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A review on mechanical and durability properties of concrete with waste rubber aggregate

Atık kauçuk agregalı betonların mekanik ve durabilite özellikleri üzerine bir inceleme

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Abstract

This study examines the use of rubber particle (RP) recycled from waste vehicle tires, which is one of today's most serious environmental problems in concrete. For this purpose, studies on rubber aggregate concrete (RAC) were compiled and analyzed. The physical, mechanical and durability properties of RAC were investigated. When the results were analyzed, the addition of rubber decreased the compressive and flexural strength, and the modulus of elasticity. The porosity percentage, water absorption, sorptivity and water permeability of RAC generally increased with increasing rubber percentage and rubber size. The addition of rubber aggregate to the concrete increased the toughness of the concrete up to 3 times because of the energy absorbing property of the rubber particles (RPs). Besides, the addition of rubber had positive effects on the properties of concrete such as abrasion resistance and freeze-thaw resistance. The drying shrinkage of RAC varies depending on the percentage, size and stiffness of RPs. The findings reveal that less than 10% of RPs should be used in concrete for structural applications where strength is important.

Keywords: Waste vehicle tires, Physical, Mechanical and durability properties, Recycling, Rubber aggregate concrete.

Öz

Bu çalışma günümüzün en önemli çevresel problemlerinden biri olan atık araç lastiklerinden geridönüştürülmüş kauçuk parçacıklarının betonda kullanımını incelemektedir. Bu amaçla kauçuk agregalı beton (RAC) üzerine yapılmış çalışmalar derlenmiş ve analiz edilmiştir. RAC'lerin fiziksel, mekanik ve durabilite özellikleri araştırılmıştır. Sonuçlar analiz edildiğinde; kauçuk ilavesi RAC'nin basınç ve eğilme dayanımını ve elastisite modülünü düşürmektedir. RAC'nin boşluk yüzdesi, su emmesi, kılcallığı ve su geçirimliliği kauçuk yüzdesi ve kauçuk boyutunun artışıyla genel olarak artmıştır. Enerji sönümleme özelliğinden dolayı betona kauçuk parçacıklarının agrega olarak ilavesi betonun tokluğunu 3 katına kadar çıkarmıştır. Bunun yanı sıra betonun aşınma direnci ve donma-çözülme direnci gibi özelliklerinde kauçuk parçacıklarının ilavesi olumlu etkiler yapmıştır. RAC'nin kuruma büzülmesi kauçuk parçacıklarının yüzdesine, boyutuna ve rijitliğine bağlı olarak değişmektedir. Elde edilen bulgular; dayanımın önemli olduğu yapısal uygulamalar için kauçuk parçacıklarının betonda %10'dan daha az kullanılması gerektiğini ortaya koymaktadır.

Anahtar kelimeler: Atık araç lastikleri, Fiziksel, Mekanik ve durabilite özellikleri, Geridönüşüm, Kauçuk agregalı beton.

1 Introduction

As a result of industrialization and production in the world, environmental wastes are one of the main problems of both developed and developing countries today. Especially today, the large amount of waste tire rubber causes environmental pollution as well as a serious threat to public health. Some of these waste tires are used as a different fuel in cement factories and power plants. Today, many studies are carried out to use waste tire rubber as a recycling material in the construction and transportation sector. A lot of work has been done on the use of these waste materials in concrete, either by replacing aggregates or replacing them with cement. It is generally used as an asphalt additive on highways, as an aggregate in concrete, as an energy absorber on the sides of the docks in ports, and as a concrete barrier on highways by being added to concrete due to its energy absorption feature.

The workability of RAC produced with rubber fibers gradually reduces with increasing rubber content [1]. It was concluded that the slump of concrete decreases with the addition of waste RPs to concrete [2]. Ozbay et al. (2011) used cement and blast furnace slag as a binder in concrete and produced RAC samples by substituting part of fine aggregate with crumb rubber at 5%, 15% and 25% by volume. It was concluded that the slump value of the RACs declined with the increasing crumb rubber content [3]. Similar results were found by Al-Mutairi et al. (2010) [4]. However, Aiello and Leuzzi (2010) found that the slump of RAC produced by substituting coarse and fine aggregates with RPs in certain proportions is higher than that of the reference concrete (RC) [5].

According to Issa and Salem (2013); a good compressive strength is achieved when the use of recycled crumb rubber as fine aggregate in concrete is less than 25%. Significant decreases were observed in the compressive strength of RAC when it is used at more than 25% [6]. Güneyisi et al. (2004) investigated the mechanical properties of RACs with and without silica fume. The compressive strength decreases due to the increasing RP content [7]. Ganjian et al. (2009) stated that the compressive strength of RACs decreased with increasing RP percentage [8]. Freitas et al. (2009) showed that the use of waste rubber at a rate of 15% by volume in concrete reduces the compressive strength of RAC by 48% [9].

Boudaoud and Beddar (2012) produced RAC by substituting normal aggregates with RPs at certain proportions in concrete. It has been shown that the flexural strength of the RACs reduced substantially with increasing RP percentage [10]. Liu

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et al. (2015) determined that the flexural strength of RACs obtained by using 10%, 20% and 30% RPs in concrete decreased up to 19.4% [11]. Lv et al. (2019) used cement and fly ash as binders and produced RAC samples by replacing fine aggregate with RPs. It has been determined that there is a linear decrease in the flexural strength of RAC with increasing RP content, and there is a 41% decline in the 28-day flexural strength at 50% replacement [12].

Gupta et al. (2014) carried out various experiments on 2 different concrete mixtures containing rubber ash and rubber ash + rubber fiber. As a result of these experiments, the elasticity modulus of the concretes containing both rubber ash and concretes containing rubber ash + rubber fiber was lower than the RC. The modulus of elasticity of the reference mixture was found to be 27.55 GPa for water/cement (w/c) ratio of 0.45, while that of the RAC containing 20% rubber ash was found to be 24.74 GPa. A similar decrease was found in the dynamic modulus of elasticity. Many studies support that the addition of rubber to concrete brings about a decrease in the modulus of elasticity of concrete [13].

One of the most important features of RAC is its high toughness. Therefore, studies on its use as a concrete barrier on highways due to its energy-absorbing feature are continuing. Atahan and Sevim (2008) examined the energy absorption capacity of RAC with RPs and found that the energy absorption capacity of RAC samples containing 20% waste rubber was 46.14% higher than that of the RC. The energy absorption capacity of the RAC samples containing 100% waste RPs was 186.82% higher than the RC [14]. Tantala et al. (1996) revealed that the RAC samples made by substituting coarse aggregate with RPs at 5% and 10% by volume exhibited higher toughness than the RC [15]. Topçu and Avcılar 1997(a,b) proposed the use of RACs where vibration damping is required. They also stated that the impact resistance of RAC increases with the addition of RP to the concrete [16],[17]. Similar findings were found by Eldin and Senouci (1993) [18].

RAC with lower unit weight was obtained with the addition of RPs to the concrete. Pelisser et al. (2011) stated that the addition of RPs substantially affects the density of the concrete. The density of RACs containing RPs decreased by 13% in comparison the density of RC [19]. Mohammed et al. (2012) produced a lightweight to mediumweight hollow concrete block with crumb rubber depending on rubber percentage. In addition, there is a little decline in the density of the concrete by replacing the cement with silica fume at certain rates [20]. Gupta et al. (2014) investigated the effect of using RP instead of fine aggregate on the mechanical and durability properties of concrete. In the study, it was found that the density of the concrete decreased by adding rubber ash or rubber fibers into the concrete. The density of both rubber ash-based concretes and concretes containing rubber ash+rubber fiber decrease with increasing rubber percentage for 0.35, 0.45 and 0.55 w/c ratio [13]. Similar results were found by Bravo and Brito (2012) [21].

One of the most significant parameters influencing the service life of concrete is its resistance to environmental effects. Properties such as freeze-thaw and permeability are extremely important in terms of affecting the durability of concrete. Savas et al. (1997) investigated its resistance to environmental effects. Properties such as freeze-thaw and permeability are extremely important in terms of affecting the durability of concrete. Savas et al. (1997) performed an experimental study on the fast freeze-thaw durability of RACs. Various RAC samples were obtained by replacing cement with ground RPs at 10%, 15%, 20% and 30% by weight. RACs containing 10% and 15% ground waste tire rubber showed durability performance higher than 60% compared to the RC. However, it was determined that RACs containing 20% and 30% ground waste tire rubber could not meet the conditions specified in the ASTM C 666, Procedure A standard [22]. Topçu and Demir (2007) subjected concrete samples to 30 freeze-thaw cycles to investigate the durability properties of RACs containing RP in various proportions. They stated that RPs can be used instead of aggregate in structures where durability is important but strength is not [23]. The use of RPs in concrete as an alternative to air entrainment was investigated to provide freeze-thaw resistance in concrete. The findings have shown that RPs can be utilized to provide freeze-thaw resistance in concrete [24].

In this study, the effects of various types of RPs added into concrete as aggregates on the mechanical and durability properties of concrete were compiled and analyzed. The effect of using from 0% to 30% rubber on the slump, compressive strength, flexural strength, modulus of elasticity, porosity, unit weight, water absorption, sorptivity, water permeability, freeze-thaw and abrasion resistance of concrete was studied. The effect of using rubber from 0% to 100% on the toughness and drying shrinkage of concrete was investigated. All results were compared and analyzed.

2 Content of tire and classification of waste tire rubber

Tire is a composite material consisting of rubber (natural and synthetic rubber), carbon black, steel fiber and other inorganic materials. Rubber and carbon black make up the majority of the tire content. Table 1 shows the typical chemical composition of tires. As it can be seen from Table 1, natural and synthetic rubber usually make up 40%-55% by weight of the tire. The carbon black ratio generally varies between 25%-30% by weight. Carbon black content can be up to 40% of the weight of the tire [35]. Besides, steel can be found up to 15% by weight in waste tire. The chemical composition of RPs obtained from waste tires is shown in Table 2. According to this; carbon (C) is the most abundant element in RPs and can reach up to 92%. In addition, elements such as oxygen (O), sulphur (S), zinc (Zn), magnesium (Mg), aluminum (Al), silicon (Si), nitrogen (N), hydrogen (H) and ash can be found at certain percentages in RPs. Figure 1 shows the recycling process of waste tire as aggregate. Waste tire passing through many stages turns into various waste products as chips rubber, granule rubber and powder rubber. In addition, steel and textile are also separated in the recycling process of waste scrap tires. Tires are classified in various ways according to their size. Car tires, truck tires, bus tires, tractor tires, heavy-duty vehicle tires and bicycle tires are among the general tire types. Car and truck tires are the leading waste tire rubbers.

In general, waste tire rubber used in concrete is divided into 3 classes as chipped rubber, crumb rubber and ground rubber.

1) Chipped/shredded rubbers are generally replaced by coarse aggregate. It is necessary to shred the tire in two steps to produce this rubber size. At the end of the first step, 300-430 mm long and 100-230 mm wide rubber is obtained. In the second step, the particles obtained at the end of the first stage are cut and their size is reduced by 100-150 mm. If fragmentation is gone on, particles of 13-76 mm are obtained and are named as shredded particles [8],

Tablo 1. Typical chemical composition of tires.

References	Natur. and synt. rubber	Carbon black	Steel	Sulphur	Ash	Acetone	Organic mat.	Additives
[25]	40-55	30-38	-	≤ 5	3-7	10-20	-	-
[26]	40-55	20-25	-	-	-	-	-	20-40
[27]	51	25	-	-	-	-	-	24
[28]	45	28	13	-	-	-	-	14
[29]	57.1	27.4	-	-	7.2	8.3	-	-
[30]	55	30	-	1	-	-	-	14
[31],[32]	45.2	25.8	-	-	0.9	14.2	-	13.9
[33],[34]	56.05	28.43	-	-	5.11	9.85	-	0.56
[8]	41	28	14-15	-	-	-	-	16-17
[35]	45	40	-	-	-	-	15	-
[36]	38.3	31.3	-	3.23	5.43	7.3	-	14.44
[37]	44.6	30.7	-	0.5	4.2	16.9	-	3.1

Tablo 2. Chemical composition of RPs from waste tire.

Reference	C	O	S	Zn	Mg	Al	Si	Na	Ga	N	H	Polymer	Ash	Org.
[38]	87.5	9.24	1.07	1.77	0.14	0.08	0.2	-	-	-	-	-	-	-
[39]	31.3	-	3.23	-	-	-	-	-	-	-	-	38.3	5.43	-
[13]	87.51	9.23	1.08	1.76	0.14	0.08	0.2	-	-	-	-	-	-	-
[40]	40	-	-	-	-	-	-	-	-	-	-	45	-	15
[25],[41]	30-38	-	0-5	-	-	-	-	-	-	-	-	40-55	3-7	-
[42]	83.2	1.89	1.58	-	-	-	-	-	-	0.39	7.32	-	-	-
[43]	91.5	3.3	1.2	3.5	-	-	-	0.2	0.1	-	0.2	-	-	-

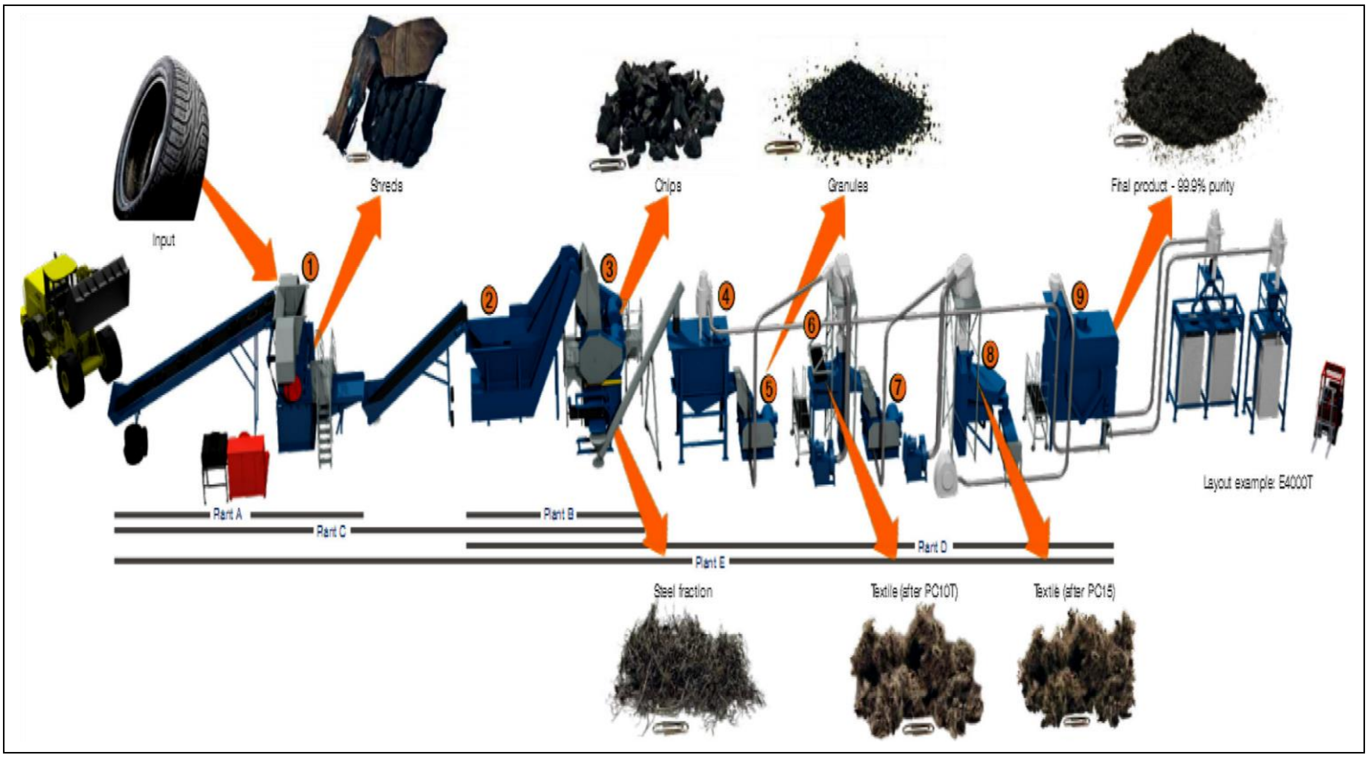

Figure 1. Recycling process of waste tire as rubber aggregate [44].

2) Crumb rubber replaced by fine aggregate (sand) is produced by special mills where big RPs are turned into smaller RPs. Different sizes of RPs can be produced depending on the type of grinders used in this process and the production temperature. By a simple method, RPs are produced with high irregularity ranging from 0.425 to 4.75 mm [8],
3) The reduction in the size of ground rubber that can replace cement depends on the equipment used. Used tires are generally exposed to two steps, magnetic separation and screening. Rubber fractions of various sizes are obtained in more complex operations. The sizes of the particles obtained in micro grinding processes vary in the range of 0.075-0.475 mm [8]. Figure 2 shows the types of waste tire rubber used in RAC.

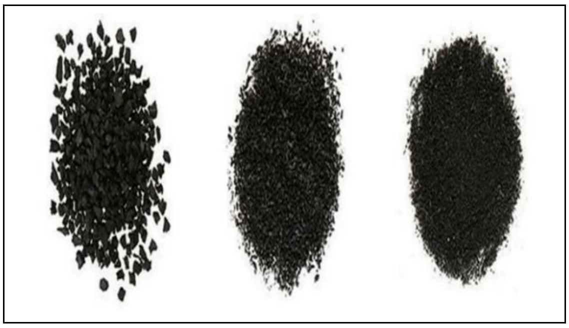

Figure 2. Types of waste tire rubber used in concrete [45].

3 Research and analysis of studies in the literature

3.1 Slump

When the slump values in Figure 3 are examined, it has been observed that increasing the RP percentage generally reduces the slump of the concrete. In the study conducted by Topçu and Demir (2007), the decrease in slump value in RACs containing 30% RPs was 8.52%, while Lv et al. (2015) found the decrease in slump value in RACs containing the same rubber percentage as 9.30% [23],[46].

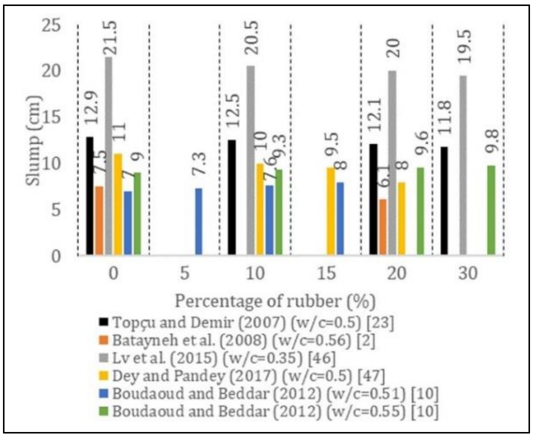

Figure 3. Slump value of RACs.

Similar findings were found by other researchers. However, Boudaoud and Beddar (2012) found that the addition of RPs to the concrete made with two different w/c ratios increased the slump of the concrete between 8% and 14% [10]. Yildirim and Duygun (2017) stated that the slump of the concrete increased with the addition of waste electrical cable rubber to the concrete. It has been stated that it significantly reduces the cohesion in concrete due to the round shape and hydrophobic properties of the waste electrical cable rubber and causes an increase in the slump [48]. These results are supported by other results in the literature [49]-[51]. While water absorption of plastic aggregates is effective on the increase and decrease in slump, Yildirim and Duygun (2017) drew attention to the decrease in cohesion that occurs in case of excess water in the mixture, in addition to water absorption [48].

Figure 4 shows the relationship between the percentage of rubber in RAC and the slump value. There is a very powerful relationship between the slump and the rubber percentage.

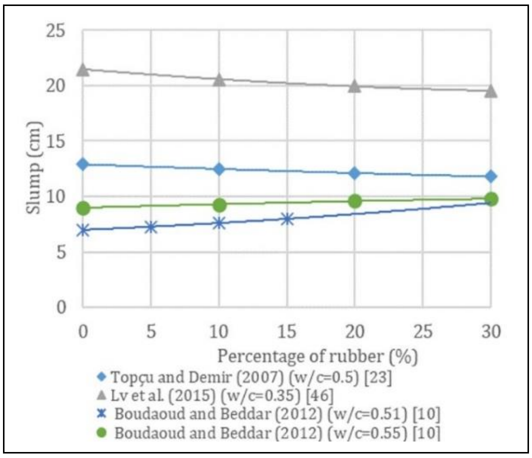

Figure 4. Relationship between percentage of rubber and slump value.

3.2 Compressive strength

The compressive strength of RACs with different rubber percentages is shown in Figure 5.

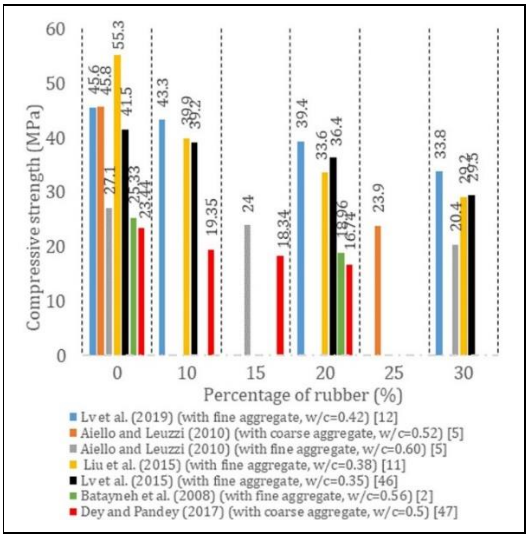

Figure 5. Compressive strength of RACs.

The compressive strength of RACs with 10%, 15%, 20% and 30% rubber percentage were found to be 13.97%, 16.60%, 23.77% and 31.68% lower on average compared with the RC, respectively. When the results in Figure 5 were analyzed, it was determined that the compressive strength of RACs decreased between 25.8% and 47.1% with the increase of rubber amount from 0% to 30%. Besides, it can be understood from Figure 5 that there is a decrease in the compressive strength of RAC produced by replacing fine aggregate or coarse aggregate with RPs. When the results are evaluated as a whole, it is estimated that the decline in the compressive strength of RAC is due to the weak bond between the cement matrix and RPs. Gerges et al. (2018) aimed to produce 4 different concrete quality classes as 30 MPa, 35 MPa, 40 MPa and 50 MPa. They used waste rubber powder in concrete by replacing fine aggregate (sand) with waste rubber powder at 5%, 10%, 15% and 20%. In the case of adding 20% of waste rubber powder to the concrete classes of 30 MPa, 35 MPa, 40 MPa and 50 MPa, the compressive strength of the RACs decreased by 70.5%, 63.3%, 62.5% and 63.3% compared to the RC, respectively [52]. Ling (2011) determined that when the sand is replaced by RPs varying in size of 1-5 mm at a rate of 30% by volume, the 28-day compressive strength of RACs with 0.45, 0.50 and 0.55 w/c ratios decrease by 48.7%, 37.7% and 52.7%, in turn. Besides, it was suggested in that study that the waste rubber percentage in concrete blocks should not go beyond 10% and 40% by volume for structural applications and non-structural applications, respectively [53].

Figure 6 shows the relationship between the percentage of rubber in RACs and the compressive strength. This strong relationship indicates that as the percentage of RP increases the compressive strength of RAC decreases.

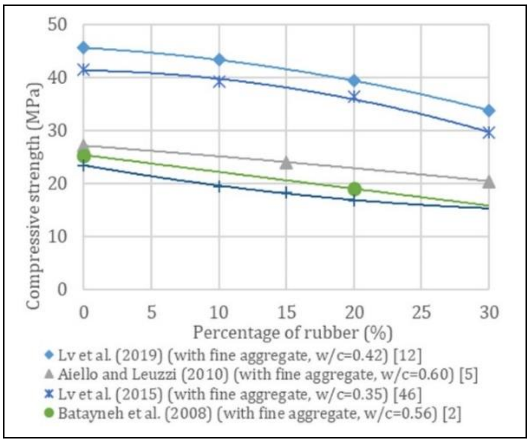

Figure 6. Relationship between percentage of rubber and compressive strength.

3.3 Flexural strength

In Figure 7, the flexural strength of RACs containing various percentages of waste rubber aggregate is shown. When the results are examined, it is seen that the flexural strength of RAC decreases with increasing rubber percentage in all studies. It is seen that there is a decrease between 19% and 23.7% in the flexural strength of RACs containing 30% RPs compared to RC. The average decrease in flexural strength of RACs containing 10%, 15%, 20% and 30% RPs was found to be 6.15%, 7.95%, 16.31% and 21%, respectively. In addition, decreases in flexural strength were observed in both RACs produced by replacing coarse or fine aggregate with RP at certain rates. It is also seen from the available data that the average decrease in flexural strength with increasing RP percentage is less than that of compressive strength. Feng et al. (2019) added waste RPs of 0.85 mm size to the concrete by replacing sand with RPs at 10%, 20%, 30%, 40% and 50%. The flexural strengths of RACs with 10%, 20%, 30%, 40% and 50% waste rubber percentage were found to be 9.7%, 17.4%, 19.8%, 27.5% and 37.7% lower than the flexural strength of the RC, respectively. It was found that RAC with 30% rubber percentage had the highest deformation [54]. Bisht and Ramana (2017) replaced the fine aggregate with 0.6 mm waste RPs at a rate of 4%, 4.5%, 5% and 5.5% by weight. It was found that the flexural strength of RACs with 4%, 4.5%, 5% and 5.5% rubber percentage by weight were 2.9%, 7.4%, 14.9% and 16.5% lower than that of the RC, respectively. In addition, it was stated that the irregularity of the shape of the waste RPs used in that study harmed the adherence between the waste RPs and cement paste [55].

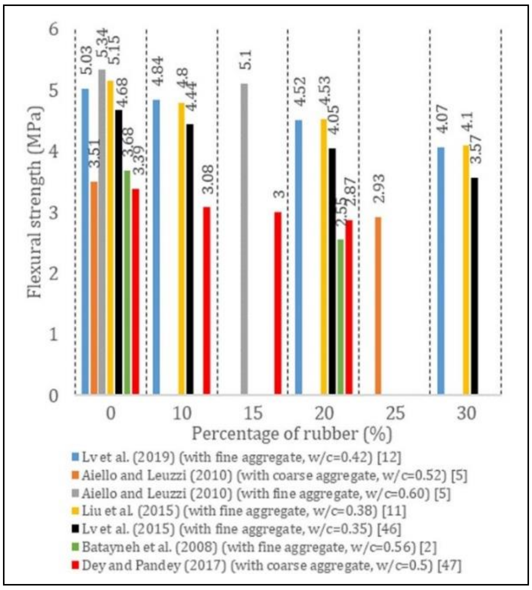

Figure 7. Flexural strength of RACs.

In Figure 8, the strong relationship between the percentage of rubber in RAC and the flexural strength is shown. The flexural strength decreases with the increase of rubber percentage.

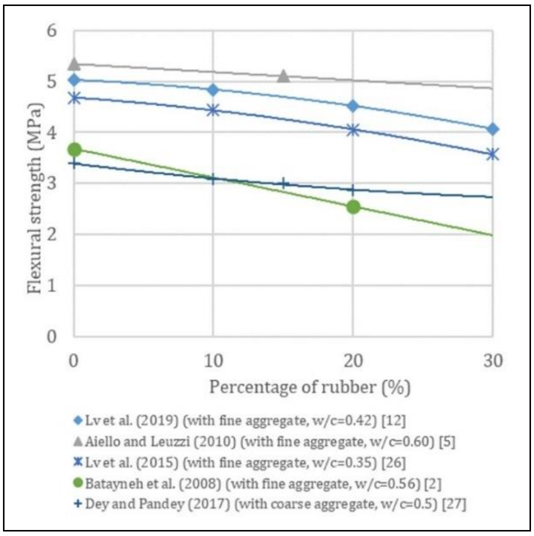

Figure 8. Relationship between percentage of rubber and flexural strength.

3.4 Unit weight

In Figure 9, the unit weights of the RACs containing various percentages of waste rubber aggregate are shown. As it can be understood from the results in Figure 9; In general, it was determined that the unit weight of the RC varies between 2300 kg/m³ and 2450 kg/m³. The unit weights of RACs with 10%, 15%, 20%, 25% and 30% rubber percentage are respectively 2.20-10.63%, 2.42%-12.54%, 4.53%-14.07%, 2.87%-16.07% and 4.98%-9.34% lower compared to the RC.

However, Lv et al. (2015) reduced the unit weight of concrete up to 1820 kg/m³ by using lightweight aggregate. The unit weight of the RAC decreased by 27.4% compared to that of the RC as a result of the 100% replacement of the fine aggregate with the recycled RPs and decreased to 1321 kg/m³ [46]. A reduction of up to 16% was achieved in the unit weight of RAC containing 25% rubber aggregate. As the amount of rubber aggregate increased, the unit weight of all RACs decreased. In addition, the decline in the unit weight of the RAC produced by the replacement of the coarse aggregate with the RPs is higher than the decline in the unit weight of the RAC produced by the replacement of the fine aggregate with the RPs due to higher specific gravity of coarse aggregate.

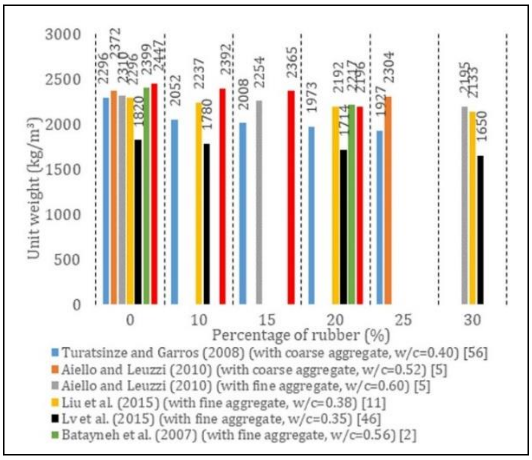

Figure 9. Unit weight of RACs.

3.5 Modulus of elasticity

In Figure 10, the modulus of elasticity of RACs containing different percentages of waste rubber aggregate is shown. As the amount of rubber aggregate increased, the modulus of elasticity of the RAC decreased. While the decrease in the modulus of elasticity of RAC containing 5% rubber aggregate was 2.4% on average compared with the RC, the decrease in the modulus of elasticity of RAC containing 30% rubber aggregate increased to 31.6% on average. The highest decrease in the modulus of elasticity was found in the study by Liu et al. [11] with 51.2%. Increasing the percentage of RP helps to increase the inelastic deformation capacity of the concrete and contributes to the more ductile mode of the concrete. It has been determined that a reduction of 27.7% in the modulus of elasticity of the concrete occurred with the 15% replacement of the waste electrical cable rubber with the fine aggregate in the concrete [48].

3.6 Toughness

One of the most important advantages of RAC is that it has generally more toughness than normal concrete. Figure 11 shows the increase in toughness of RACs containing various percentages of RPs. When these results are examined, the increase in toughness of RAC containing 15% rubber aggregate is between 17% and 25%, while the increase in toughness of RAC consisting of 100% rubber aggregate reaches 187%. The 100% replacement of the coarse and fine aggregate with the RP has increased the toughness of the concrete approximately 3 times. İt is seen that the replacement of rubber with coarse aggregate or fine aggregate or both increases the toughness. Similar results were found by many researchers that rubber aggregate increases the toughness of RAC [61],[62].

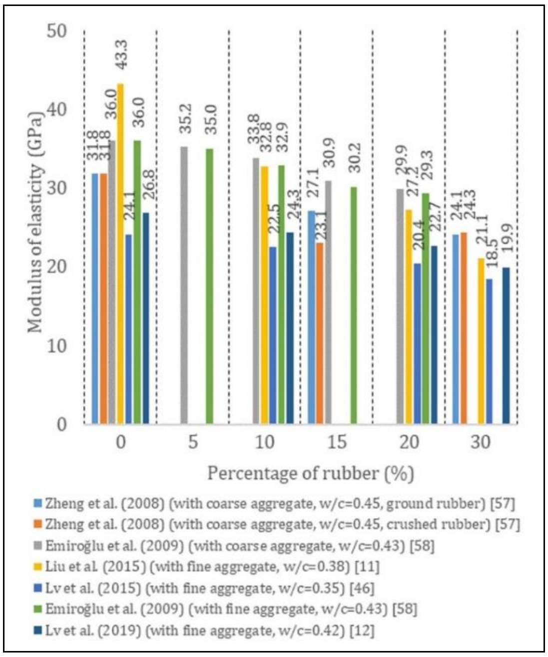

Figure 10. Modulus of elasticity of RACs.

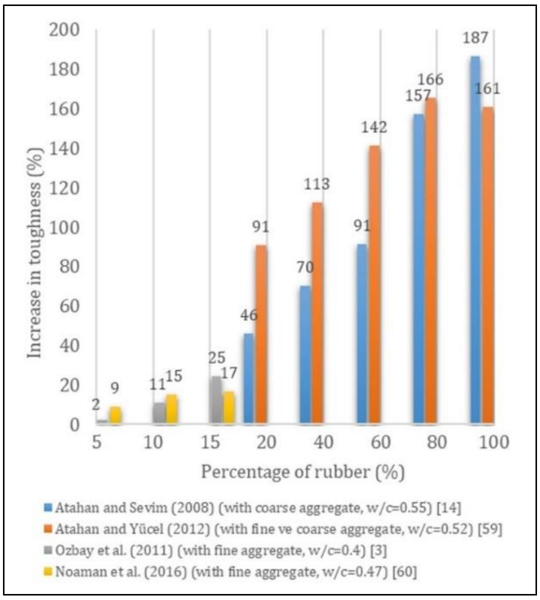

Figure 11. Increase in the toughness of RACs.

However, there are some studies stating that the addition of RPs to concrete reduces the toughness of concrete [30],[63]-[67]. Rubber aggregate was added to the concrete by replacing the waste iron ore as aggregate in concrete with rubber at the rate of 0%, 10%, 20%, 30% and 40% by volume. It has been found that RPs cause about 50% reduction in fracture toughness of concrete. It has been stated that this decrease may be caused by the increasing porosity of concrete with increasing RPs. It has been explained that the poor interface between the cement paste and the RPs allows a crack to develop easily around the RPs [63].

Nematzadeh and Mousavimehr showed a reduction in the toughness of RAC by up to 48% when fine aggregate is replaced with RPs at 7.5% and 15% by volume [30]. Mousavimehr and Nematzadeh found that the toughness of RACs containing 15% and 30% rubber aggregate decreased by 47% and 57% compared to the RC, respectively [64]. Medina et al. used RPs instead of coarse aggregate at a rate of 0%, 20%, 40%, 60%, 80% and 100% by volume. While the toughness of RC without rubber was found to be 6970 kJ, the toughness of RACs containing 20%, 40%, 60%, 80% and 100% rubber aggregates changed by -21.1%, -62.6%, +2.2%, -78.6% and -74% compared to the RC, respectively [65]. Chaikaew et al. added the RPs to the concrete by replacing the fine aggregate with RPs at 10% and 20% by volume. The flexural toughness of the RC was found to be 1.80 N.m. The flexural toughness of RACs containing 10% and 20% rubber aggregate decreased by 14.4% and 23.3% compared to the RC, respectively [66].

3.7 Freeze-thaw resistance

Freeze-thaw resistance, which is one of the most important factors affecting the durability of concrete, has a significant effect on the predicted service life of reinforced concrete structures. In addition to its mechanical properties such as compressive strength, tensile strength, and modulus of elasticity, freeze-thaw resistance is also measured to determine the long-term performance of concrete. Gesoglu et al. (2014) studied the mechanical properties and freeze-thaw resistance of pervious RACs using two different rubber types. 240 and 300 freeze-thaw cycles were performed. No clear difference was observed between the performance of the pervious RAC and the performance of RC without rubber aggregate, up to 240 cycles. However, a mass loss of up to 34% occurred in concretes without rubber aggregate at cycles of more than 300 cycles. It has been found that RPs significantly increase the freeze-thaw resistance of concrete [68].

Si et al. (2017) investigated the durability properties of RACs and mortars produced with RPs exposed to sodium hydroxide (NaOH) solution. The RPs were added to the concrete by replacing at 15%, 25%, 35% and 50% with fine aggregate. After 246 freeze-thaw cycles, mass loss and decrease in dynamic elasticity modulus decreased in RAC. This decrease is even more evident in RAC samples produced with RPs exposed to NaOH solution. It has been stated that the addition of RPs increases the freeze-thaw resistance of concrete [69].

The progress in the freeze-thaw resistance of the RAC is ascribed to the air gaps created by the RPs in the concrete [70]-[73]. Freeze-thaw resistance of RAC increases with increasing RP percentage due to the flexible properties of RPs. Richardson et al. found that after 70 freeze-thaw cycles, a mass loss of 0.6% and 0.07% occurred for concrete with natural aggregates and RAC with rubber aggregate, respectively [70].

Pham et al. studied the effect of improving RPs on the freeze-thaw resistance of RAC. After 200 freeze-thaw cycles, the RC without RPs, RAC with untreated rubber aggregate, and RAC with rubber aggregate coated with copolymer showed a mass loss of 4.1%, 0.5% and 1.5%, respectively. RAC produced with untreated RPs showed the best performance in freeze-thaw performance [73]. Wang et al. (2019) stated that RPs with low elasticity can be deformed more easily compared to natural aggregate and therefore, volume shrinkage increases in RAC. Concrete mixes containing polypropylene fibers and 15% RPs restricted the expansion due to freeze-thaw cycles and the expansion was similar to that of the RC. In addition, the release of internal stresses due to the expansion of the RPs provided freeze protection to the RAC [74]. Assaggaf et al. explained that the use of RPs in appropriate amounts and gradation in concrete is a good option to prevent damage caused by freeze-thaw [75].

3.8 Porosity, water absorption, sorptivity and water permeability

Percentage of porosity, water absorption, sorptivity and water permeability are factors that significantly affect the durability of concrete. Low porosity ratio, low water absorption, low sorptivity and low water permeability significantly increase the durability performance of concrete. Many researchers have investigated the effect of RP on the porosity percentage, water absorption, sorptivity and water permeability of RAC. In most of the studies, it was stated that the water absorption of the RAC increases with increasing RP content [76]-[81]. The amount of voids in the concrete increased with the increase of RPs, which increased the water absorption of the RAC [55],[78],[82],[83].

Besides, the percentage and size of RPs are important parameters on the water absorption of RAC. It was replaced the coarse aggregate with chipped RP up to 10% and found that the water absorption of the RAC increased with the increase of chipped RP. However, it was determined that the water absorption of the RAC produced with powder rubbers replaced by cement decreased. However, it has been determined that the presence of cracks during oven drying in concrete samples causes the RAC to absorb more water [8]. The effect of RP percentage on the water absorption values of RAC was investigated. The 28-day water absorption of RACs containing crumb RP from 0% to 20% with an increase of 2.5% is shown in Figure 12.

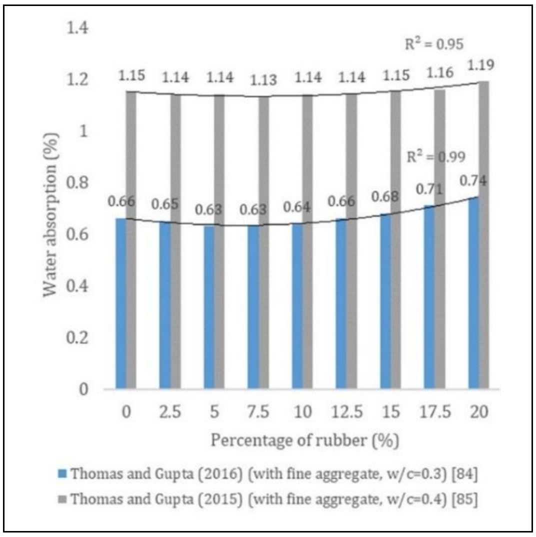

Figure 12. Water absorption of RACs.

When the studies are examined as a whole; Adding rubber up to 10% to the concrete caused a partial decrease in the water absorption of the RAC. However, it is seen that the addition of more than 10% rubber crumb increases the water absorption of the RAC. For this reason, it can be said that 10% rubber percentage is critical for the water absorption of RAC. Increasing the w/c ratio also increased the water absorption. The correlation coefficient between rubber content and water absorption varies between 0.95 and 0.99. Gheni et al. stated that there is a nearly linear relationship between the water absorption of concrete and the percentage of RP [82].

It was determined that the addition of RPs to the cement paste reduces the capillary water absorption of the cement paste and this is due to the lack of water absorption of the RPs [86]. In addition, It was investigated the water absorption of RAC samples containing crumb rubber after they were kept in magnesium sulfate ($MgSO_4$) solution for 91 and 182 days. They stated that keeping the RACs in MgSO4 solution increases the water absorption of these concrete and at the same time, the waiting time in the solution causes an increase in the water absorption values [85]. Su et al. (2015) stated that RAC with RPs of different sizes with good gradation showed better water absorption performance than RAC with one-dimensional RPs [87].

It was investigated the effect of the percentage and size of RP on the sorptivity of concrete. While the sorptivity height of the RC without rubber aggregate was 1.71 mm, the sorptivity height of the RAC containing 30% rubber aggregate was found to be 1.04 mm. As the percentage of rubber increased, the sorptivity of RAC generally decreased [88]. Similar trends have been found by other researchers [86],[89]. This situation can be clarified for the following reasons. Due to the hydrophobic properties of the rubber, the contact angle between the RPs and the cement paste is more than 90, which causes a decrease in the repulsion power of the water. Another reason is that RPs increase the curvature and length of the capillary channels, preventing water and ion ingress into the RAC samples [90]. In addition, the sorptivity height (1.06 mm) of RAC produced with RPs of 2-4 mm size was found to be lower than the sorptivity height (1.22 mm) of RAC produced with RPs of 0-0.3 mm size [88].

Sambucci et al. used completely ground tire rubber (GTR) particles instead of sand in the mortar. Two different mortar mixtures with rubber aggregates were produced: A singly-sized rubber mortar mixture (SSM) containing 100% GTR powder and a combined-sized rubber mortar (CSM) mixture containing 75% GTR granules and 25% GTR powder. In addition, RC containing 100% sand was produced. A slight increase was found in the sorptivity value of RACs compared to the RC. It has been stated that poor adherence between the cement matrix and the RPs may cause this situation. Besides, it was understood from the SEM images that the weak interface between the cement matrix and the RPs was more evident in the presence of GTR granules. This indicates more water penetration in mortar mixes containing GTR granules than in other mixtures [91].

Siad et al. examined the effect of using waste rubber aggregate instead of silica sand on the various properties of engineered cementitious composites (ECC). For this purpose, ECC mixtures containing 5%, 10%, 15%, 20% and 30% crumb rubber sand or 30% and 40% rubber powder sand were prepared. It was determined that the sorptivity value of the ECC mixture with crumb rubber sand up to 10% was close to that of the control mixture without rubber (Ctl-ECC). However, the use of 30% crumb rubber sand provided a significant increase of 26.9% in the 28-day sorptivity compared to Ctl-ECC. On the other hand, the 28-day and 360-day sorptivity of the ECC mixture containing 30% rubber powder sand were found to be 12.5% and 37.6% lower than that of the Ctl-ECC mixture, respectively. It has been stated that this may be because the air gaps in the interfacial transition zone (ITZ) in the case of using rubber powder sand are less than that of the fine RPs [92].

Azevedo et al. conducted studies on the properties of high-performance RAC in which crumb rubbers are partially replaced by fine aggregate. It has been found that capillary water absorption increases with increasing RP [93].

Water permeability is directly related to the capillary pores in the concrete and affects the durability of the concrete. Water permeability is an important factor for reinforced concrete structures, especially in marine structures and parts of construction that are in direct contact with groundwater. Figure 13 shows the depth of water penetration of RACs with rubber aggregates. As it can be seen in Figure 13, the depth of water penetration generally increased with increasing RP percentage. The increase in the percentage of RPs causes porosity and micro-cracks in the concrete, which increases the depth of water penetration of the RAC. As it can be seen in Figure 13, the depth of water penetration of the RAC containing 2.5% rubber aggregate is similar to that of the RC. However, the use of rubber aggregate above 2.5% significantly increased the depth of water penetration compared to the RC. The water permeability of the RAC containing 20% rubber aggregate increased by 310%, 275%, 163% and 225% compared to the RC [33],[84].

Muñoz-Sánchez et al. stated that the weak ITZ between cement paste and RPs increases the water permeability of concrete [25]. It has been found that the water permeability of the concrete increases as the size of the RPs increases [8]. Su et al. replaced the fine aggregate by 20% with RPs of 3, 0.5 and 0.3 mm in size. The highest depth of water penetration was found in the RAC containing larger RPs (3 mm). It has been stated that the use of larger RPs will cause improper distribution of the particles in the RAC, increasing the water permeability of the RAC. The water permeability of the RACs with rubber aggregate in the size of 3, 0.5 and 0.3 mm increased by 209%, 42% and 38%, respectively, compared to the RC [87]. Bisht and Ramana replaced the fine aggregate with 0.6 mm RPs at 4%, 4.5%, 5% and 5.5%. The water permeability of the RAC increased up to 35% with the increase of the rubber percentage [55].

Khern et al. investigated the effect of the treatment method on the properties of RAC by treating RPs with 3 different methods. For this purpose, RPs were treated separately with water, 20% NaOH solution and 5% calcium hypochlorite ($Ca(ClO)_2$) solution for 2, 24 and 72 hours. To make a comparison, a RAC without treating the RPs and a RC without rubber aggregate were prepared. In all concretes, RPs were used by replacing 8% with coarse aggregate. The results showed that ($Ca(ClO)_2$) had a more positive impact on compressive strength and water permeability compared with water and NaOH solution. While the depth of water penetration of the RAC produced with RPs without any treatment was 41 mm, the depth of water penetration of the RAC produced with RPs treated with ($Ca(ClO)_2$) was found to be 24 mm. In addition, it was determined that the depth of water penetration of the RAC produced with RPs treated with ($Ca(ClO)_2$) was even less than the depth of water penetration (31 mm) of the RC without RP [94].

Kumar et al. studied the effect of RPs and quartz sandstone on water permeability and sorptivity of concrete by using RPs instead of fine aggregate and quartz sandstone instead of coarse aggregate. Three quartz sandstone replacement percentages (0%, 50%, and 100%) and five RP replacement percentages (0%, 2.5%, 5%, 7.5%, and 10%) were considered.

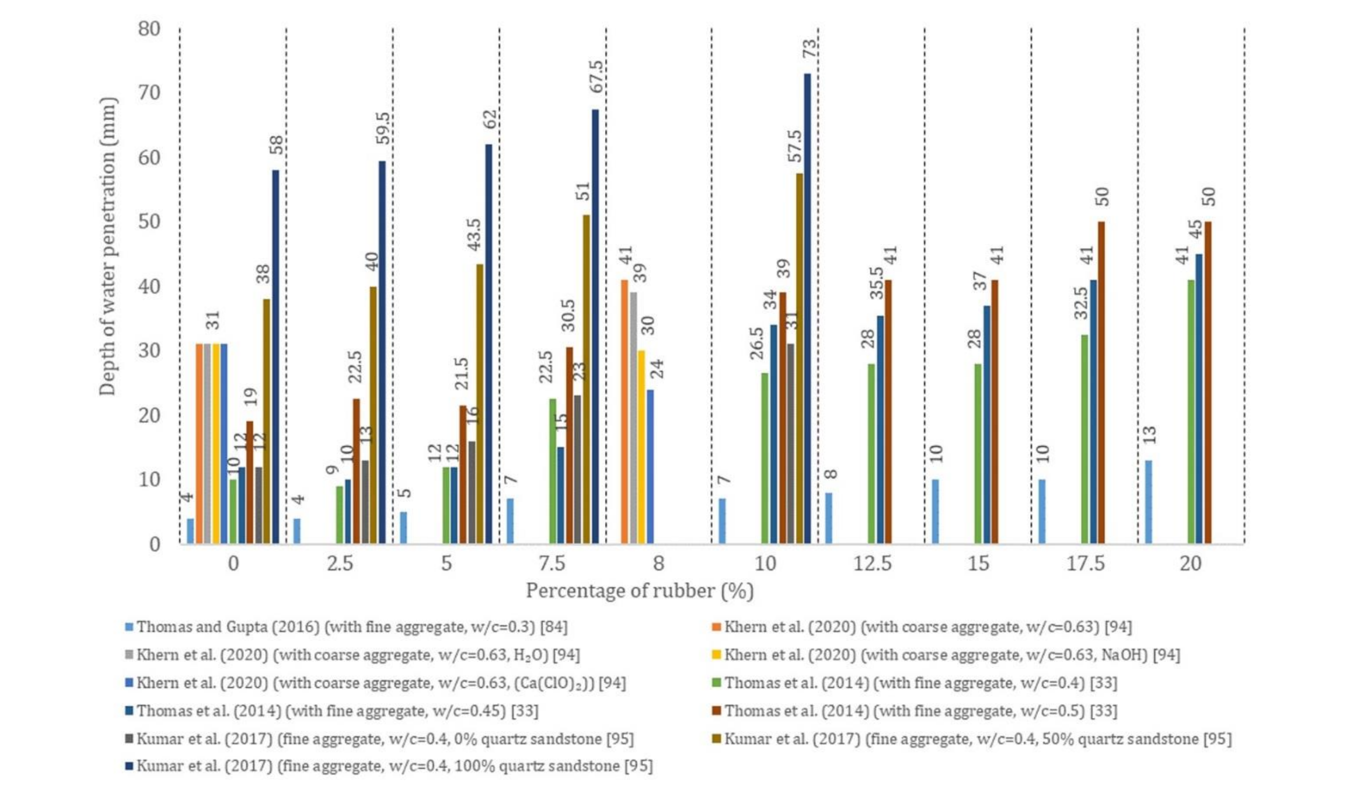

Figure 13. Depth of water penetration of RACs.

The depth of water penetration of the concrete increased as the percentage of rubber and quartz sandstone increased. The highest water penetration depth of 73 mm was obtained from the RAC sample containing 100% quartz sandstone and 10% RPs. In the light of the results found, it was recommended in that study to use 50% of quartz sandstone and 7.5% of rubber in concrete [95].

3.9 Abrasion resistance

In Figure 14, the depth of wear of RAC is shown depending on the percentage of rubber. The depth of wear of RAC generally reduces as the percentage of RP increases. However, an insignificant increase in the depth of wear of RAC with 10% rubber percentage was observed compared to that of RAC with 7.5% rubber percentage. For 0.5, 0.3 and 0.27 w/c ratios, the depth of wear of the RC samples was found to be 1.58, 1.42 and 0.91 mm, respectively, while the depth of wear of the RAC samples containing 10% rubber percentage was found to be 1.35, 1.14 and 0.55 mm. The addition of RPs increased the abrasion resistance of RAC. For 0.5, 0.3 and 0.27 w/c ratios, the depth of wear in the RAC samples containing 20% rubber decreased by 34%, 32% and 58%, respectively, compared to the RC without RP. In addition, the reduction in the w/c ratio also reduced the depth of wear of the concrete.

Kang et al. (2012) investigated the abrasion resistance of RAC by adding 5%, 7.5%, 10% and 15% rubber crumb to the concrete. The addition of 5%, 7.5%, 10% and 15% rubber crumb increased the abrasion resistance of the RAC by 35%, 47%, 94% and 116%, respectively, compared to the RC [97]. There are also results in the literature that RPs increase the depth of wear of RAC.

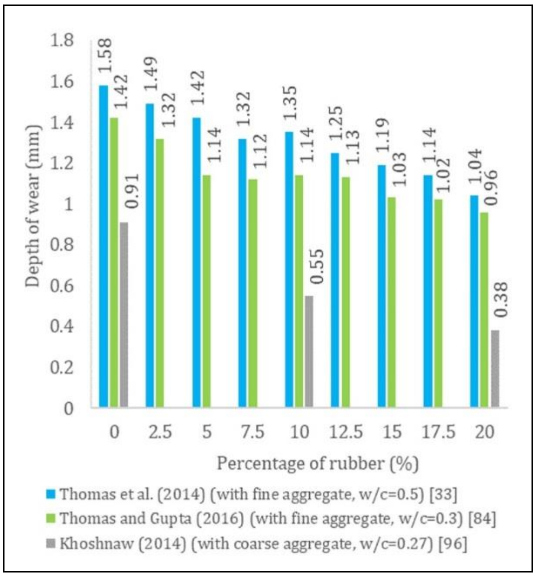

Figure 14. Depth of wear of RACs.

Bisht and Ramana (2017) investigated the mechanical and durability properties of RAC by adding 0.6 mm long crumb rubber to concrete at the rates of 0%, 4%, 4.5%, 5% and 5.5%. In the abrasion resistance test, the depth of wear of the RAC samples containing crumb rubber increased by 15% compared to the RC. It has been stated that this decrease in abrasion resistance is due to the low adherence between crumb rubber and cement paste [55]. Similar findings obtained using the acoustic emission technique were also found by Ridgley et al. [98]. Ridgley et al. found the depth of wear of self-compacting

RC containing cement, fly ash and metakaolin as binder and without RP to be 0.71 mm, while the depth of wear of self-compacting RACs containing 10%, 20% and %30 RP were 0.93 mm, 1.24 mm and 1.51 mm, respectively [98]. Onuaguluchi found that the abrasion performance was improved by pre-coating the RPs with limestone powder and adding silica fume to the RAC [99].

3.10 Drying shrinkage and expansion

Drying shrinkage and expansion are volume changes in concrete as a result of physical and chemical factors. The shrinkage that occurs in the volume of the concrete is called the drying shrinkage and the increase in the volume of the concrete is called the expansion. Table 3 shows the drying shrinkage and expansion results performed on RACs by various researchers.

As it can be understood from Table 3, the addition of RPs increased the drying shrinkage of concrete in general [69],[74],[100]-[104],[109]. Wang et al. (2019) produced mortar samples by substituting the fine aggregate with RPs of 0.6-2.8 mm in size at 10% and 15% by volume.

It was found that the addition of 15% RP enhanced the drying shrinkage of the mortar. It has been stated that rubber aggregate will deform more easily under drying shrinkage stress because of its lower rigidity than normal fine aggregate [74],[104].

However, the addition of macro polypropylene (PP) fiber to the mortar with RP reduced the drying shrinkage of the mortar with rubber aggregate by 15.5%, making it lower than the reference mortar without rubber aggregate. It has been stated that the increased drying shrinkage caused by increasing RP percentage can be compensated with macro PP fiber [74]. Si et al. (2017) examined the drying shrinkage of mortars with 15% and 25% RPs. In addition, the effect of pretreatment of RPs with NaOH was investigated on durability. It was stated that drying shrinkage increased with increasing RP content.

Tablo 3. Literature findings on drying shrinkage and expansion of RAC.

Ref.	Rubber size (mm)	Replacement of RP (%)	Replacement pattern	w/c or w/b	Findings
[74]	0.6-2.8	10 and 15% by volume	Fine aggregate	0.44	The drying shrinkage increased compared to reference specimen without RPs.
[100]	0.3 and 6	5, 10, 15 and 20% by volume	Fine aggregate	0.35	The length change of mortar with 5% and 20% RPs had 35% and 95% higher compared to that of the reference sample, respectively.
[69]	1.44-2.83	15 and 25% by volume	Fine aggregate	0.5	The length change of mortar with 25% RPs had 0.006% higher than reference mortar without RPs.
[101]	5–10 mesh and 0-30 mesh	10, 20, 30 and 40% by weight	Fine aggregate	0.29 and 0.4	The drying shrinkage generally increased with increasing RP percentage for both normal strength concrete and high strength concrete. The drying shrinkages at 28 days were found to be 430 and 240 micro-strain for both normal strength concrete and high strength concrete, respectively.
[102]	<4.75	10, 20, 30 and 40% by volume	Fine aggregate	0.4 and 0.45	Adding RP to concrete caused more drying shrinkage compared to RC. The highest drying shrinkage was obtained from the mixture with 40% RP and 0.45 w/c.
[103]	0-20	20, 40 and 60% by volume	Fine aggregate and coarse aggregate	-	The addition of RP increased the total shrinkage by 15.5, 59 and 127% for 20, 40 and 60% RP percentage, respectively.
[104]	sieve No. 6 and sieve No. 26	10, 20 and 30% by volume	Fine aggregate	0.47	The drying shrinkage of RACs containing 30% RPs was found to be about 0.080 and 0.13% for No. 6 and No. 26 RP sizes, respectively. The drying shrinkage increased with increasing RP content and size.
[105]	40 mesh	1, 1.5 and 2 % by volume	Fine aggregate	-	The drying shrinkage of RACs containing at 1, 1.5 and 2% RPs was found to be 10%, 16% and 26% less than that of RC, respectively.
[106]	1-5	10% by volume	Fine aggregate	0.5	Adding RP to concrete made both the drying shrinkage and expansion lower.
[107]	maximum size: 4.75	5, 10, 15, 20, 25 and 30% by volume	Fine aggregate	0.5	The drying shrinkage decreased as the percentage of RP increased.
[108]	1-4	10, 20, 30, 40 and 50% by weight	Fine aggregate	0.51	The 28-day drying shrinkage value of concretes with 10, 20 and 30% RP for 0.51 w/c was found to be lower than that of the RC. However, the drying shrinkage increased significantly when 40% and 50% RP were used.
[109]	600 µm-2.36 mm	2.5 and 5% by volume	Fine aggregate	0.15	The drying shrinkage increased with increasing crumb rubber content
[110]	75–150 µm	50, 70 and 90% by weight	Fine aggregate	0.8, 1 and 2.5	The drying shrinkage of the mortar with RP was close to the reference mortar. It was found that the drying shrinkage decreases as the size of the RP decreases up to the micro size.

The change in length of the mortar sample with 15% RP content and untreated with NaOH was 0.003% higher than that of the reference sample without RP. It has been stated that RPs with low rigidity in the mortar can reduce the internal constraints and thus cause an increase in drying shrinkage. The length changes of the mortar samples treated with NaOH and containing 15% and 25% RP were 0.002% and 0.006% higher than that of the reference sample. It has been found that drying shrinkage is reduced if RPs are treated with NaOH for the same rubber percentage. Besides, it was found that the pre-modified mortar samples showed better performance in terms of ASR expansion than untreated mortar samples for the same rubber percentage [69]. Yung et al. (2013) replaced normal fine aggregate with RP by 5%, 10%, 15% and 20% in concrete. It was determined that the drying shrinkage increased with increasing RP content and reached the maximum value in the case of 20% rubber aggregate addition. The change in drying shrinkage of RACs with 20% rubber aggregate was 95% higher than that of the RC [100]. It was expressed that the drying shrinkage increased with increasing RP content and size [104].

Conversely, it was found in some studies that the addition of RP to mortar or concrete reduces drying shrinkage or expansion [105]-[108]. Sun et al. (2020) replaced the fine aggregate with RPs of 40 mesh size at a rate of 1%, 1.5%, and 2%. Drying shrinkage values of RACs containing 1%, 1.5% and 2% rubber aggregate were 10%, 16% and 26% lower in comparison with the RC, respectively. This situation was explained by the following situations. First, the moisture content in the RACs with crumb rubber is lower than that of the RC, which stand for that the RC is more susceptible to humidity and temperature changes. In addition, there are more crystalline hydration products in the RC than in the samples with the crumb rubber. This implies that the volume shrinkage in the RC is higher than that of the RACs with crumb rubber. The second reason is that the rubber crumb causes changes in the pore structure of the material. RPs affect the capillary void pressure of the concrete preventing the evaporation of capillary water, thus reducing volume shrinkage [105]. In another study, it was stated that adding RPs to concrete makes both drying shrinkage and expansion lower [106]. It was found that the addition of RP up to 30% for 0.51 w/c decreased the drying shrinkage of RAC compared with that of the RC but the addition of 40% and 50% RP significantly increased the drying shrinkage of RAC [108]. It has been determined that the drying shrinkage of the mortar produced with rubber powder is close to that of the RC [110].

4 Overview of literature and suggestions

As it seen in Table 4, the effect of RAC properties is given as increasing (+) and decreasing (-) according to the literature. If there is an increase in the feature in the relevant literature, the literature number used is written in the (+) sign, and if there is a decrease, it is written in the (-) sign. Slump test results; it sometimes increased and sometimes decreased depending on the change in water absorption according to the type of RP. It reduces slump values since RP obtained from vehicle tires absorbs more water. The other RPs, which are not vehicle tires increase the slump values since they also reduce the cohesion in concrete. It has been observed in all literature reviews that the RAC also gets lighter due to the low unit weight of the RPs and the unit weight values decrease as expected.

Tablo 4. Literature findings on the mechanical and durability properties of RAC.

Properties	References	
	+	-
Slump	[10],[48]-[51]	[2],[23],[46],[47]
Unit weight		[2],[5],[11],[46],[56]
Compressive strength		[2],[5],][11],[12],[46],[47]
Flexural strength		[2],[5],[11],[12],[46],[47]
Modulus of elasticity		[11],[12],[46],[57],[58]
Toughness	[3],[14],[59],[60]	
Freeze-thaw resistance	[68]-[70],[73]-[75]	
Porosity, water abs., sorptivity and perm.	[8],[33],[55],[76]-[84],[87],[91]-[95]	[86],[88],[89]
Abrasion resistance	[33],[84],[96],[99]	[55],[98]
Drying shrinkage and expansion	[69],[74],[100]-[104],[109]	[105]-[108]

In addition, the other mechanical property, toughness increased while important mechanical properties such as compressive strength, flexural strength and modulus of elasticity decreased. Normally, the decrease in compressive and flexural strength is attributed to the poor adherence of the RP and concrete interface and to the low strength of plastic aggregates. The modulus of elasticity decreases as RP increases RAC ductility and reduces strain. An elastic material, RP increases the energy absorption capacity in concrete by absorbing energy under impact effect. On the other hand, while some of the durability properties are positively affected by RPs, some of them are negatively affected. While the literature agrees on the increase in freeze-thaw resistance, it is undecided about the other durability properties given in Table 4. Porosity, water absorption, sorptivity and permeability depended on the properties of water absorption, amount and size, type of RP, which also affect the slump feature in the same way and this has created an unstable situation in the literature. Although it is generally thought that wear resistance, drying shrinkage and expansion increase, there are also contradictory research results and this variability is thought to be due to the same reasons.

According to the results of all compilation literature; The type of RP, the amount and the size of use are very important. Although waste vehicle tires were mainly preferred in the studies, other rubber types were also used. Although intensive research has been done on the subjects whose research results are given, it has been seen that there is still a need for more research on subjects such as impact effect, performance under temperature, thermal conductivity, sound absorbing, autogenous shrinkage, chemical resistance, adherence with steel and cost. The studies on the use of RAC as a barrier on highways are limited. By focusing on studies on this subject, both the cost will be reduced and the human injuries and deaths will be less due to the energy absorption capacity of the RAC. In addition, vehicle damage caused by accidents should remain at a lower level. On the other hand, the use of RAC in this area can be investigated, since the runways of airports are subject to constant static and dynamic loading. Since airport runways are areas that require high impact and fatigue performance, studies on impact and fatigue performance can be done by using RAC and fibers together. RP-containing wall blocks can be produced and used because of the sound absorbing feature of RAC.

5 Conclusion

When the studies were evaluated in general, the following conclusions were drawn regarding RACs.

Various types of RPs added to the concrete affect the workability of the concrete negatively by reducing the slump of the concrete in general. It has also been found that some rubber additives increase the slump of concrete due to the decrease in cohesion rarely. The unit weight of the RAC decreased up to 1600 kg/m^3 depending on the added rubber percentage. This showed that lightweight RAC can be obtained by adding RPs to concrete. 10% rubber content is a critical level for water absorption of RAC. When used at rates below this value, the water absorption of RAC decreases, while the water absorption percentage of RAC increases at rates above this value. It has been seen that it is more appropriate to add RPs of different sizes with good gradation to the concrete instead of one-dimensional RPs. At the same time, the sorptivity and water permeability of the RAC increased with increasing RP content. However, the negative effect can be compensated or minimized by using the appropriate amount and size of RPs.

The addition of RPs significantly reduced the compressive strength of the RAC. It was determined that the compressive strength of RAC containing 30% RPs decreased by about 50% compared with that of the RC. Therefore, it is considered that it would be appropriate not to use more than 10% RPs in structures where strength is important. The flexural strength of RAC reduced with increasing rubber percentage, as did the compressive strength. An average of 21% decrease in the flexural strength of the RAC occurred with the addition of 30% rubber. However, this reduction in flexural strength is less than the reduction in compressive strength. The elastic modulus of RACs gradually reduces with the percentage of rubber added, and this reduction reaches up to 50% in the case of using 30% rubber. Thus, it contributes to a more ductile behavior of concrete by helping to enhance the inelastic deformation capacity of concrete. The replacement of normal aggregate with RPs in the concrete provided an increase in the toughness of the concrete by up to 187%. The high toughness of RAC allows it to be used as a concrete barrier, and this can also help prevent damage due to impacts.

The freeze-thaw resistance of the concrete has increased thanks to the RPs added to the concrete. In addition, the freeze-thaw resistance of the RAC produced with RPs exposed to NaOH solution was improved. The use of rubber on concrete roads can be considered thanks to this feature of RAC. In general, the depth of wear of RACs decreased with the increase of the RP percentage. The drying shrinkage of RACs varies according to the size, stiffness and content of the RPs.

The addition of waste RP to concrete generally has positive effects on properties such as toughness, freeze-thaw resistance and abrasion resistance of RAC but causes a reduction in the mechanical properties of RAC. Therefore, adding RP to the concrete without causing a significant decrease in the mechanical properties of the concrete will contribute positively to many properties of the concrete and thus the recycling of the waste material will be ensured. The poor adherence between RP and cement matrix in concrete causes a decline in the mechanical properties of the RAC, thus limiting the use of more than 10% RP in concrete in structures where strength is important. Therefore, more studies should be done on improving the interface between cement matrix and RPs.

6 Author contribution statements

Within the scope of the doctoral thesis, Arif YILMAZOGLU carried out a literature review on RACs and collected data from various studies and analyzed these data. Arif YILMAZOGLU wrote the article in light of the collected information. The control of the article was done by the doctoral thesis advisor, Salih Taner YILDIRIM.

7 Ethics committee approval and conflict of interest statement

It is not necessary to obtain permission from the ethics committee for this article. The authors declare that there is no conflict of interest with any person/institution for this article.

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