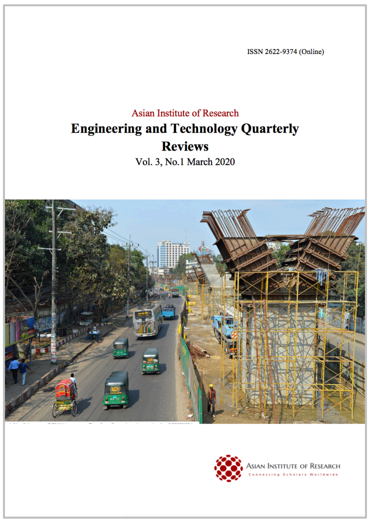

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Enhancing Physical, Mechanical and Thermal Properties of Rubberized Concrete

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Abstract
This research aims to develop a low density concrete, characterized by high porosity and reduced thermal conductivity with slight to no compromise over strength, employing scrapped waste tires. Although, literature on the topic is available that addresses benefits and drawbacks of rubberized concrete, this experimental work was formulated to suggest an optimum dose of crumb rubber that imparts sufficient strength and workability in addition to insulation and low weight. Four types of specimens were cost and tested, containing 0, 5, 10 and 15% crumb rubber as partial replacement of sand in ordinary concrete, using ASTM standards. Specially constructed heat transfer measurement device was used to find out the thermal conductivity of the specimens. Scanning electron microscopy was carried out to examine the micro-structure of rubberized concrete. Results reveal that thermal conductivity and density lower by 30% and 15% respectively and porosity increases by 34% at 15% partial replacement of sand by rubber. Higher concentration of voids along the interface were observed at 15% replacement indicating poor bonding and a weaker ITZ, leading to reduced strength. Based on the results, 5% optimum dosage is recommended, which enhances porosity by 5%, compressive strength by 5.5%, and reduces slump by 16%, thermal conductivity by 16% and density by 2% respectively.

Keywords: Concrete, Waste Rubber Tires, Thermal Conductivity, Density, Strength, Porosity

1. Introduction

The effective use of recycled and waste materials in construction applications and the solution of environment problem by recycling have attracted many researchers in the recent past (Ahmed, Khitab, Mehmood, & Tayyab, 2020; Bolden, 2013; Hassan Riaz, Khitab, & Ahmed, 2019; Jalil et al., 2019; Riaz, Khitab, Ahmad, Anwar, & Arshad, 2019). The rate of production of rubber around the globe varies from country to country. More than 3.6 million tons of rubber is produced by United States per year. Iran and Malaysia produce 0.1 and 0.2 million tons of rubber each year, respectively (Abdollahzadeh, Masoudnia, & Aghababaei, 2011; Bakri, Fadli, Bakar, & Leong, 2007). As shown by studies, rubber tires after their lifespan, contain materials, which cannot be decomposed in an environment-friendly manner and lead to severe environmental problems. Rubber can be decomposed via burning, but it adversely affects the atmosphere. Alternatively, these scrap tires can be used in concrete as replacement of aggregates (A.Sofi, 2018; Herrera-Sosa, Martínez-Barrera, Barrera-Díaz, Cruz-Zaragoza, & Ureña-Núñez, 2015; Sohrabi & karbalaie, 2011; Toutanji, 1996). The demand for tires continuously increases as the number of vehicles increases. As the scrap rubber tires are not easily biodegradable, therefore it is acute challenging for the industries to handle such waste. On the other hand, the natural aggregates used for making concrete are finite and are rapidly dwindling. The frequent use of conventional concrete also necessitates a careful selection of the constituent materials for avoiding undesirable consequences like alkali-silica or alkali carbonate reactions and many others (Anwar Khitab & Anwar, 2016; Munir, Kazmi, & Wu, 2017; Munir, Kazmi, Wu, & Patnaikuni, 2018). Following paragraph highlights some of the important works, regarding use of waste rubber particles in concrete.

Kaloush et al. studied the addition of crumb rubber as substitute of air-entraining agent for concrete, using higher rubber contents (30, 60, 90, 120 kg/m^3 of concrete) (Kaloush, Way, & Zhu, 2005): They have reported that the addition produces air-entrained concrete with reduced unit weight, compressive and tensile strength. In addition, the rubberized concrete shows a ductile failure. Benazzouk et al. have investigated the effect of powdered tire rubber as addition to cement paste on both the physico mechanical and water absorption properties (Benazzouk et al., 2007): They have reported that the composite satisfies the basic requirement of construction materials. Ghedan et al. studied the partial replacement of coarse aggregates by chipped rubber particles treated with and without saline (Ghedan & Hamza, 2011): They have reported a reduced thermal conductivity with rubber aggregates. In addition, they have reported that saline treated aggregates recover some of the loss in compressive strength. Yusuf et al. proposed a model that can predict the compressive strength of rubberized concrete and aid structural designers who are considering rubberized concrete as a promising alternative to conventional concrete in seismic zones (Youssf, ElGawady, Mills, & Ma, 2014). Xue et al. investigated the use of crumb rubber for enhancing the energy dissipation capacity of concrete (Xue & Shinozuka, 2013): Their work revealed that the damping coefficient enhanced by 62% and the seismic response acceleration reduced by 27%. Khalid et al. studied the effect of crumb rubber on workability of concrete (Khalid & Hameed, 2015): They have reported zero slump at 40% replacement of sand by crumb rubber. Aslani et al. investigated the effect of rubber particles as partial replacement of fine and coarse aggregates on properties of concrete (Aslani & Khan, 2019): They have reported enhanced deformation and energy absorption with the rubberized concrete with reduced mechanical strength and workability. Oprişan et al. studied rubberized concrete short columns (Oprişan et al., 2019): They confined the columns with Aramid fiber-reinoforced polymer jackets for restoring the loss of compressive strength due to rubber particles. They have reported enhanced peak stresses and axial strains with rubberized concrete. From previous studies, it is quite clear that inclusion of rubber particles reduces workability and mechanical strength. The loss of workability led the researchers to employ some viscosity modifiers and supplementary cementitious materials, while employing rubber particles in concrete (Güneyisi, 2010; Topçu & Bilir, 2009). The loss of mechanical strength was compensated with some supplementary cementitious materials and special techniques (Elchalakani, 2015; Ghedan & Hamza, 2011; Güneyisi, 2010; Oprişan et al., 2019). Many other researchers have termed rubberized concrete as a good insulating materials with lower density but at the same time have also mentioned it a low strength material (Benazzouk, Douzane, Mezreb, Laidoudi, & Quéneudec, 2008; Marie, 2017): Ironically, all major studies for examining thermal conductivity and/or strength have used high volume ratios, starting from 10%. Although, higher thermal insulations were obtained, but they were also accompanied by drastic lower strength. Additionally, the previous studies present some segregated knowledge about the topic: Either durability or strength with physical characteristics were the main objectives (Benazzouk et al., 2007, 2008). Also, microscopic analysis of the specimens is missing in most of the past studies.

This research project was intended to investigate the effect of lower percentages (5, 10 and 15%) of rubber particles on physical, mechanical and durability aspects (all in one) of ordinary concrete. The study is supplemented with a rigorous microscopic analysis too. The overall intent was to enhance knowledge about the rubberized concrete and to develop light weight material with low thermal conductivity and reasonable strength and workability.

2. Materials and Methods

Both control and rubberized concrete samples were casted using the local cement, sand and coarse aggregates as per standard ASTM procedures (ASTM, 2013). A grade C-53 cement was used and its chemical composition and physical properties are given in Table 1.

Table 1. Chemical and physical properties of cement

Chemical Composition of cement used		Physical Properties of Cement	
Gypsum	1%	Specific gravity	3.15
Silica	30%	Normal Consistency(%)	30%
Iron Oxide	2%	Soundness(mm)	2%
Magnesium Oxide	1%	Fineness(%)	1%
Aluminum Oxide	5%	Initial Setting time (minutes)	30
Lime	61%	Final Setting time(minutes)	610

Lawrencepur river sand was used as fine aggregates. Coarse aggregates were acquired from the renowned limestone quarry of Margalla near the capital Islamabad and its characteristics are shown in Table 2. The selected quarries are well-documented, tested and contain inert materials. All constituents were carefully decided for avoiding any unfavorable consequences as mentioned above.

Table 2. Physical properties of fine aggregates

Physical Properties of Sand		Physical Properties of Coarse Aggregates	
Specific Gravity	2.69	Specific Gravity	2.48
Fineness Modulus	2.72	Bulk Density(kg/m^3)	1598
Bulk Density (Kg/m^3)	1500	Dry rodded density(kg/m^3)	1610
Dry rodded Bulk Density(Kg/m^3)	1850	Water absorption(%)	1.49
Water absorption(%)	3.88	Void(%)	34.11
Water Content (%)	2.01	Impact Value(%)	13.20

Crumb rubber was produced in the laboratory by shredding the waste tires and scrubbing with sandstone. The finished product is shown in Figure 1. The physical properties of crumb rubber are mentioned in Table 3.

Figure 1. Crumb rubber

Table 3. Physical properties of crumb rubber

Specific Gravity	1.66
Color	Black
Surface	Moderately rough
Fineness Modulus(%)	4.1
Water absorption(%)	1.25

By comparing Tables 2 and 3, it is quite clear that crumb rubber should result in light-weight finished products owing to lesser specific gravity than that of the replaced sand. From particle size analysis, it was observed that crumb rubber contains relatively coarser particles, and have lesser water absorption than sand. The low water absorption values add to the quality of concrete.

The sieve analysis of sand and sand-crumb rubber mix as per standard ASTM methods are shown in Figure 2. *The mix was prepared in a way that sizes remain within the limits, defined in ASTM standards for fine aggregates* (A. Khitab, 2012).

A

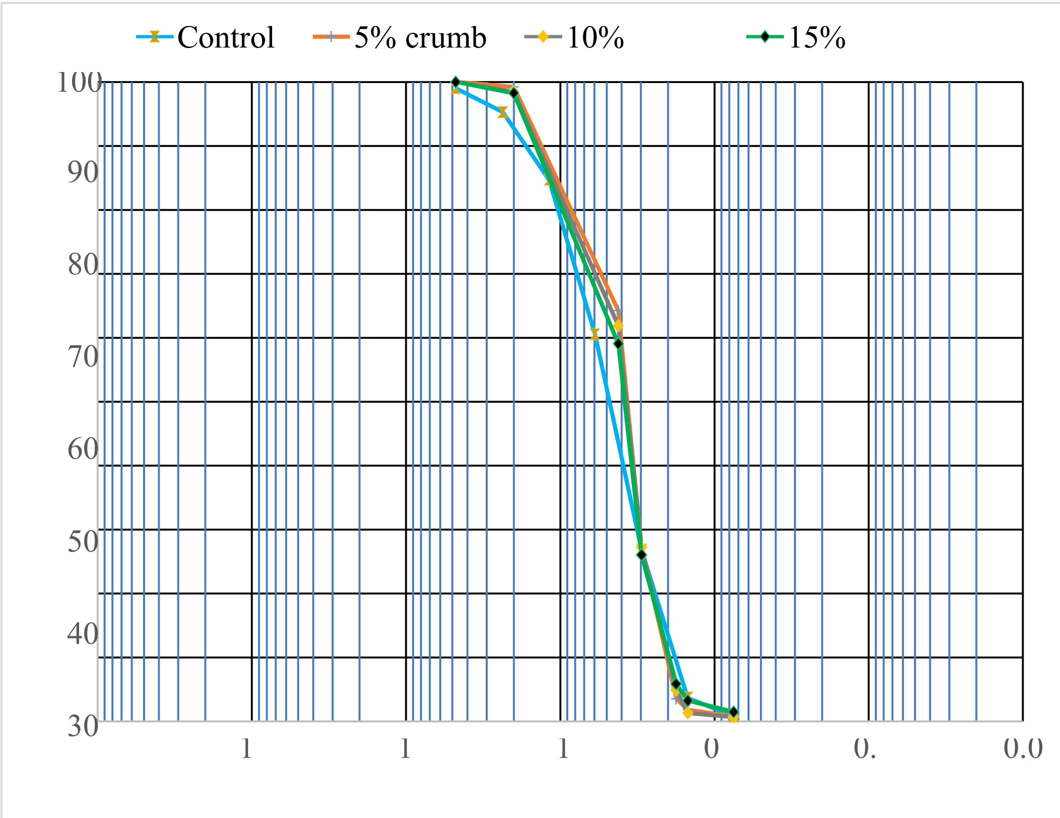

Figure 2. Sieve analysis of sand

thorough mix design was prepared for both the control units (Co) and the modified units (partially replaced sand) with notations as C5, C10, C15. After a series of initial trials, the mix design was selected as 1:1.56:3.12 (cement: sand: coarse aggregates), with water to cement ratio of 0.45. The composition of the mixes is shown in Table 4.

Table 4. Concrete compositions (per cubic meter of concrete)

Sample	Cement (kg)	Sand (kg)	Crumb Rubber (kg)	Coarse Aggregate (kg)	Water (l)
Co	390	608	0	1217	175.5
C5	390	578	30	1217	175.5
C10	390	547	61	1217	175.5
C15	390	517	91	1217	175.5

The samples after mixing properly were casted carefully according to ASTM C-192 (ASTM C192 /C192M, 2019). The molds were buttered properly by applying diesel oil and were thoroughly cleaned by using sand paper. The Casting was done into three layers. Each layer was tempted 25 times. The molds were removed after 24hrs and the specimens were engraved by the date of casting as an identity and then were put inside the curing tank having clean water.

3. Results with Discussions

3.1 Workability

A true slump was observed in all the fresh specimens regardless of rubber quantity. The results are summarized in Table 5.

Table 5**.** Variation of Slump with rubber content

Specimen	Slump (mm)
Co	48
C5	40
C10	31
C15	22

From the results as given in Table 5, it is clear that the workability decreases with rubber content. The reduced workability is attributed to lower specific gravity of rubber particles, which hinder the compaction efforts in a slump test. The results are in close coordination with the previous studies (Khatib & Bayomy, 1999).

3.2 Density

Fresh and hardened densities of the specimens are mentioned in Table 6. It can be seen that both the densities decrease with increase in rubber content. The effect is attributed to the lower specific gravity of the rubber content as compared to that of sand, and the induction of voids due to poor compaction. The induction of voids was confirmed from microstructure of the specimens, which is mentioned in the coming paragraphs.

Table 6**.** Variation of fresh and hardened densities with rubber content

Specimens	Fresh Density(Kg/m^3)	Hardened Density(Kg/m^3)
Co	2512	2448
C5	2455	2404
C10	2176	2278
C15	2008	2098

3.3 Compressive strength

Compressive strength results are presented in Table 7: It indicates that the strength increases from that of the control specimen, by 4% at 5% modification, and then gradually decreases. At 5% replacement, the rubber particles hold cement products in a better way due to its rough texture and flakiness: This was also confirmed through SEM of C5 given in Figure 4. As the rubber content increases, the sample becomes less dense, the rubber particles come in contact with other rubber particles and tend to act like a good shock absorber to withstand the blows during the process of rodding: This in turn does not help reducing the voids and the strength is reduced.

Table 7 Variation of compressive strength (MPa) with rubber content

Notation	3 Days	7 Days	28 Days
Co	10.5	18.2	28.1
C5	11.5	19.9	29.6
C10	11	17.3	26.3
C15	10.3	14.9	22.5

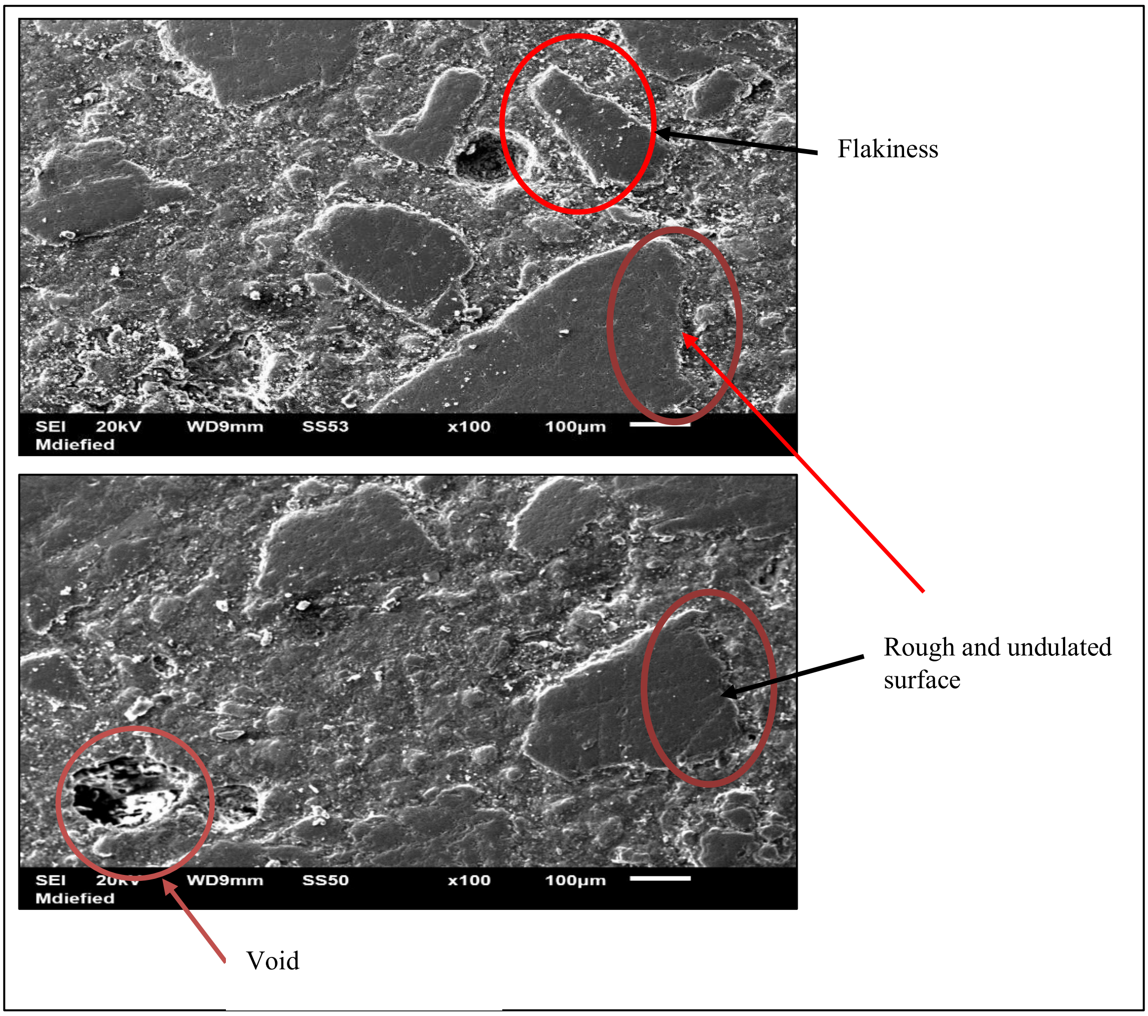

Figure 3. Microstructure concrete with 5% rubber content

Figure 3 shows that the flakiness of the rubber particles and its rough and undulated surface provides mechanical friction with the surrounding cement paste. Also, the rubber particles at lower content seem reasonably distributed in the cement matrix, with fewer voids: This in turn enhances the compressive strength of the concrete specimens at lower rubber content. However, at higher rubber contents, the rubber particles were seen agglomerated, poorly distributed, and resulting in higher void content: This overcame the beneficial rubber particle shape effect and mechanical friction, and resulted in lowering the strength of the specimen.

3.4 Thermal Conductivity

Thermal conductivity was measured, using a specially built device shown by a schematic diagram in Figure 4 based on the principle of common measurement techniques. The testing specimen was placed between a heat source and a heat sink. The sample was heated by the heat source with known steady-state power input and the resulting temperature drop ΔT across a given length (separation) of the sample was measured by temperature sensors after a steady-state temperature distribution was established. The temperature sensors employed can be thermocouples and thermometers. Thermocouples are the most widely used sensors due to their wide range of applicability and accuracy. The resulting measurement error in ΔT due to temperature sensor shall be less than 1% (ASTM C177-13, 2013).

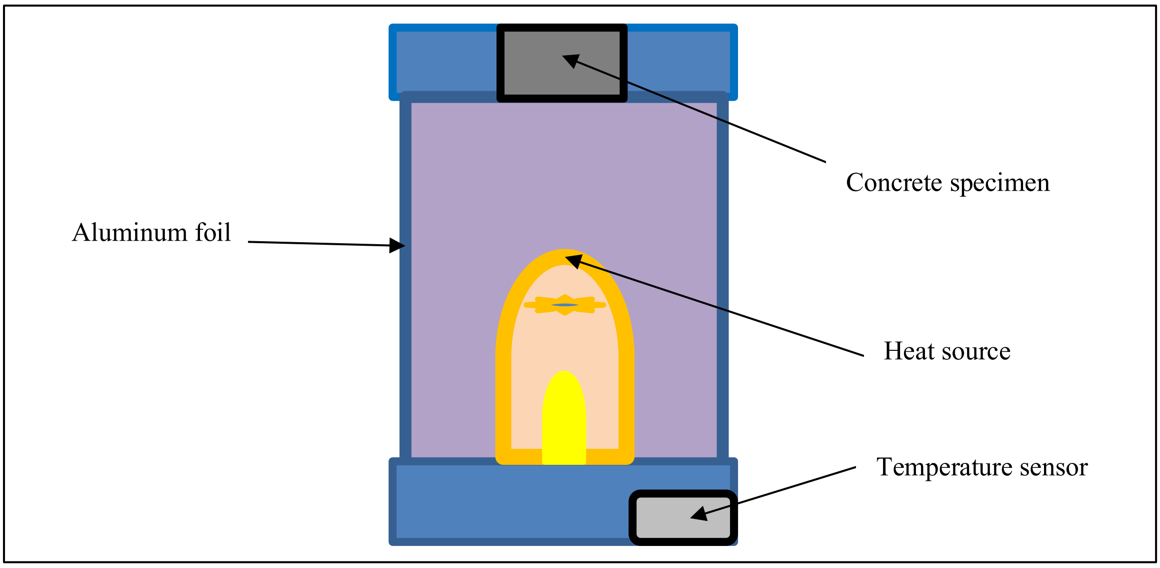

Figure 4. Schematic diagram for thermal conductivity measurement

Thermal conductivity k of the sample was calculated using Fourier's law of heat conduction, as given in equations *(1)* and *(2)*:

$$Q = k.A.\Delta T \qquad (1)$$

$$k = Q.L/A.\Delta T \qquad (2)$$

In the above equations, Q is the amount of heat flowing through the sample and bears the same units as power, A is the cross-sectional area of the sample, L and ΔT are the distance and temperature difference between temperature sensors, and k represents thermal conductivity. The actually developed assembly with concrete specimens are shown in Figure 5.

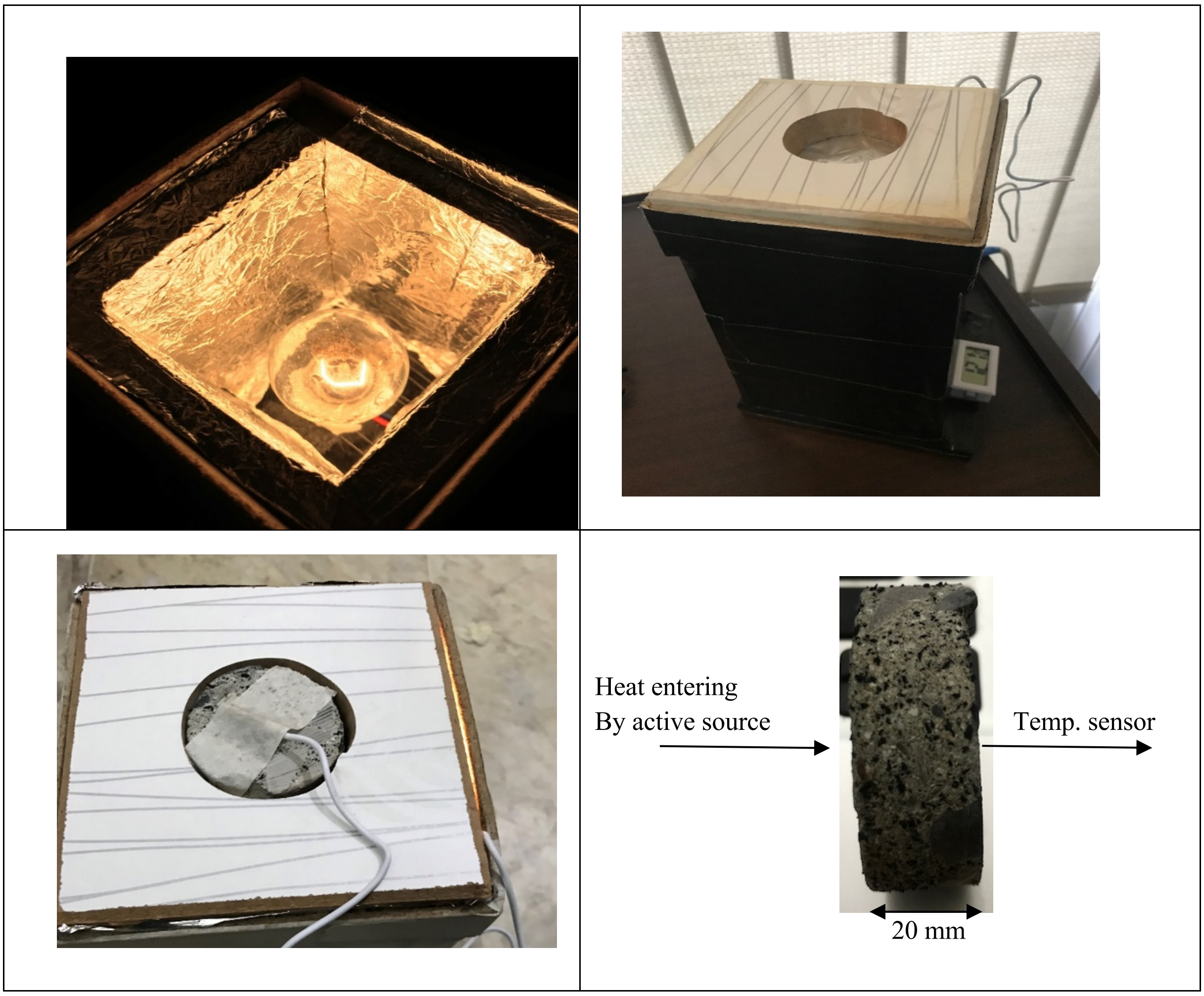

Figure 5. Thermal conductivity measurement device

The variation of thermal conductivity with rubber content is shown in Figure 6. From the figure, it seems that thermal conductivity varies linearly with rubber content. Variation of thermal conductivity with rubber content can be represented mathematically as follows:

$$k = -0.02x_r + 0.995 \quad (3)$$

Where, k is the thermal conductivity in $W.m^{-1}K^{-1}$ and x_r is the rubber content as percentage replacement of sand. According to Asadi et al., thermal conductivity of ordinary concrete varies from 1-2 $W.m^{-1}K^{-1}$ (Asadi, Shafigh, Abu Hassan, & Mahyuddin, 2018): From the results, it was observed that the thermal conductivity can be reduced by 30% with 15% replacement of sand by rubber content. The decrease of thermal conductivity of concrete can be related to increase in void content and low thermal conductivity of rubber compared to sand. Previous studies indicated that the rubber present in cementitious mixtures increases the air content even without adding air-entraining admixture. Benazzouk et al. reported that air content increases from 2 to 17%, when amount of rubber increased from 0 to 50% (Benazzouk et al., 2007). Air has thermal conductivity of 0.0026 W/mK, which serves to improve the specimen thermal insulation property. The other factor is the thermal conductivity of rubber particles itself. Thermal conductivity of rubber varies between 0.05-0.13 W/mK for particle size range between 1-12 mm. When crumb rubber particles replace sand, which has higher thermal conductivity, the overall thermal conductivity of mixtures decrease. The variation of thermal conductivity as density of concrete is shown in Figure 7.

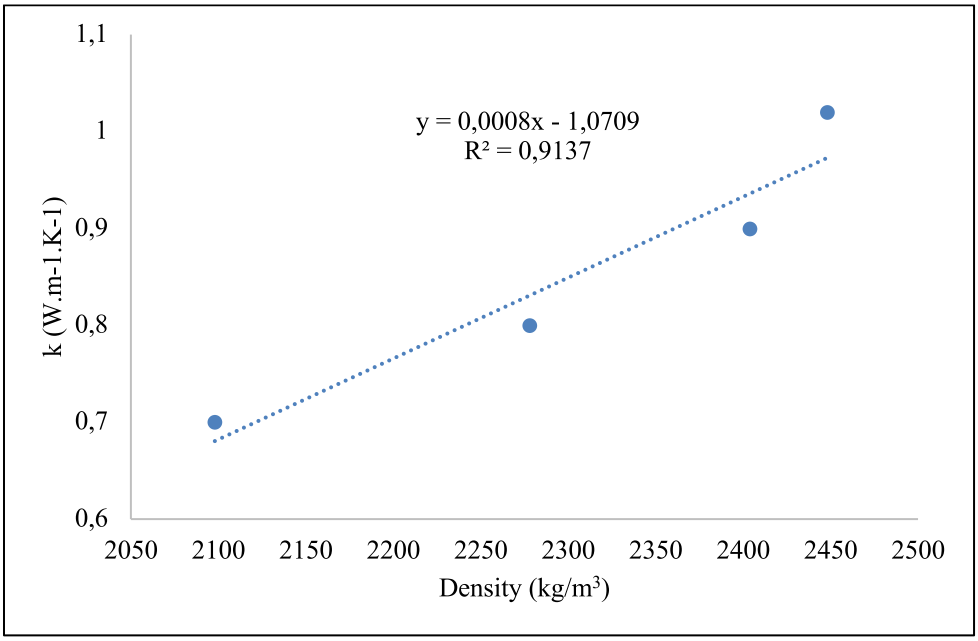

Figure 6. Variation of thermal conductivity as a function of hardened density of concrete

Figure 6 shows that there is a linear improvement in thermal insulation with decrease in density. Control specimens have thermal conductivity of 1.02 $Wm^{-1}K^{-1}$, which reduces to 0.7 $Wm^{-1}K^{-1}$ at 15% replacement.

3.5 Porosity

Concrete comprises a porous heterogeneous structure as it sets: Porosity is an important parameter affecting the durability, freezing and thawing performance and corrosion resistance of concrete (A. Khitab, Lorente, & Ollivier, 2005). Method of vacuum water absorption was used to determine the porosity of concrete (Anwar Khitab, 2005; Li, Dong, Li, & Li, 2015). The results show that the porosity increases with increase in rubber content. The results showed that the crumb rubber worked as the air-entraining agent which can enhance the porosity of concrete. The porosity was determined at regular intervals, which revealed that the porosity increases as the amount of crumb rubber increases. The results are indicated in Table 8.

Table 8. Variation of porosity with time and rubber content

Time	15 min	30 min	1 hr	2 hr	4 hr	8 hr	16 hr	24 hr	48 hr
C0	4.51	4.949	5.38	5.56	5.98	6.12	6.49	6.78	6.83
C5	4.67	5.46	5.96	6.12	6.26	6.58	6.98	7.12	7.2
C10	5.129	5.88	6.11	6.56	6.82	7.02	7.73	8.01	8.16
C15	5.878	6.23	6.87	7.12	7.42	7.96	8.16	9.07	9.17

Control and C15 specimens, when dipped in water are shown in the Figure 7: C15 shows a lot of air bubbles on top surface, which confirms the presence of air in the modified concrete.

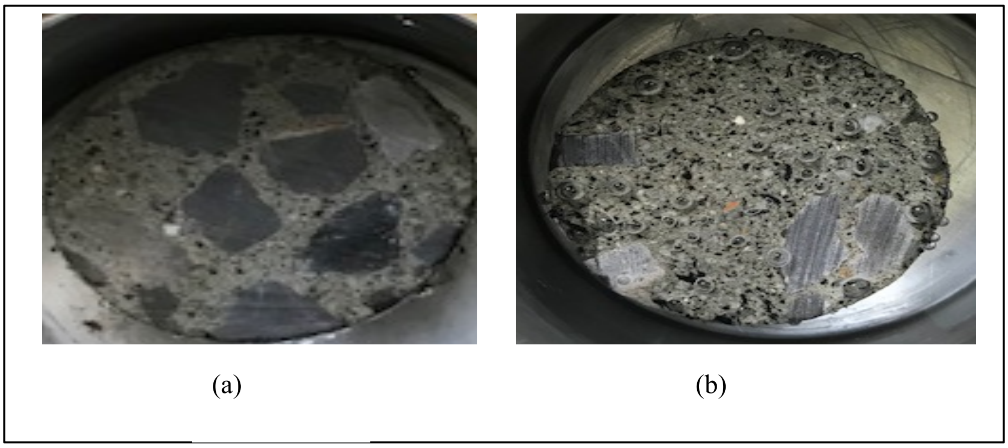

Figure 7. Air bubbles (a) control specimen (b) specimen having 15% rubber as partial replacement of sand

3.6 Interstitial zone

The ITZ is of paramount importance in studying short-term as well as long-term properties of cementitious materials: It is characterized by a thin interface layer that exists between the aggregates and the paste matrix. This is a region of gradual transition of properties, where the effective thickness of the region varies with the microstructural feature being studied, and with degree of hydration. The ITZ of the rubberized concrete (C15) is shown in Figure 8, where the cement matrix is concentrated on right side and the ITZ is on left hand side. It can be seen that ITZ is highly porous.

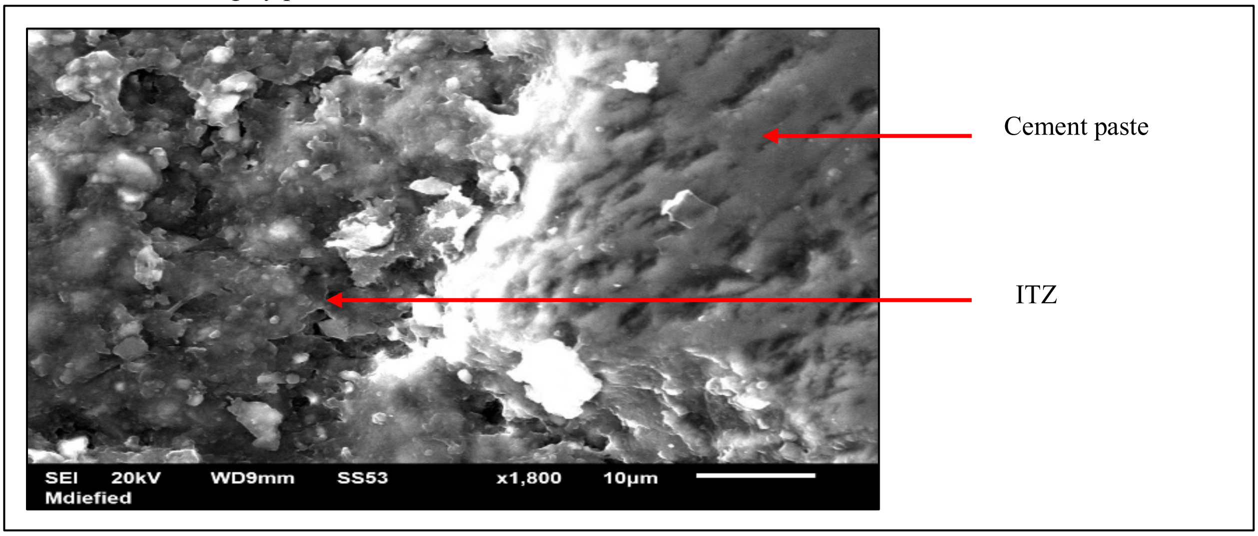

Figure 8. Cement paste and ITZ in concrete containing 15% rubber content

Figure 9 shows the interior of ITZ: It can be seen that the pore inside the ITZ range in size from 1 to several micrometers with connectivity at certain locations.

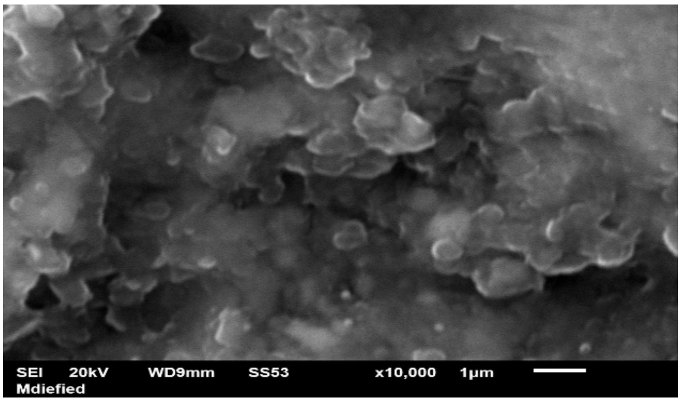

Figure 9. Porous structure of ITZ in rubberized concrete

As mentioned before, the rubber particles have sharp edges and rough surfaces, and as they might enhance friction, they also might entrap air between them and cement paste and increase the pore content as well as their connectivity. Hence the interfacial transition zone of crumb rubber concrete is weak. Weakness of ITZ is more pronounced at higher concentrations, which lead to drastic reduction in mechanical strength of the material, from 28 MPa for control specimens to 22.5 MPa for specimens containing 15% crumb rubber.

4. Conclusions

This research investigated the effect of crumb rubber on the thermal conductivity of the rubberized cement mortar. The thermal conductivity was measured using a specially made device based on the principle of common measurement techniques. From the findings of the experimental work, the following conclusions may be drawn:

This research focused on the effect of crumb rubber on strength, thermal conductivity, porosity and ITZ of the rubberized cement concrete. From the findings of the experimental work, the following conclusions may be drawn:

- The partial replacement of sand via crumb rubber decreases the workability of concrete and ensures a true slump due to decrease in viscosity of concrete mix.
- Compressive strength increases up to 5% partial replacement of sand by crumb rubber by 4%. This is attributed to rough surface and flakiness of rubber particles, which seem dominant at lower concentrations.
- Compressive strength decreases at 10% and 15% replacement levels. Highly porous structure of ITZ was observed at 15% replacement level, which reduced the strength.
- Partial replacement of sand by rubber particles ensures lightweight materials. The density of the concrete lowers by 14.5% at 15% replacement.
- Partial replacement of sand by rubber particles reduces thermal conductivity of concrete. Thermal conductivity lowers by 30% at 15% replacement.
- Partial replacement of sand by rubber particles increases porosity of concrete. Porosity increases by 34% at 15% replacement.
- Rubber particles were observed to entrap air, making ITZ highly porous: This makes ITZ of rubberized concrete, weaker than the control material.
- Based on the results, 5% partial replacement is recommended, which not only reduce density, and thermal conductivity, but also enhance compressive strength and maintain reasonable workability.

Declaration of Conflict of Interests
The author(s) declare(s) that there is no conflict of interest.

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