



RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

## Thermo-Mechanical Performance of Rubberized Concrete: A Sustainable Alternative to Conventional Aggregates

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Article Info.	Abstract
<i>Article history:</i>  Received 25 August 2025  Revised 24 October 2025  Accepted 31 October 2025  Published 31 March 2026	In response to increasing environmental challenges and the global demand for sustainable construction materials, this study explores the potential of rubberized concrete incorporating crumb rubber as a partial replacement for fine aggregate. The primary objective is to evaluate the influence of rubber content (0% to 50%) on the thermo-mechanical properties of concrete, including compressive strength, split tensile strength, flexural strength (modulus of rupture), elastic modulus, and thermal properties such as conductivity, expansion, heat resistance, and heat capacity. A total of 128 concrete specimens were prepared using a fixed mix ratio (1:1.05:2.46) with a water-to-cement ratio of 0.47. Experimental tests are conducted to determine slump, density, mechanical strengths, and thermal characteristics. The results reveal that increasing crumb rubber content can significantly reduce compressive strength (from 42.61 MPa to 15.69 MPa), split tensile strength (from 1.81 MPa to 1.09 MPa), and flexural strength (from 4.53 MPa to 2.70 MPa), while enhancing workability and thermal insulation. Thermal conductivity decreases from 0.947 W/m·K to 0.614 W/m·K, indicating better insulation capacity. Although elastic modulus and thermal expansion are not directly tested, reduced density and improved thermal behavior suggest favorable performance under high-temperature conditions. The novelty of this work lies in its systematic investigation of high-volume crumb rubber replacement and the integration of both mechanical and thermal analyses, addressing a gap in existing research. These findings demonstrate the suitability of rubberized concrete for non-structural or thermally demanding applications such as fire-resistant walls and insulating elements, while also promoting solid waste recycling and sustainable building practices.

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### 1. Introduction

The continuous growth of industrialization and urban development has contributed to serious global environmental challenges such as excessive natural resource consumption, waste accumulation, and high carbon emissions. The cement and concrete industries alone are responsible for nearly 8% of global CO<sub>2</sub> emissions, making sustainable alternatives urgently necessary [1, 2]. Among the various eco-friendly approaches, the reuse of waste tire rubber in concrete has attracted substantial research attention due to its dual environmental and economic benefits [3–5]. Crumb rubber (CR), derived from shredded end-of-life tires, can partially replace natural aggregates in concrete production, thereby mitigating landfill pressure and reducing dependence on nonrenewable materials [6–8]. Incorporating rubber aggregates into concrete produces a composite known as rubberized concrete (RC), which offers enhanced ductility, toughness, energy absorption, and impact resistance [9–11]. These characteristics make RC suitable for applications in flexible pavements, vibration-damping elements, seismic-resistant structures, and sound insulation components [12, 13]. Despite its advantages, the inclusion of rubber particles often results in decreased compressive and tensile strength due to the hydrophobic nature of rubber and its weak bonding with the cementitious matrix [14, 15]. Various surface treatment methods and hybrid reinforcement approaches have been investigated to overcome these drawbacks, including pre-treating rubber with sodium hydroxide, silica fume coating, or partial replacement of cement with pozzolanic materials [16–18]. These strategies have shown promising results in enhancing interfacial adhesion and restoring part of the lost strength. Recent studies have expanded the scope of rubberized concrete research beyond mechanical performance to include thermal and thermo-mechanical properties [19, 20]. This shift is driven by the increasing demand for energy-efficient and fire-resistant building materials. The lower density and thermal conductivity of rubberized concrete make it an attractive choice for structures exposed to high thermal gradients or requiring superior insulation [21–23]. However, most investigations focused on low to moderate rubber replacement levels (10–30%), leaving the effects of high replacement ratios (≥40%) on both mechanical and thermal performance largely unexplored [24, 25].

Comparable studies with alternative waste materials, such as plastic aggregates, have reported successful replacement up to 50%, providing a basis for high-rubber content applications [26]. To address this research gap, the present study introduces a novel and comprehensive investigation into the mechanical, thermal, and sustainability performance of high-rubber-content concrete, exploring replacement levels up to 50%. Unlike previous research that isolated mechanical or thermal evaluations, this study provides an integrated assessment of strength, ductility, thermal conductivity, and insulation capacity. By combining experimental data with sustainability perspectives, the research

Nomenclature & Symbols			
RC	Rubberized Concrete	ft	Splitting Tensile Strength (MPa)
CEM I 42.5R	Portland-Limestone Cement (Karasta cement classification)	W/m·K	Watt per Meter-Kelvin (Unit of Thermal Conductivity)
W/C	Water-to-Cement Ratio	E	Elastic Modulus (GPa)
LOI	Loss on Ignition (%)	$\lambda$ (Lambda)	Thermal Conductivity (W/m·K)
INS	Insoluble Material (%)	$\Delta L / L$	Linear Thermal Expansion or Strain
$f_c$	Compressive Strength (MPa)	t	Temperature (°C)
LSF	Lime Saturation Factor	p	Applied Load in Flexural Strength Test (N)
$\rho$ (Density)	Concrete Density (kg/m <sup>3</sup> )	l	Span Length in Flexural Test (mm)
S (Slump)	Workability Measured in the Slump Test (cm)	b	Width of Specimen (mm)
kg/m <sup>3</sup>	Kilogram per Cubic Meter (unit of density)	d	Depth/Height of Specimen (mm)
C <sub>3</sub> S, C <sub>2</sub> S, C <sub>3</sub> A, C <sub>4</sub> AF	Main Clinker Phases in Cement (Tricalcium Silicate, Dicalcium Silicate, Tricalcium Aluminate, Tetracalcium Aluminoferrite)	CR	Crumb Rubber (Recycled Rubber Particles Used as Fine Aggregate Replacement)
fr	Modulus of Rupture / Flexural Strength (MPa)	MPa	Megapascal (Unit of Stress/Strength)

establishes new insights into balancing performance and environmental responsibility in high-rubber concrete design. The outcomes aim to provide a foundation for developing next-generation, energy-efficient, and sustainable concrete materials.

## 2. Methodology

The research methodology includes the properties of the materials used in the study, the mixing techniques, the type and size of the samples, and the tests performed on the developed mixtures in both their fresh and hardened states. Additionally, the dimensions, test setup, load application, and measurements of the rubberized concrete elements are given, along with information on their flexural and mechanical behavior.

### 2.1. Materials

The following is a brief description of the materials used in fabricating the specimen.

#### 2.1.1. Cement

This study utilized Karasta cement, produced in northern Iraq, classified as Portland-limestone blended cement (CEM 11/A-L) in accordance with BS EN 197-1:2011. The cement, marketed as CEM I 42.5R, was tested in the Civil Engineering Department laboratories at the University of Garmian. Its chemical and physical properties were assessed to ensure suitability for concrete production. While several parameters satisfied the standard requirements, some chemical components exceeded the typical ranges for CEM 11/A-L. Specifically, the C<sub>3</sub>A content (5.44%), Loss on Ignition (8%), and Insoluble Material (4.3%) are slightly above standard limits (C<sub>3</sub>A ≤ 5%, LOI ≤ 5%, Insoluble Material ≤ 3.5%), and the CaO content (63.45%) is slightly higher than the typical range (60 ± 2%). These variations may influence early hydration, strength development, and durability, particularly under demanding environmental or thermal conditions. However, the cement is still appropriate for general construction applications, and its effects on concrete performance are carefully considered in this study. Physical characteristics, including setting times and soundness, meet BS EN 197-1 specifications, confirming that Karasta cement is suitable for the production of high-percentage rubberized concrete (CRC). The primary oxide compounds and possible clinker phases (C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A, C<sub>4</sub>AF) were calculated using Bogue equations, providing insight into the cement’s hydration potential and long-term performance. The results are presented in Tables 1 and 2.

Table 1. Chemical analysis of Karasta cement (CEM 11/A-L)

Test	Result (%)	BS EN 197-1 Standard	Compliance
Loss on Ignition (LOI)	8.0	≤ 5	NOT PASSED
Insoluble Material (INS)	4.3	≤ 3.5	NOT PASSED
Al <sub>2</sub> O <sub>3</sub>	3.93	—	—
SiO <sub>2</sub>	23.53	—	—
SO <sub>3</sub>	2.23	≤ 3.5	PASSED
CaO	63.45	60 ± 2	Slightly High
Fe <sub>2</sub> O <sub>3</sub>	2.94	—	—
MgO	2.14	≤ 5	PASSED
Calculated Compounds (Bogue)			
C <sub>3</sub> S	42.49	—	—
C <sub>2</sub> S	35.64	—	—
C <sub>3</sub> A	5.44	≤ 5	Slightly High
C <sub>4</sub> AF	8.96	—	—
L.S.F (Lime Saturation Factor)	0.85	0.66–1.02	PASSED

Table 2. Physical analysis of Karasta cement

Property	Test Result	BS EN 197-1 Standard	Compliance	Test Method
Initial Setting Time (min)	135	≥ 45	PASSED	ASTM C191 (Vicat)
Final Setting Time (min)	235	≤ 600	PASSED	ASTM C191 (Vicat)
Soundness – Le Chatelier Expansion (mm)	4	≤ 10	PASSED	ASTM C151

2.1.2. Fine aggregate

Kalar quarry's air-dried sand, which was readily available locally, was utilized. ASTM C33 was used to grade the sand, and Table 3 displays the limits.

Table 3. Fine aggregate graded

Sieve size mm	% passing	ASTM limits	
		Lower	Upper
9.52	100	100	100
4.75	96	95	100
2.36	87	80	100
1.18	73	50	85
0.6	26.8	25	60
0.3	16.5	10	30
0.15	5.3	2	10

2.1.3. Coarse Aggregate (Gravel)

Air-dried coarse aggregate that was readily available locally from Kalar Quarry was utilized. ASTM C33 was used to grade the coarse aggregate, and Table 4 displays the limits. Although the 2.7% passing through the 4.75 mm sieve falls within the ASTM C33 limits (0–15%), the relatively low percentage suggests a limited presence of fine material, which may slightly affect workability and should be considered in the mix design.

Table 4. Coarse aggregate graded

Sieve size mm	% passing	ASTM limits	
		Lower	Upper
19	100	100	100
12.5	94.3	90	100
9.52	62.1	40	70
4.76	2.7	0	15
2.36	0	0	5

2.1.4. Crumb rubber

Crumb rubber, also referred to as recycled rubber, ranges in size from 0.150 mm to 4.75 mm and has a density of 498 kg/m<sup>3</sup>, as indicated in Fig. 1 and Table 5. It has a variety of applications in construction and material engineering.



Fig. 1. Crumb rubber

Table 5. Sieve analysis of crumb rubber

Sieve size mm	% passing	ASTM Standard Limits	
		Lower	Upper
9.52	100	100	100
4.75	97	95	100
2.36	81	80	100
1.18	53	50	85
0.6	31	25	60
0.3	20.4	10	30
0.15	8.4	2	10

2.2. Mixing details

To achieve the necessary concrete compressive strength, over a dozen trial mixes were made; two concrete mix proportions were chosen, one for regular concrete and one for high-strength concrete. Table 6 display the chosen mix as well as their mix and proportions. Mixtures for Concrete Each of the 128 mixtures that were made included seven cubes measuring 100 x 100 x 100 mm, two large cylinders measuring 100 mm and 200 mm, and two prisms measuring 100 x 100 x 450 mm. While seven mixtures of rubberized concrete were prepared with the addition of crumb rubber at 5%, 10%, 15%, 20%, 30%, 40%, and 50% of fine aggregate replacement, the first controlled specimens were prepared

without any crumb rubber inclusion. All mix proportions are presented by weight, and Table 6 provides a comprehensive summary of the materials used in each mix. Although graphs are included later to analyze the effect of rubber replacement on individual properties, Table 5 serves as a quick reference for all mixture compositions used in the experimental program.

Table 6. Selected concrete mixes and their proportions

Mix	Replacement	Water(kg)	Cement(kg)	Coarse aggregate (kg)	Sand(kg)	C.R(kg)
1	0%	209.28	445.28	1096.98	468.00	0.00
2	5%	209.28	445.28	1096.98	444.53	9.51
3	10%	209.28	445.28	1096.98	421.13	19.02
4	15%	209.28	445.28	1096.98	397.74	28.49
5	20%	209.28	445.28	1096.98	374.34	38.11
6	30%	209.28	445.28	1096.98	327.55	56.98
7	40%	209.28	445.28	1096.98	280.75	76.04
8	50%	209.28	445.28	1096.98	233.96	94.91

2.3. Tests

2.3.1. Compressive strength

Compressive strength was evaluated using cube specimens. As shown in Fig. 2, a total of 32 samples were tested for all mixes, with each test conducted on 100 × 100 × 100 mm cubes. The average value of the tested cubes was taken as the representative strength for each curing age. According to ASTM C109/C109M-16 and BS 1881-116 standards, compressive strength was measured at 14 and 28 days of curing [27].



Fig. 2. Compressive strength machine

2.3.2. Splitting tensile strength

For this test, 16 samples were used for each mix, and Normal Strength Concrete was tested for tensile strength using cylinders that were 200 mm high and 100 mm in diameter. Every age group uses cylinders, and the reading for that age group is calculated as the average of these cylinders. According to ASTM C496-2011 [28], tensile strength is measured at age 28 days, as illustrated in Fig. 3.



Fig. 3. Splitting tensile strength machine

2.3.3. Modulus of rupture

Tests were performed for the sixteen concrete with prisms 100x100x450 mm, and loaded in one point, the point load was located in 155mm according to ASTM C78 which equation is  $R = \frac{3PL}{2b \cdot d^2}$ , p= applied load, L= span length (mm) equal to 155 mm, b=width which equal to 100 mm and d= high of sample which equal to 100mm, as depicted in Fig. 4 [29].

2.3.4. Thermal Conductivity

Thermal conductivity tests were performed on eight concrete mixes using ASTM E1953 or a modified steady-state method suitable for low-conductivity materials [30]. The specimens used were disk-shaped or slab-shaped samples with flat, smooth surfaces to ensure proper contact with the measurement device (Fig. 5). The purpose of the test was to determine the impact of substituting crumb rubber for fine aggregate (sand) at replacement levels of 0%, 5%, 10%, 15%, 20%, 30%, 40%, and 50%. The thermal conductivity ( $\lambda$ ) in units of W/m K was measured at room temperature and in dry conditions using a guarded hot plate or thermal needle probe device. Rubber's high air content and low thermal conductivity had a major effect on the concrete matrix's heat transfer properties. The concrete's thermal conductivity steadily dropped as the quantity of rubber in it increased. For instance, the thermal conductivity dropped from 0.947 W/m K at 0% replacement to 0.614 W/m K at 50% replacement. The low thermal conductivity (~0.2 W/m K) of rubber particles and the extra voids added to the matrix, which obstruct heat flow pathways, are the causes of this decrease. The findings demonstrated that, in comparison to regular concrete, rubberized concrete offers better thermal insulation qualities.



Fig. 4. Modulus of rupture machine



Fig. 5. Thermal Conductivity samples

3. Results and Discussion

The experimental results displayed in Table 7 are discussed and contrasted in this section. Valid ranges for the different variables used in this study were first examined. Based on the outcomes of the experimental tests, the ideal ranges for the water-to-cement (WC) ratio, rubber content, and sand content were determined. Next, a range of rubber treatment techniques was investigated. The specimen arrays were then constructed in order to assess the rubberized concrete's mechanical and physical characteristics.

Table 7. Thermal Conductivity, Mechanical and Fresh Properties of Rubberized Concrete

Mix	Replacement	Density (Kg/m <sup>3</sup> )	Slump (cm)	Compressive (MP) 28 days	Compressive (MP) 14 days	Split tensile Strength (MPa)	Modulus of Rupture (MP)	Thermal Conductivity (W/m K)
1	0%	2361.00	19.8	42.61	30.26	1.81	4.53	0.947
2	5%	2332.33	19.6	35.08	25.04	1.69	4.39	0.890
3	10%	2302.00	19.4	33.34	23.13	1.55	4.01	0.855
4	15%	2283.67	19.2	30.00	20.82	1.52	3.79	0.825
5	20%	2231.33	19	26.43	18.30	1.44	3.50	0.770
6	30%	2093.67	18.5	26.01	18.06	1.41	3.35	0.716
7	40%	2076.21	17.5	20.59	12.83	1.19	2.79	0.653
8	50%	2062.33	16.5	15.69	13.02	1.09	2.70	0.614

3.1. Compressive strength

The compressive strength is a crucial factor since it establishes a concrete structure's capacity to bear axial loads. From Mix 1 (42.61 MPa) to Mix 8, the data clearly show a downward trend in compressive strength (15.69 MPa), indicating that performance was significantly impacted by changes in mix composition or proportions. Variations in the water-to-cement ratio, aggregate content, curing conditions, or additive inclusion may be the cause of this. While Mixes 7 and 8 are below the usual thresholds for structural-grade concrete, suggesting that they may not be sufficient for load-bearing applications, mix 1 is notably the strongest and could be used as a guide for the best mix design (Fig. 6).

3.2. Split tensile strength

The second set of the results of all 8 samples was as follows in 28 days, as shown in Table 7. From 1.81 MPa for Mix 1 to 1.09 MPa for Mix 8, the split tensile strength values for the eight concrete mixes exhibit a distinct declining trend. This decrease illustrates how modifications to the

mix design have a detrimental effect on the concrete's tensile strength. Maintaining a sufficient split tensile strength is essential for avoiding cracking and guaranteeing durability under tensile stresses because concrete inherently has a lower tensile strength than compressive strength. Whereas Mix 8's much lower value indicates it might need extra reinforcement or adjustments to meet performance standards, mix 1, which has the highest tensile strength, is the most dependable for structural applications. This pattern emphasizes a balanced mix of proportions to maximize the tensile performance of concrete structures, shown in Fig. 7.

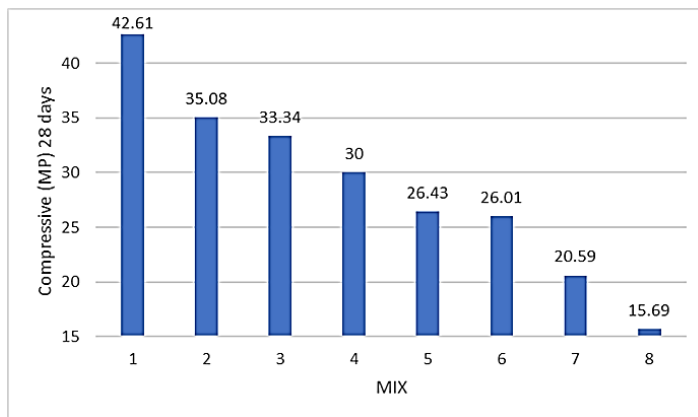


Fig. 6. Compressive strength of mixtures at 28 days

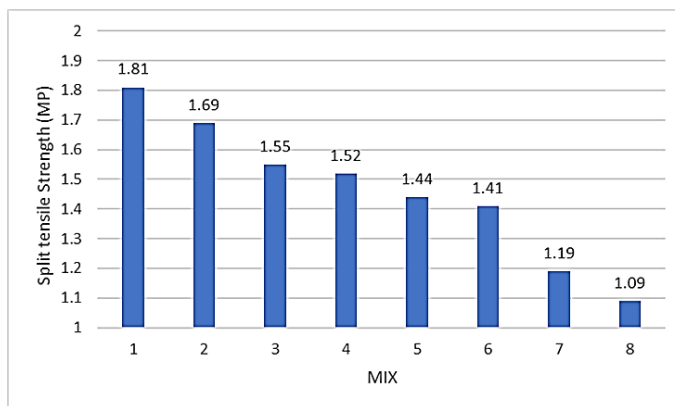


Fig. 7. Split tensile strength mixtures at 28 days

### 3.3. Modulus of rupture

Table 7 displays the results of the Modulus of Rupture (MOR) test, which demonstrates a distinct and steady decline in flexural strength over the course of 28 days for each of the eight concrete mixes. With the highest MOR value of 4.53 MPa, Mix 1 demonstrated strong structural performance and superior resistance to bending stresses. Mix 8, on the other hand, had the lowest MOR (2.70 MPa), indicating a considerable decrease in flexural capacity. This gradual drop in MOR values from Mix 1 to Mix 8 demonstrates how the concrete's resistance to flexural loads is affected by methodical mix design modifications, such as adjustments to the cement content, water /cement ratio, or aggregate quality. The durability and safety of structural concrete elements depend on proper flexural strength, which can only be achieved by optimizing mix proportions. These results highlight the significance of this, as shown in Fig. 8.

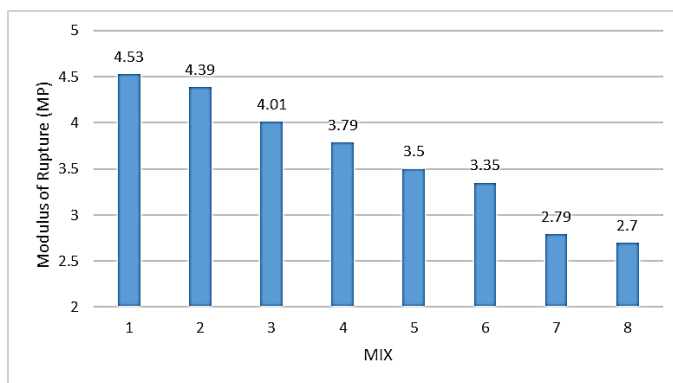


Fig. 8. Modulus of rupture of concrete mixtures

### 3.4. Slump test

The eight concrete mixes' slump test results demonstrate a noticeable and progressive decline in workability from Mix 1 to Mix 8. Mix 8 had the lowest slump value at 16.5 cm, indicating a stiffer mix with less flowability, while Mix 1 had the highest slump value at 19.8 cm, indicating a more workable and fluid concrete mix. This gradual decline in slump values suggests that the concrete is becoming less workable due to changes in the mix composition, such as a lower water-to-cement ratio, an increase in aggregate proportion, or a decrease in water content. Concrete placement, compaction, and finishing all depend on maintaining sufficient workability, and the trend indicates that lower-numbered mixes would be easier to handle and place on-site compared to the higher-numbered ones, as shown in Fig. 9.

### 3.5. Density

Table 7 displays the outcomes of all eight samples. The densities of the eight concrete mixes show a progressive decrease from Mix 1 to Mix 8, ranging from 2361 kg/m<sup>3</sup> for Mix 1 to 2062.33 kg/m<sup>3</sup> for Mix 8. This downward trend indicates that the mixes are becoming lighter over time, which could be due to the addition of lightweight materials, changes in aggregate type, or gradation changes. Lower-density concrete can be useful for reducing the overall weight of structures, even though it usually results in decreased strength and durability. Therefore, understanding and controlling density is essential to achieving the optimal balance between structural performance and weight, depending on the specific requirements of the application as shown in Figs. 10 and 11.

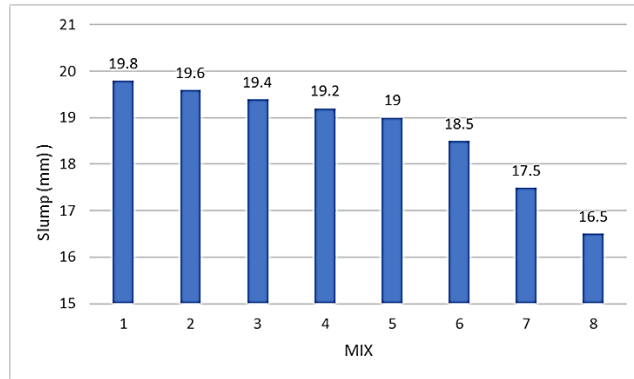


Fig. 9. Slump test of concrete mixtures

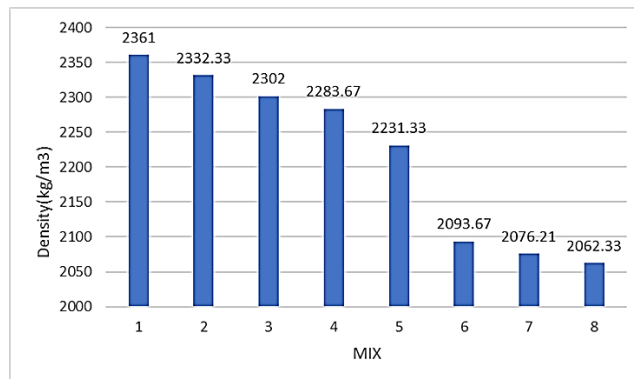


Fig. 10. Density of concrete mixtures at 28 days

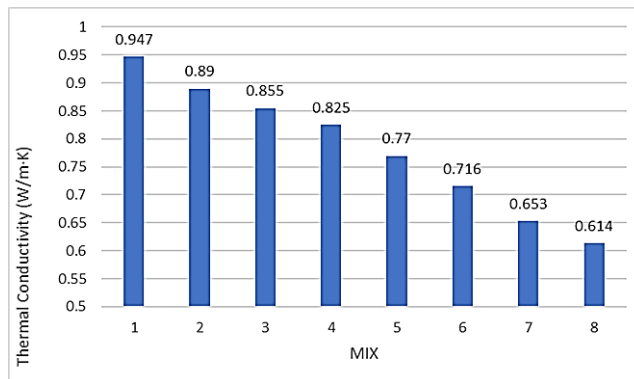


Fig. 11. Thermal conductivity of mixtures

#### 4. Conclusions

This study investigated the effect of crumb rubber as a partial replacement for fine aggregate on the mechanical, physical, and thermal properties of concrete. The results indicated that the compressive strength decreased consistently with increasing rubber content. Also, the strength reduction ranged from 42.61 MPa (0% rubber) to 15.69 MPa (50% rubber), representing a 63% decrease. The mixes with up to 20% rubber replacement maintained acceptable structural strength (>25 MPa) and are suitable for conventional structural applications. Split tensile strength was also dropped from 1.81 MPa (0% rubber) to 1.09 MPa (50% rubber), a 40% decrease. However, rubber content above 30% may require additional reinforcement to maintain tensile capacity. Furthermore, flexural strength decreased from 4.53 MPa to 2.70 MPa (~40% reduction) with increasing rubber content. In this regard, mixes with  $\leq 20\%$  rubber exhibited sufficient flexural performance for structural elements. Accordingly, density decreased from 2361 kg/m<sup>3</sup> to 2062 kg/m<sup>3</sup> (12.6% reduction), enhancing lightweight characteristics while slightly compromising strength. Slump also decreased from 19.8 cm to 16.5 cm, indicating reduced flowability at higher rubber contents. Referring to the thermal conductivity, the results indicated a steadily reduction of this property from 0.947 W/m K (0%) to 0.614 W/m K (50%), which demonstrates the improved thermal insulation potential of rubberized concrete. Considering mechanical performance, workability, density, and thermal properties, 15–20% rubber replacement was recommended as the optimum range. Moreover, concrete with >30% rubber is better suited for non-structural or thermally demanding applications rather than load-bearing elements. In this aspect, high rubber content promotes environmental benefits by recycling waste tires and reducing sand consumption. Despite reduced mechanical properties at high replacement levels, the thermal efficiency and sustainability are significantly enhanced. On top of this, Local Karasta cement (CEM 11/A-L) can be effectively used in rubberized concrete, though slight chemical deviations may influence early-age performance. However, careful mix design and curing are essential to balance structural strength and thermal insulation. Overall, this research provided a comprehensive evaluation of rubberized concrete up to 50% fine aggregate replacement, offering novel insights into high-rubber-content mixes under local Iraqi material conditions, and contributes to sustainable and thermally efficient construction practices.

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