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Research Article

Thermal conductivity, abrasion resistance, and compressive strength of end-of-life tire aggregate incorporated concrete

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ABSTRACT

Recycling end-of-life tires is a global problem that requires an urgent solution. Storing and preserving these tires is a challenge that delays facing potential problems instead of solving the problem. In this context, recycling waste tires without harming the environment and at low costs has been the focus of many researchers. For several decades, the possibility of grinding these tires to aggregate size for concrete and substituting them with natural aggregate has been the subject of research by scientists working in this field. In this regard, this study aims to experimentally investigate the influence of waste rubber aggregate on some engineering properties of concrete, such as ultrasonic pulse velocity-based quality assessment, abrasion resistance, thermal conductivity characteristics, and mechanical performance, namely, compressive strength. Another significant side of the study was establishing a statistical relationship and correlation between the w/c ratio and substitution level of waste rubber aggregate and the experimental outputs. The experimental study indicated that the waste rubber aggregate decreased the concretes' compressive strength, but it improved the thermal conductivity characteristics and abrasion resistance of the concretes manufactured in this study. On the other hand, the statistical analysis revealed that the input parameters have meaningful effects on the engineering properties of the concretes, and there is a strong correlation between these properties.

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1. INTRODUCTION

Waste materials considered obsolete and/or unwanted materials are substances free from some production steps or domestic activities, such as commercial, agricultural, industrial, or mining operations. According to the United Nations Environmental Protection Agency, waste materials are handled in two classes: hazardous and non-hazardous. Hazardous waste materials, including chemicals, substances obtained from by-products of commercial production processes or heavy metals, and household items that are inactive and removed from the house, can potentially harm

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the environment or the health of living creatures. However, idle materials that have the potential to be reused and/or recycled may be considered non-hazardous waste materials.

The Tire Manufacturers Association states that when used correctly, idle tires do not lead to any environmental problems. However, it is also stated that when it comes to misuse, waste tires can harm the environment and health. Therefore, despite the fact that they do not pose a hazard in their current condition, idle tires can be considered hazardous waste because of the release of high amounts of toxic gases, heavy metals, and mineral oil when burnt. In addition, due to the shape they have, these tires can host many rodents and flies by holding water in the areas where they are stored and become a home for reptiles. This situation may not only negatively influence human health but also deteriorate the natural habitat in such regions.

China, European Union countries, the United States of America, Japan, and India, produce the majority (about 88%) of waste (scrap) tires worldwide. Compared to Japan (about 91%) and the United States (about 89%), the European Union countries (about 96%) are the most developed regions in the world in terms of recycling and/or recovery of idle tires [1]. Since rubber tires take a long time to naturally biodegrade, their reuse or recycling is an urgent matter of concern [2, 3]. Within this scope, various recycling or reuse methods have been developed and proposed to recycle these idle tires. For that purpose, the recycling of end-of-life tires is carried out by five methods: retreading method, energy recovery, pyrolysis technique, product recycling, and material recycling.

Retreading replaces the worn outer part of the tires, consisting of treads and grooves, with a new one, which is used to extend the life of the tires. However, due to their weak structure, about 85% of car tires are generally not suitable for retreading, while truck tires are more suitable for this process than car tires because they are better maintained and have a more substantial structure. If the tires are not found suitable for retreading recycling method, they become waste material that needs to be disposed of and recycled by another method. Reducing waste tires by incineration is the most accessible, practical, and profitable method, as it provides high heat energy (a relatively higher calorific value than coal) [4]. Tire-derived kilns can be widely used in the cement industry, as the clinker production kiln requires a temperature higher than 1200 ºC, which ensures complete combustion of all tire components.

Moreover, the use of shredded tires is also allowed in these kilns [1]. Although this fuel is widely used in clinker kilns in the cement industry because it increases the thermal efficiency of steam boilers and kilns when burned together with coal, it can also be used as fuel together with ground rubber wastes in thermal power plants, industrial boilers, and paper, pulp, iron, and steel factories [1, 5]. However, because of the release of high amounts of toxic, dangerous, and polluting gases, burning waste tires is prohibited or restricted by law in many countries [6, 7].

Another method used to recycle end-of-life tires is pyrolysis, which simultaneously and irreversibly changes the chemical composition and physical phase of organic matter through thermochemical decomposition by breaking down chemical bonds at high temperatures under non-oxidative conditions [8]. In this context, the waste tire is converted into valuable components such as pyrolysis oil, carbon black, and hydrocarbon gas through the pyrolysis method. Using end-of-life tires in the manufacture of tire derivative products is another recycling method for idle tires. In this context, although each company recycles idle tires in a different area, these may be generally categorized as traffic-related products, sidewalks, paving stones, greenways, pathways, paving, sports field surfacing and playground paving materials, mat, synthetic turf, accessibility (wheelchair) ramps, animal care products, landscaping, and rubber mulch, and siding material. Recycling end-of-life tires in the form of crumbs and chips as an inexpensive filling material can also be considered in this context. For that purpose, waste tires are mechanically ground to obtain the tire chips and crumb rubber in a required size using different ways [9].

On the other hand, since recycling, as mentioned above, is either not environmentally friendly, costly, or does not produce a sustainable solution, it has encouraged people to look for alternative ways to reuse or recycle idle tires. In this sense, using idle tires in various forms in civil engineering projects with a wide application area and a sizeable industrial volume is an effective and environmentally friendly way of getting rid of these tires. Considering the amount of ready-mixed concrete (160 million tons in Türkiye, 620 million tons in Europe [10], approximately 4.4 billion tons in the world [11] – for 2019) and asphalt roads (46 million tons in Türkiye and 300 million tons in Europe [12], 375 million tons in the U.S.A. [13] – for 2017) produced around the world, it can be said that using waste rubber tires in these two sectors of civil engineering will be a very practical, environmentally friendly, and the innovative way [14, 15]. Raw materials from natural reserves are not unlimited; therefore, complying with the waste hierarchy, also known as the three Rs of solid waste management (Reduce-Reuse-Recycle), is essential to create a sustainable life [16].

Over the past decade, studies on rubber-substituted (or rubberized) concretes have shown that rubber substitution adversely affects concrete's mechanical properties. In this context, it was stated that the most effective parameters on the mechanical properties of concrete are rubber aggregate size, substitution level, and the water-to-cement ratio of concrete [17, 18]. Gupta et al. [19] and Lv et al. [20] reported that increasing the waste tire aggregate replacement level caused a regular decrease in

Table 1. Chemical compositions and physical properties of Portland cement

Chemical compositions (%)											Physical properties	
CaO	SiO_2	Fe_2O_3	Al_2O_3	SO_3	MgO	TA	L.I.O.	I.S.	Cl^-	FL	Specific gravity	Blaine fineness (m^2/kg)
62.8	19.0	4.7	4.0	2.6	1.73	0.45	2.63	0.68	0.01	1.31	3.15	374

TA: Total alkaline (Na_2O+0.658K_2O); LIO: Loss in ignition; IS: Insoluble residue; FL: Free lime.

compressive strength. Similar findings were reported by Güneyisi et al. [17] and Gesoğlu et al. [18], not only for compressive strength but also for flexural strength. The decrease in flexural tensile strength of concrete at different levels of substitution has also been reported by Su et al. [21] and Mohammed and Adamu [22]. In addition, studies have revealed that after the 30% substitution level, the integrity of the concrete is seriously lost, porous concrete is obtained, and its mechanical properties are lost at severe rates. Güneyisi et al. [17] incorporated waste tire aggregate at 50% and observed a 75% decrease in flexural strength, while Lv et al. [20] reported a similar decrease at a 100% waste tire replacement level. Also, Güneyisi et al. [17] reported a more than 80% reduction in compressive strength at a 50% waste tire replacement level. In this context, since waste tire aggregate in concrete production seriously deteriorates the mechanical performance, it is important to investigate the use of such concretes in manufacturing non-bearing elements, especially as insulation material, rather than for structural purposes.

For this reason, this study mainly aims to examine the effect of the use of end-of-life tires as aggregate (hereupon named waste rubber aggregate) at various replacement levels on the engineering properties such as compressive strength, abrasion resistance, thermal conductivity, and ultrasonic pulse velocity of concretes produced at various water-to-cement ratios. Various water-to-cement (w/c) ratios and waste rubber aggregate substitution levels were considered experimental parameters.

2. MATERIALS AND METHODS

2.1. Materials

In the present study, the binding material used in the production of rubberized concrete was Portland cement (CEM I 42.5 R) with a specific gravity of 3.15 and a Blaine fineness of 374 m^2/kg. The chemical compositions and physical properties of this cement procured from ÇİMSA are presented in Table 1.

In all concrete mixtures produced within the scope of the study, river sand was used as fine aggregate, and basalt crushed stone in two different sizes was used as coarse and medium aggregates. The results of the sieve analysis of fine, medium, and coarse aggregates with the specific gravity values of 2.73, 2.79, and 2.78, respectively, are given in Figure 1. Besides, the fineness modulus of the river sand was 1.9, and the 24-hour water absorption value was 0.70%, while the 24-hour water absorption value of both the medium and coarse basalt crushed aggregates was 0.65%.

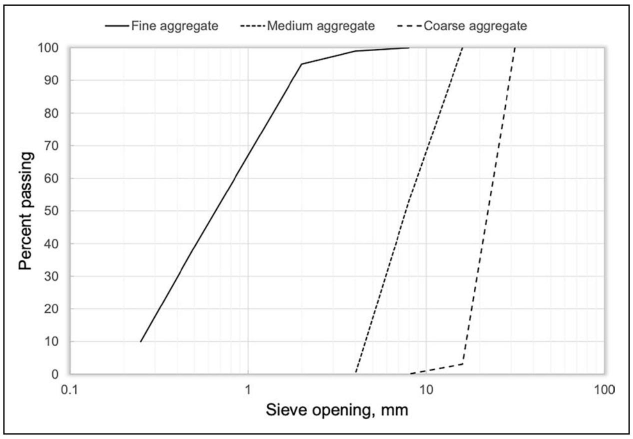

Figure 1. Sieve analysis results of natural aggregates.

Table 2. Technical properties of MasterGlenium 51

Properties	
Material's structure	Polycarboxylic ether based
Appearance	Brown - liquid
pH value	6–7
Alkaline content (%)	≤3.0 (by weight)
Chlorine ion content (%)	≤0.1 (by weight)

The aggregates obtained from end-of-life tires constituting the main theme of this study are rubber pieces called crumb rubber (Fig. 2a) and tire chips (Fig. 2b), which are obtained during the preparation of the surface of the tires for the recapping during the treading of the old tire with a mechanical scraping tool. The specific gravity of the crumb rubber replaced with the fine aggregate was 0.91, and the specific gravity of the tire chips substituted for the medium and coarse aggregates was 1.01. Both tire aggregates had a 24-hour water absorption value of 0.

In order to achieve the desired workability performance in concrete mixtures, a superplasticizer with the commercial name of "MasterGlenium 51" produced by B.A.S.F. construction chemicals was used. Its specific gravity was 1.07, and the other technical properties are given in Table 2.

Figure 2. High-resolution photos of **(a)** crumb rubber and **(b)** tire chips.

Table 3. Mixture proportions of concretes (kg/m³)

Mix ID	Cement	Water	Natural aggregate			Rubber aggregate		Superplasticizer
			Fine	Medium	Coarse	Crumb	Chips	
PC|35	550	192.5	674.6	603.2	429.3	0.0	0.0	5.50
RC|35-10	550	192.5	604.7	540.7	384.8	23.4	38.8	6.05
RC|35-20	550	192.5	535.3	478.7	340.7	46.6	77.2	6.60
RC|35-30	550	192.5	463.4	414.4	294.9	69.1	114.6	7.15
PC|45	450	202.5	701.2	627.0	446.3	0.0	0.0	2.70
RC|45-10	450	202.5	628.7	562.2	400.1	24.3	40.3	3.15
RC|45-20	450	202.5	556.7	497.8	354.3	48.4	80.3	3.60
RC|45-30	450	202.5	482.2	431.2	306.9	71.9	119.2	4.05
PC|55	350	192.5	748.5	669.3	476.4	0.0	0.0	1.05
RC|55-10	350	192.5	671.3	600.3	427.3	26.0	43.0	1.40
RC|55-20	350	192.5	594.7	531.8	378.5	51.7	85.8	1.75
RC|55-30	350	192.5	515.5	461.0	328.1	76.9	127.5	2.10

2.2. Mixture Proportions and Concrete Production

Concrete manufactured within the scope of the present study was designed at 0.35, 0.45, and 0.55 w/c ratios and cement dosages of 550 kg/m³, 450 kg/m³, and 350 kg/m³, respectively. In this way, three w/c ratio-based concrete mixture series were designed, and in each concrete series, the natural aggregate was replaced with waste rubber aggregate at the substitution levels of 10%, 20%, and 30%, and hence, three rubberized concrete series were designed from each w/c ratio. It is well-known that incorporating waste rubber aggregate into concrete and increasing its content deteriorates some characteristics of concrete. In general, especially after the 30% substitution level, it is stated that the waste rubber aggregate significantly worsens concrete performance. For this reason, although recycling waste rubber as aggregate in concrete production was intended, in this study, up to 30% substitution was considered to achieve some mechanical performance.

On the other hand, the conventional concrete used for structural applications is usually produced at a w/c ratio of 0.55. In the present study, the aim of using w/c ratios of various levels is to monitor the impact of rubber replacement on average, moderately high, and high-strength concretes of common use. Thereby, 12 concrete mixtures, three of which were plain and nine of which were rubberized, were manufactured in the current study. The exact mix proportions of both plain and rubberized concretes are presented in Table 3. The superplasticizer contents given in the last column of Table 3 were designated during the manufacturing by trial and error to achieve the plastic consistency in each mixture. Besides, in the Mix ID column of Table 3, the P.C. and R.C. are used to abbreviate the plain and rubberized concrete, respectively, and the numbers following these abbreviations represent the w/c ratio and rubber aggregate substitution level, respectively. For instance, the concrete mixture represented with the I.D. of R.C. |55-20 was produced at a w/c ratio of 0.55 and a waste rubber aggregate substitution ratio of 20%, while that represented with the I.D. of P.C. |45 was manufactured completely with natural aggregate at a w/c ratio of 0.45.

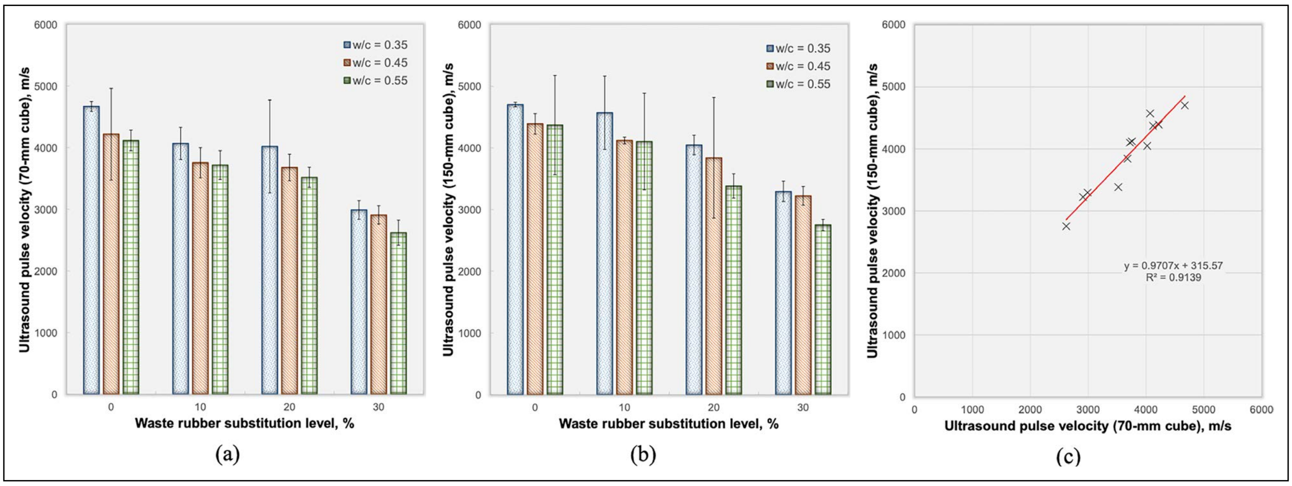

Figure 3. Variation in U.P.V. values of concretes regarding waste rubber substitution levels: **(a)** measured on 70-mm cube, **(b)** measured on 150-mm cube, and **(c)** relationship between U.P.V. values measured on 70-mm and 150-mm cubes.

In the present study, all concrete mixtures were manufactured using an electrical revolving pan mixer having a capacity of 20 liters and following the same mixing process and sequence since the consistency and homogeneity, accordingly, strength development of concretes are significantly affected by the production process. For this reason, first of all, the natural and waste rubber aggregates and cement were put into the mixer, and the mixer was allowed to be rotated until the homogeneous mixing of dry ingredients was achieved. Subsequently, the just mixed water and superplasticizer mixture was slowly poured onto these homogeneously mixed dry ingredients. After the water-superplasticizer mixture was completely added, the mixer continued to be rotated for 5-6 minutes to obtain a homogeneous concrete mixture.

Immediately after the concrete production was completed, the slump test was performed, and then three 150-mm cubic samples were taken for the compressive strength test, and three 70-mm cubic samples were taken for the Böhme abrasion and thermal conductivity coefficient (T.C.C.) tests. Since the ultrasonic pulse velocity (U.P.V.) test is a non-destructive test method, it was measured on the same samples taken for compressive strength and Böhme abrasion tests before they tested for compressive strength and abrasion resistance. All the samples were taken by compacting with a vibrator and kept in a laboratory condition for 24 hours, and then water curing was applied till the test day.

2.3. Methods

In the first stage of the testing program, the nondestructive tests, ultrasonic pulse velocity, and thermal conductivity coefficient were carried out on the samples. The instructions given in ASTM C597 [23] were followed while measuring the U.P.V. values of the concrete produced in the present study. The U.P.V. test was performed on both 70-mm and 150-mm cubic samples to examine the effect of size on the U.P.V. values of concretes. On the other hand, the thermal properties of concrete mixtures were determined using a thermal property analyzer called Hot Disk TPS 500 S, which measures the heat transmission coefficient with the hot disk method [24]. Before being tested, 70-mm samples are kept in an oven at 105 °C for 24 hours to become oven-dry. The hot disc sensor is placed between two oven-dry cube samples taken from the same mixture [25]. Afterward, the average T.C.C. of the cube samples, i.e., the concrete mixture, was determined by measuring with a thermal conductivity device. The compressive strengths of concrete mixtures produced in this study were measured concerning ASTM C39 [26]. The abrasion resistance of the concretes was measured using the Böhme abrasive wheel, and the instructions recommended in DIN52108 [27] were followed while conducting the test. All tests were performed on three samples and the results presented are average.

3. RESULTS AND DISCUSSION

3.1. UPV Results

The U.P.V. value, a powerful non-destructive testing method, gives an idea about the existence of cracks and voids in the concrete and the uniformity of concrete. The U.P.V. values of the concrete mixtures were measured on 70-mm and 150-mm cubic samples. In addition to assessing the concrete quality in terms of U.P.V. values, it was aimed to show how the specimen size influences the U.P.V. results. The variation in the U.P.V. values measured on 70-mm and 150-mm cubes and the standard deviation values are demonstrated in Figures 3a and 3b, respectively. The plain concretes produced in the present study at any w/c ratio had U.P.V. values of more than 4000 m/s for both 70-mm and 150-mm cubic samples. Among the concrete mixtures, the P.C. |35 has a U.P.V. value of more than 4500 m/s and is regarded as high-quality concrete [28]. In addition,

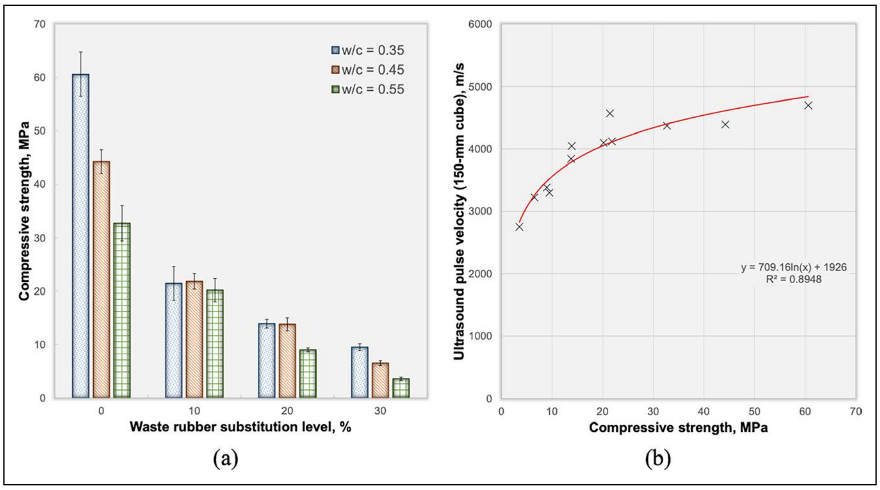

Figure 4. **(a)** Variation in the compressive strength of the concretes regarding the w/c ratio and waste rubber substitution level and **(b)** the relationship between the U.P.V. values and compressive strength of concretes.

the mixture named R.C. |35-10 had a U.P.V. value of more than 4500 m/s when measured on 150-mm cubic samples and a U.P.V. value of more than 4000 m/s and less than 4500 m/s when it was measured on 70-mm cubic samples.

However, the results revealed an adverse influence of waste rubber aggregate incorporation on the U.P.V. values of the concrete. It was observed that substituting the natural aggregate with the waste rubber aggregate resulted in systematical decreases in the U.P.V. values. The main reason behind this effect is the pores led by waste rubber aggregate particles. Since the U.P.V. measurement decreases with increasing the void content of the material, substituting the natural aggregate with the waste rubber aggregate and increasing the substitution level directly reduced the U.P.V. values due to the decrease in the concrete quality. In other words, the waste rubber aggregate particles create a porous structure in the concrete, thus reducing the density of the concrete. This increases the transition time of sound waves from the transmitting probe to the receiving probe. Therefore, the lowest U.P.V. values were measured on the concrete mixtures containing 30% waste rubber aggregate. Apart from the porous structures created by the waste rubber aggregate particles, the nature of these particles absorbs such ultrasonic waves and prevents their passage. This may also decrease the passage velocity of the ultrasonic waves from one probe to another. For these reasons, increasing the substitution level of waste rubber aggregate from 0% to 10% gradually dropped the concrete quality grade from high/good quality to good/poor quality, regarding the classification Feldman gave [29].

A similar reduction in the U.P.V. values of the concretes was observed when the w/c ratio was increased from 0.35 to 0.55. Of course, the porous structure in the cement paste is caused by the high amount of water content in the concrete produced by a higher w/c ratio. The porous structures in the cement paste of such concretes result in slow propagation of the ultrasonic waves, thus decreasing the U.P.V. values. Another significant finding achieved in the current study is the relationship between the U.P.V. values measured on the 70-mm and 150-mm samples. A linear relationship with a relatively high coefficient of determination value was achieved between the U.P.V. values of the 70-mm and 150-mm cubic concrete samples manufactured in the present study (Fig. 3c). When the figure is investigated, it would be seen that the measurement taken on the 150-mm cubes yielded higher U.P.V. values. This is directly related to the frequency and amplitude of the ultrasonic waves. Therefore, it was found that the larger size of the specimen yields a more precise U.P.V. measurement.

3.2. Compressive Strength Results

The variation in the 28-day average compressive strength regarding the w/c ratio and waste rubber aggregate substitution level and the standard deviation values are shown in Figure 4a. The 28-day average compressive strength of plain concretes produced at w/c ratios of 0.35, 0.45, and 0.55 were about 60 MPa, 44 MPa, and 33 MPa, respectively. This w/c ratio-dependent dramatic decrease in the compressive strength is an expected and known phenomenon. Similarly, it has been observed that the compressive strength of concrete systematically decreases as the waste rubber content increases. One of the important reasons why waste rubber aggregate decreases the concrete strength is that it creates a more porous and voided structure in the concrete. However, it should also be stated that the difference between the modulus of elasticity of the natural aggregate-cement paste phase and that of rubber aggregate particles plays a significant role in this impact. When compressive loads are applied to concrete, natural aggregate, and cement paste, which have a relatively similar modulus of elasticity, exhibit nearly similar strains, but the waste rubber aggregate from tires, which has a much lower modulus of elasticity than

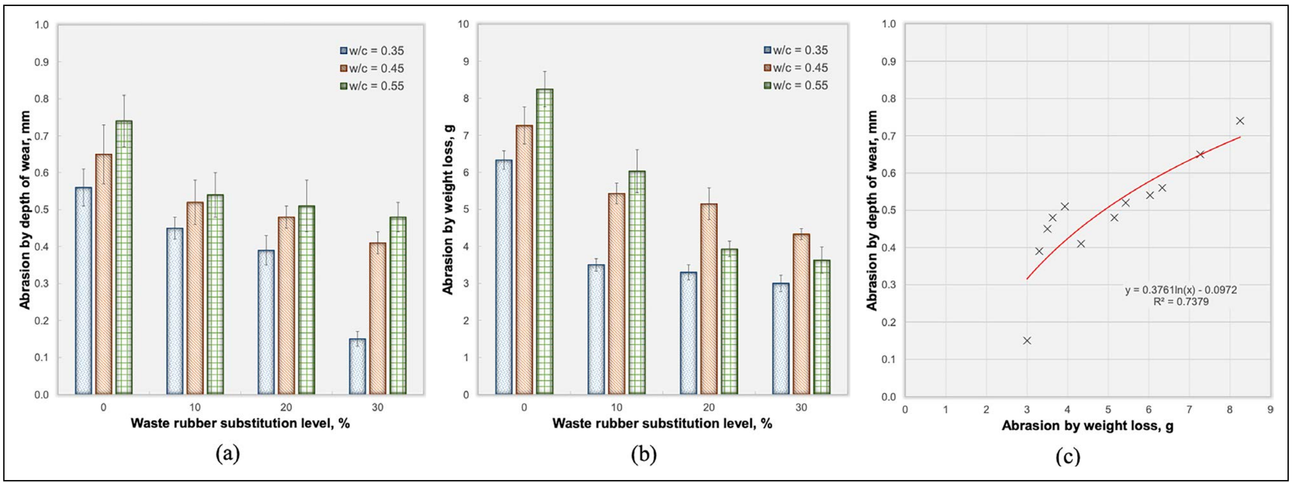

Figure 5. Variation in abrasion resistance of concretes with w/c ratio and waste rubber substitution levels in terms of **(a)** abrasion by the depth of wear, **(b)** abrasion by weight loss, and **(c)** the correlation between abrasion by the depth of wear and abrasion by weight loss.

both, shows more strain than natural aggregate and cement paste. Therefore, under loading, waste rubber aggregate particles behave as a void in the solid structure of concrete, and thereby, the concrete containing such material in its constitution will yield lower compressive strength. Besides, even though the substitution of waste rubber aggregate causes a severe decrease in the compressive strength of the concrete, it should be noted that it increases the ductility of the concrete based on the observations during the test. In addition, it should be noted that another main reason for the compressive strength decreasing effect of waste rubber aggregate is that the interfacial transition zone between cement paste and waste rubber aggregate is more significant than that formed between the cement paste and natural aggregate. Many scientists reported similar influences of waste rubber aggregate incorporation into the concrete in the literature. For example, Güneyisi et al. [17], examining the effect of waste rubber aggregate substitution level and water-binder ratio on compressive strength, reported that increasing the content of waste rubber aggregate systematically reduces the compressive strength and causes more than an 80% decrease in compressive strength for both water-binder ratios (0.4 and 0.6) at 50% substitution level. Also, Gupta et al. [19] and Lv et al. [20] reported that increasing the amount of waste tire causes a regular decrease in compressive strength. Therefore, using waste rubber aggregate after certain substitution levels does not allow concrete production for structural purposes.

Furthermore, since the U.P.V. value of concrete material is mainly related to its modulus of elasticity, and there is a strong relationship between the modulus of elasticity and mechanical properties of concrete, constructing a correlation between the U.P.V. and compressive strength can be accepted on this basis [30]. In this context, Figure 4b demonstrates the relationship between the compressive strength and U.P.V. values that were measured on 150-mm cubic samples of concrete produced in this study. A strong logarithmic correlation with a relatively high coefficient of determination value was established between the compressive strength and U.P.V. values of the concretes of the present study.

3.3. Abrasion Resistance Results

The abrasion resistance of the concretes manufactured in this study was determined using Böhme abrasive wheel test, and it was described in terms of abrasion by the depth of wear and abrasion by weight loss. In this regard, Figures 5a and 5b, respectively, show the variation in the abrasion by the depth of wear and abrasion by weight loss following the w/c ratio and waste rubber substitution level. In addition, to establish a relation between these two different abrasion descriptions, Figure 5c is presented. The lowest abrasion resistances using the depth of wear and weight loss were observed in the plain concrete mixtures (P.C. |35, P.C. |45, and P.C. |55). Among these mixtures, the lowest performance was seen in the concrete mixture produced at a higher w/c ratio. The abrasions in P.C. |35, P.C. |45, and P.C. |55 coded concretes using the wear depth were 0.56 mm, 0.65 mm, and 0.74 mm, respectively. A 30% increase in the abrasion by the wear depth was seen as the w/c ratio increased from 0.35 to 0.55.

On the other hand, the abrasions by weight loss for these concretes, respectively, were about 6.3 g, 7.3 g, and 8.3 g. A similar trend was also observed in the abrasions of the concrete mixtures when the abrasion by weight loss was considered. This is precisely related to the weak structure of cement paste formed at high w/c ratios. Weak cement paste tends to wear out quickly, while strong cement paste resists abrasion and holds together.

The results revealed that incorporating waste rubber aggregate into the concrete improved the abrasion resistance

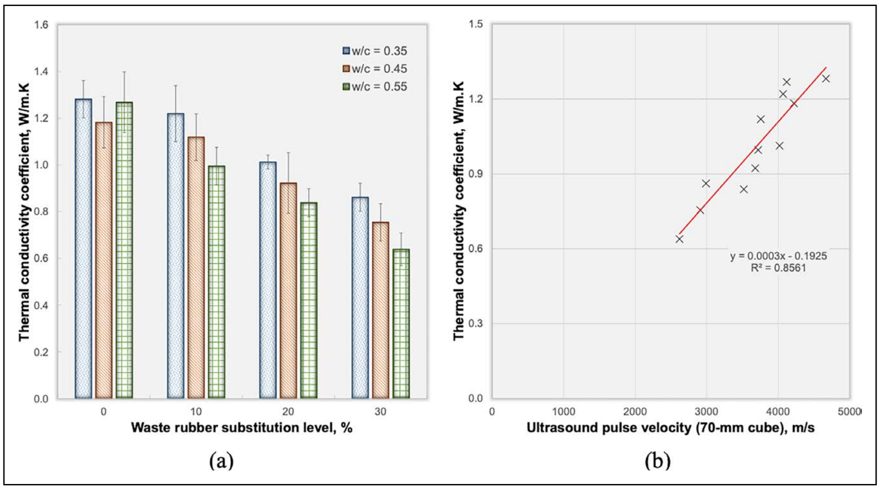

Figure 6. **(a)** Variation in the head conductivity factor of the concretes about the w/c ratio and waste rubber substitution level and **(b)** the relationship between the U.P.V. values and head conductivity factor of concretes.

of the concretes. When Figures 5a and 5b are investigated, it will be seen that the abrasions in the concrete mixtures in terms of both the depth of wear and the weight loss were enhanced as the waste rubber aggregate substitution level increased. There are two reasons for this situation: firstly, the soft nature of the waste rubber aggregate, and secondly, the light weight of the waste rubber aggregate compared to both cement paste and natural aggregate particles. The waste rubber aggregate particles, with their soft structure nature, exhibit higher abrasion resistance to the abrasive dust used in this test, and thereby, the concretes containing waste rubber aggregate yield lower abrasion values in terms of both the depth of wear and the weight loss. Besides, waste rubber, which usually wears very little, causes less mass loss due to its low unit weight when abraded. Gesoğlu et al. [31], who produced previous concretes containing waste rubber aggregate, also concluded that waste rubber aggregate positively affects the abrasion resistance of concrete. Likewise, in general, it has been reported in the studies available in the literature that waste rubber aggregate substitution improves the abrasion resistance of concrete [22, 32, 33].

On the other hand, Abdelmonem et al. [34] reported reductions of up to 47% in the abrasion resistance of concrete at 10%, 20%, and 30% in waste rubber aggregate substitution levels. Similarly, Bisht and Ramana [35] reported that using waste rubber aggregate at the level of 5% in concrete production reduces the abrasion resistance of concrete by 18%. Researchers who obtained such findings associated this situation with low adhesion between cement paste and waste rubber aggregate particles.

The relation between the abrasion by the depth of wear and abrasion by weight loss indicated a moderate logarithmic relationship between these two abrasion identification ways. By this correlation, it could be stated that using one of these abrasion descriptions, the abrasion resistance of concretes can be determined.

3.4. Thermal Conductivity Results

The variation in the thermal conductivity coefficients of the concretes according to w/c ratios and waste rubber aggregate substation levels is presented in Figure 6a. The results showed that the w/c ratio did not affect the thermal conductivity coefficients of plain concretes. However, a decrease in the T.C.C. of concretes and a noticeable effect of the w/c ratio on the T.C.C. of concretes emerged from incorporating the waste tire aggregate into the concrete. As the content of waste rubber aggregate increased, the thermal conductivity coefficient systematically decreased. By increasing the waste rubber aggregate substitution level from 0% to 30%, a decrease of 33% and 36% was observed in the T.C.C. of concretes produced at w/c ratios of 0.35 and 0.45, respectively, while a 50% reduction was seen for concrete produced at w/c ratio of 0.55. Considering the results of these experiments, it can be comprehended that the waste rubber aggregates, which reduce the T.C.C. of the concrete, have improving thermal insulation characteristics. The thermal performance properties of building elements in which waste rubbers were utilized were investigated in the study conducted by Argunhan [36]. According to the findings obtained from the test results, it was reported that the T.C.C. of the concrete produced using average aggregate was 2.075 W/m.K, while the T.C.C. of the concrete containing 30% waste rubber aggregate was 1.070 W/m.K. According to Medina et al. [33], concrete made entirely of crumb rubber-based aggregate had a much lower thermal conductivity value (0.27 W/m.K) than the reference specimen (0.65 W/m.K). Aliabdo et al. [37] obtained quantitatively similar findings, noting a thermal conductivity value of 1.45 W/m.K for traditional concrete and 0.96 W/m.K and 0.60 W/m.K for rubberized concrete with 20% and 100% rubber volume fractions, respectively.

Similarly, Turgut and Yesilata [38] reported that using rubber aggregate in concrete bricks improved thermal insulation performance by 11%, and Hall et al. [39] reported that using rubber aggregate at a 30% level led to a 28% reduction in T.C.C. This shows an inverse proportionality between the waste rubber aggregate substitution level and the T.C.C. of the concrete. This results from the rubber having a much lower T.C.C. than natural aggregate and the fact that the rubber aggregates form a porous structure in the concrete. The better thermal insulation performance of rubberized concrete can also be partly attributed to the rubber particles' hydrophobic properties and the rubber surface's inherent tendency to entrap air. Thus, porous structures are formed in rubber-containing concrete during concrete production as rubber exhibits an anti-wetting behavior, resulting in increased air entrapping within the concrete. The concrete containing more porous structures will also have a lower T.C.C. value.

On the other hand, the decrease in the thermal conductivity of concrete manufactured at a higher w/c ratio may be related to the porosity of the cement paste. The higher w/c ratio makes the paste phase more porous, resulting in higher thermal insulation performance of concrete. Therefore, it is also essential to investigate whether there is a relation between U.P.V., which indicates the integrity and porous structure of concrete, and thermal conductivity. In this context, the relationship between the T.C.C.s of concretes and the U.P.V. values measured on samples of the same size is shown in Figure 6b. As seen from the figure, there is a linear relationship with a relatively high coefficient of determination value between the T.C.C. and U.P.V. values of concretes. The standard error between the observed and fitted T.C.C. values determined by regression analysis was determined as 0.084, whereas that between the observed and fitted ultrasound pulse velocity values was computed as 238.6.

4. STATISTICAL ANALYSIS

The statistical evaluation of the experimental outputs obtained in the present study was based on general linear analysis of variance (GLM-ANOVA) and Pearson correlation coefficient analysis. The GLM-ANOVA aimed to illustrate the effectiveness of the input parameters like w/c ratio and waste rubber substitution level on the experimental outputs such as U.P.V., compressive strength, abrasion resistance, and T.C.C. In order to describe the effectiveness of the input parameters on the outputs, the analysis results were assessed based on a 0.05 level of significance (also known as P-value). In this way, it aimed to determine whether the input parameters are statistically essential parameters on the outputs; in other words, whether the experimental results of this study were obtained by chance or not were evaluated. On the other hand, the Pearson correlation coefficients were determined to show the correlation among all experimental variables, not only between the inputs and outputs. The results achieved from the GLM-ANOVA method are presented in Table 4, while that attained from the Pearson correlation coefficient analysis is given in Figure 7.

V	w/c	sl	UPV70	UPV150	f_c	A_{dw}	A_{wl}	TCC
w/c	1	0	-0.315	-0.352	-0.252	0.53	0.361	-0.321
sl	0	1	-0.895	-0.901	-0.877	-0.769	-0.813	-0.922
UPV70	-0.315	-0.895	1	0.956	0.845	0.549	0.575	0.925
UPV150	-0.352	-0.901	0.956	1	0.807	0.504	0.578	0.97
f_c	-0.252	-0.877	0.845	0.807	1	0.564	0.71	0.831
A_{dw}	0.53	-0.769	0.549	0.504	0.564	1	0.851	0.528
A_{wl}	0.361	-0.813	0.575	0.578	0.71	0.851	1	0.627
TCC	-0.321	-0.922	0.925	0.97	0.831	0.528	0.627	1

Figure 7. Correlation matrix of experimental variables (***V***: variables; ***w/c***: water-to-cement ratio; ***sl***: waste rubber aggregate substitution level; ***UPV70***: UPV values measured on 70-mm cubes; ***UPV150***: UPV values measured on 150-mm cubes; f_c: 28-day compressive strength; A_{dw}: Abrasion by depth of wear; A_{wl}: Abrasion by weight loss; ***TCC***: Thermal conductivity coefficient).

Considering the P-values given in Table 4, it can be stated that the input parameters like w/c ratio and waste rubber substitution level have a statistically significant influence on the experimental outputs of the present study. In addition, since the U.P.V. values were measured on two different-sized cubic samples, the effect of size on the U.P.V. results was also statistically assessed. It was revealed that the sample size also has statistical significance on the U.P.V. results; however, its contribution to variance in the experimental results is not as much as the other two input parameters (see the values given in the sequential sum squares column). Besides, when the contribution of the input parameters is considered, it will be seen that the waste rubber substitution level than the w/c ratio much more influenced the variance in the experimental results. Furthermore, in the last column of Table 4, the R-squared values of the statistical analysis of each experimental output are presented. These R-squared values are used to interpret the relationship of an output variable with one or more input variables by percentage. The results indicate a strong relationship between the output and input variables.

Table 4. Statistical analysis of experimental test results

Dependent variable	Independent variable	The sequential sum of squares	Computed F	P-value	Significance	R-squared
Ultrasonic pulse velocity	Sample size	258302	15.01	0.001	Yes	
	w/c ratio	902534	26.23	0.000	Yes	
	Substitution level	6842237	132.54	0.000	Yes	96.47%
	Error	292525	–	–	–	
	Total	8295598	–	–	–	
Compressive strength	w/c ratio	1110.6	13.69	0.000	Yes	
	Substitution level	13128.7	141.69	0.000	Yes	90.22%
	Error	1544.3	–	–	–	
	Total	15783.5	–	–	–	
Abrasion by the depth of wear	w/c ratio	0.068550	10.09	0.012	Yes	
	Substitution level	0.141667	13.90	0.004	Yes	91.16%
	Error	0.020383	–	–	–	
	Total	0.230600	–	–	–	
Abrasion by weight loss	w/c ratio	5.7726	7.80	0.021	Yes	
	Substitution level	23.3500	21.03	0.001	Yes	92.91%
	Error	2.2208	–	–	–	
	Total	31.3434	–	–	–	
Thermal conductivity coefficient	w/c ratio	0.051491	7.88	0.021	Yes	
	Substitution level	0.417699	42.63	0.000	Yes	95.99%
	Error	0.019597	–	–	–	
	Total	0.488787	–	–	–	

On the other hand, the relationship between all variables can be comprehended by interpreting the correlation values presented in Figure 7. The negative values in the figure show the inverse relationship between the compared variables, whereas the positive values indicate the direct relationship. In this context, it can be stated that there is a strong inverse relationship between the waste rubber substitution level and the experimental outputs. However, it should be stated that this negative correlation between the waste rubber substitution level and abrasion by the depth of wear and weight loss is just a mathematical demonstration. An increase in waste rubber substitution level decreases the abrasion by the depth of wear and weight loss, not abrasion resistance. Besides, it can be stated that there is a strong positive correlation between the T.C.C. and U.P.V. values.

Similarly, the correlations between the T.C.C. and compressive strength can be meaningful. The same conclusion can be made about the correlation between U.P.V. and compressive strength. However, the interaction between the compressive strength and abrasion resistance achieved in the current study is moderate.

5. CONCLUSION

Following the findings presented above, the following conclusions can be drawn:

- The waste rubber aggregate substitution level and the w/c ratio significantly influence the U.P.V. of concrete: U.P.V. decreased as they increased. Besides, the results showed that the U.P.V. values were size-dependent; however, a significant linear relationship was found between the U.P.V. values measured in different-sized samples.
- The results revealed that the waste rubber substitution with a level of 10% resulted in a severe strength loss; however, although reducing the w/c ratio led to a slight increase in the compressive strength, it cannot be considered a complete remedy for the negative influence due to waste rubber aggregate substitution. Instead of decreasing the w/c ratio, the pozzolanic materials may be included in producing such concretes to improve their strength characteristics.
- On the other hand, waste rubber aggregate incorporation improved the abrasion resistance of concrete. As expected, concretes produced at higher w/c ratios exhibited lower abrasion resistance.

- No significant effect of the w/c ratio on the T.C.C. of plain concrete was observed. However, when waste rubber aggregate was included in the concrete, it was noticed that the w/c ratio was effective on T.C.C.
- A statistically strong relationship was observed between the T.C.C. and U.P.V. values of the plain and rubberized concretes.
- The statistical analysis showed that the experimental parameters, such as the w/c ratio and the waste rubber aggregate substitution level, had a statistically significant effect on the studied properties.
- The Pearson correlation coefficient analysis achieved a strong inverse correlation between the waste rubber substitution level and the studied properties. Furthermore, it showed strong positive correlations between T.C.C. and U.P.V. values, between T.C.C. and compressive strength values, and between U.P.V. and compressive strength values.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

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