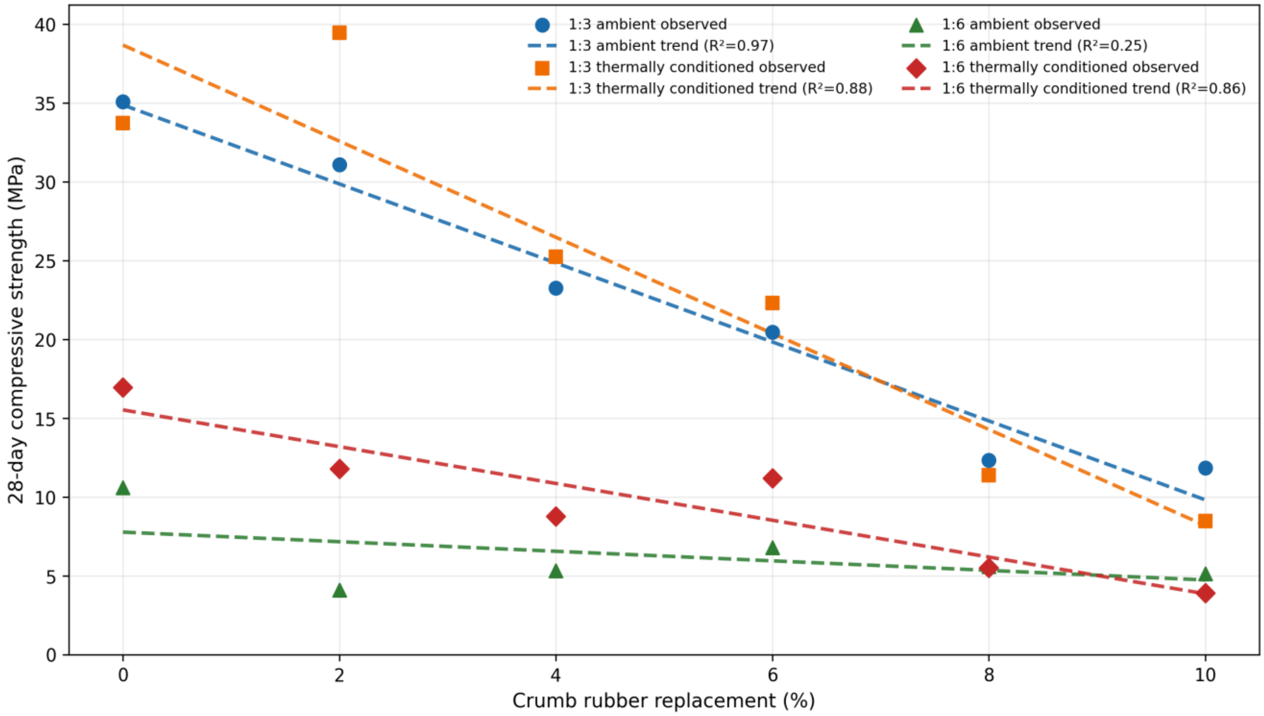

Figure 3.1 Observed 28-day compressive strengths with descriptive linear trend lines; R^2 values indicate goodness of fit

Thermal conditioning did not produce a uniform response. In the 1:3 mix, the 2% rubber specimen reached 39.46 MPa compared with 33.72 MPa for the conditioned control, but strength declined at higher replacements. In the 1:6 series, conditioned strength remained below the conditioned control at every rubber level, and its fitted decreasing trend was comparatively strong (R^2 = 0.86). Because the source report does not completely specify the conditioning temperature, exposure duration or cooling regime, the conditioned results should be treated as exploratory. The 2% observation in the 1:3 series should be checked against individual specimen records and repeated under a standardized thermal cycle before any mechanism is inferred.

3.2 Thermal conductivity

Table 3.2 shows mean thermal conductivity after 28 days.

Table 3.2 Mean thermal conductivity after 28 days

Rubber replacement	1:3 mean k W/m K	Change from control	1:6 mean k W/m K	Change from control
0%	0.0485	+0.0%	0.0591	+0.0%
2%	0.0466	-3.9%	0.0454	-23.2%
4%	0.0494	+1.9%	0.0461	-22.0%
6%	0.0523	+7.8%	0.0504	-14.7%
8%	0.0485	+0.1%	0.0346	-41.5%
10%	0.0499	+3.0%	0.0412	-30.3%

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Figure 3.2 shows observed mean thermal conductivity with descriptive linear trend lines.

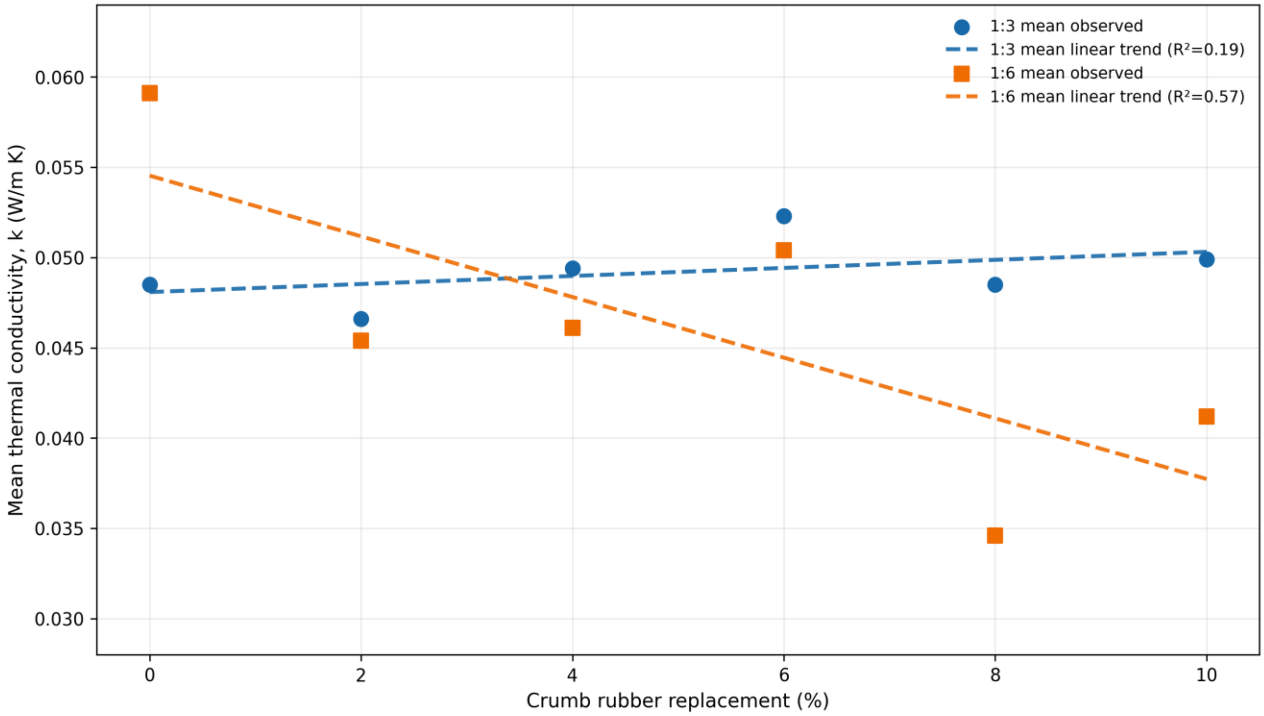

Figure 3.2 Observed mean thermal conductivity with descriptive linear trend lines

Thermal conductivity was non-monotonic with rubber content. In the 1:6 mortar, every rubber-modified mix had a lower observed mean than the control; the minimum observed mean was 0.0346 W/m K at 8%, approximately 41.5% below the control. The fitted slope was -0.00168 W/m K per percentage point of rubber, but the moderate fit (R^2 = 0.57) shows appreciable scatter. In the 1:3 mortar, the fitted slope was slightly positive (+0.000223 W/m K per percentage point) with a weak fit (R^2 = 0.19), so the present data do not establish a systematic insulation benefit for this richer mix. The variability across heat-input settings and replacement levels indicates that moisture conditioning, apparatus calibration, contact resistance, density and air content require closer control.

4 Discussion

The trend analysis confirms the principal strength penalty associated with increasing rubber content in the richer 1:3 mortar. Its high R^2 value under ambient testing supports a consistent downward relationship, while the scattered 1:6 ambient results show that a single smooth curve would overstate certainty. Strength loss is physically plausible because rubber is less stiff than mineral sand, its hydrophobic surface weakens adhesion with cement paste, and entrapped air or interfacial voids may increase. The response must nevertheless be interpreted together with binder content, grading, water demand, compaction and specimen variability.

The thermal results support further investigation of crumb-rubber mortar for insulation-oriented use, but they do not establish a unique optimum. The 8% replacement in the 1:6 series produced the lowest observed mean conductivity, whereas the moderate trend fit and rebound at 10% indicate experimental scatter or interacting effects. Rubber has low intrinsic conductivity and can interrupt heat flow, yet the measured response is also sensitive to hardened density, moisture state, pore structure, compaction and specimen-apparatus contact. An optimum should therefore be selected from replicated response surfaces with confidence intervals rather than from one isolated minimum.

For preliminary application screening, 2% replacement in 1:3 mortar offers the most defensible strength-retention option, achieving 31.09 MPa at 28 days under ambient testing. The 1:6 mortar with 8% rubber is a candidate for insulation-oriented, non-load-bearing study because it produced the lowest observed conductivity, but its low compressive strength prevents a broader recommendation. Potential applications include rendering or plaster layers, insulation backing, lightweight non-load-bearing blocks and low-load partitions. Structural use should not be inferred without code-based design checks, repeat testing and durability validation.

5 Conclusions

This study establishes that incorporating waste crumb rubber into cement mortar creates a distinct mechanical–thermal trade-off governed by rubber dosage and mortar proportion. In the richer 1:3 mortar, 2% replacement achieved a 28-day ambient compressive strength of 31.09 MPa, retaining 88.6% of the 35.10 MPa control strength while providing a modest reduction in thermal conductivity; higher replacement levels caused substantial strength deterioration. Conversely, the leaner 1:6 mortar containing 8% crumb rubber produced the lowest thermal conductivity of 0.0346 W/m·K, representing a 41.5% reduction relative to the control, although its strength was inadequate for load-bearing applications. Accordingly, 2% crumb rubber in 1:3 mortar offers the most promising strength–insulation compromise, whereas 8% in 1:6 mortar is better suited to insulation-oriented plastering, partition masonry, lightweight blocks and other non-structural components. These findings demonstrate a practical pathway for diverting waste tyres from disposal, conserving natural sand and developing resource-efficient cementitious materials with application-specific thermal performance.

6 Future Scope

Future investigations should validate these findings through at least three independently prepared batches and statistically analyse the effects of rubber content, mortar proportion and curing condition using analysis of variance and multi-objective optimization. The influence of rubber particle size, grading, moisture correction, water-to-cement ratio and mixing method should be standardized, while alkaline, silane or cementitious surface treatments and supplementary materials such as microsilica, fly ash and fibres should be examined to strengthen the rubber–paste interfacial transition zone. Comprehensive evaluation should include mortar flow, air content, hardened density, porosity, water absorption, sorptivity, bond strength, flexural strength, toughness, shrinkage, acoustic absorption and calibrated thermal conductivity. Long-term performance under wet–dry cycling, carbonation, chloride and sulphate exposure, elevated temperature and fire should also be assessed. Finally, prototype plaster panels, masonry prisms and non-load-bearing blocks should be tested alongside embodied-carbon, energy, cost and life-cycle analyses to establish technically reliable and environmentally justified replacement limits for field implementation.

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