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Research Article

The Effect of Different Proportions of Waste Rubber Substitution on Alkali-Silica Reaction and Mechanical Properties in Mortars

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ABSTRACT

This study investigates the alkali-silica reaction (ASR) and mechanical properties of mortars containing crumb and powder rubber instead of river sand. In this regard, mortars were produced using waste rubber whose ratios in the mixture are 0%, 3%, 6%, 9%, 12%, 15%, 18%, and 21%. ASR expansion, compressive and flexural strength tests were conducted on the samples. ASR measurements were performed on days 3, 7, 14, 21, and 28. Besides, at the end of the ASR experiment, the microstructures of the mortars were examined using scanning electron microscope (SEM) images. Examining the results of this study reveals that the use of waste rubber in rising portions in the mortars led to an increase in the ASR expansions of the mortars. The study shows that the ASR expansions of the mortar samples that have 9% and 15% waste rubber replacement are comparatively higher than the other mortar samples. Furthermore, the results of the SEM analysis verified this finding. The study demonstrates that 3% of waste rubber mortar samples have the highest compressive and flexural strengths. On the other side, the ASR expansion of the mortars with 3% substituted waste rubber was considerably low compared to other mortars containing waste rubber. These findings (ASR, compressive and flexural strength tests results) show that using 3% waste rubber is ideal for producing mortars and supports a sustainable production approach in the sector.

1. Introduction

Tire production has increased enormously in recent years, along with the rapid development of the automobile industry worldwide [1, 2]. Consequently, waste tires have piled up over the years, and therefore, solid waste management has become one of the most severe environmental problems worldwide [3, 4]. By the end of 2030, it is expected that 5 billion tires will be generated and 1.2 billion rubbers will be discarded [5]. Since rubber is not biodegradable, accumulating waste tires can cause serious environmental problems [6-8].

While landfill is one of the most common waste disposal methods [9], increasingly larger landfill areas are required to store the used tires [10-12]. Moreover, rainwater trapped in waste tires creates a humid environment where insects and pests can reproduce quickly [13, 14]. On the other side, fire is another threat due to the increasing numbers of waste tires because they are flammable, and the accumulation of waste tires piling up may bring about adverse effects on the environment and human health [15-17]. The negative impacts of waste tires on the environment can be minimized by recycling them in other forms, such as crumb or shredded rubber, or using them in construction and different industries [18].

Rubberized concrete (RC) is a type of concrete containing rubber particles recycled from used tires as substitutes for fine and coarse aggregates [19, 20]. Thus, waste tire rubber particles are

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recycled by partially substituting the components of cementitious mixtures [21, 22].

Concretes containing reactive aggregates are susceptible to deterioration due to Alkali-Silica Reaction (ASR), which results from sufficient humidity and temperature [23]. ASR is a harmful chemical reaction between specific amorphous silica in various natural aggregates and alkalis in cement paste [24-27]. ASR plays a critical role in the durability of concrete structures. The vital role of ASR is because the gel-form reaction product leads to internal stresses, which in turn cause the concrete structures to expand and crack [28-31]. The processes related to ASR-induced expansion and deterioration of concrete are as follows [32, 33]:

i) Transport of hydroxide, alkali, and calcium ions towards reactive aggregates,

ii) Dissolution of the silica and creation of a gel layer,

iii) Diffusing of the gel into the existing voids, defects, and pores of the aggregates,

iv) Microcracking due to the swollen gel's expansion results in overall expansion and concrete deterioration.

Replacing natural aggregates with recycled rubber particles in the concrete industry has recently led to growing scientific research [34-38]. In light of these studies, remarkable progress has been achieved regarding knowledge of the structural behavior of these materials [39-43].

1.1. Research significance

Even though numerous studies focusing on the mechanical and durability properties of RC have been carried out thus far, the number of research on the expansion and adverse effects of ASR in waste rubber-added composites is low [26]. Therefore, this study used crumb and powder rubber as waste rubber in substitution with aggregates. Different from studies in the literature, this study has a unique aspect: it used wasted rubber in eight different waste rubber ratios (0%, 3%, 6%, 9%, 12%, 15%, 18% and 21%). Moreover, in the study, ASR, compressive strength and flexural strength tests were carried out to measure mortars' engineering properties. As a result, the study aims to determine which waste rubber ratio is effective on ASR and other mechanical properties.

2. Experimental Methodology

2.1. Materials

CEM I 42.5 R type Portland cement, which is classified in TS EN 197-1 [44] standard, was used in the study. The specific chemical and physical properties of this cement are shown in Table 1. The river sand potentially resulted in ASR, was extracted from the Artvin region of Turkey, and was utilized as aggregate in this study. The specific gravity of the river sand is 2.64 g/cm^3. Previously used waste tires were recycled and separated into two different grain grades (crumbs and powder). Additionally, an insignificant amount of steel wire exists inside the waste rubbers. Later, these recycled materials were used as aggregates in mortar production.

Table 1. Properties of cement

	CEM I 42.5 R
Chemical Compositions (%)	
SiO_2	19.47
Al_2O_3	4.64
Fe_2O_3	3.39
CaO	63.62
MgO	2.55
SO_3	3.07
Na_2O	0.43
K_2O	0.79
CI^-	0.006
Insoluble residue	0.61
Loss on ignition	2.96
Physical Characteristics	
Residue on a 32-micron sieve	7.45
Specific surface (cm^2/g)	3338
Specific gravity	3.11
Beginning of setting	2hrs-30min
End of setting	3hrs-33min
Volume expansion (mm)	1.0
Compressive strength (MPa)	
2nd day	29.8
28th day	55.7

Waste rubbers having different granulometry are given in Figure 1. The specific weight of the waste rubber used in mortar production is 1.05 g/cm^3.

Figure 1. Waste rubbers with different granulometry (crumb on the left, powder on the right)

The phase identification of waste rubber was performed by X-ray diffraction (XRD) technique for scan range of 10–80° with a step size of 5° as shown in Figure 2. The abbreviations and explanations indicated in Figure 2 are C; Carbon, S; Sulfur, O_2; Oxygen, Mg; Magnesium and Si; Silisium.

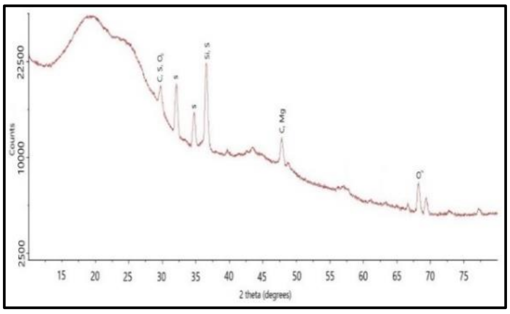

Figure 2. X-ray diffraction pattern of waste rubber

2.2. Parameters and mortar mix design

This study prepared mortar mixtures using the accelerated mortar-bar method per ASTM C 1260 [45] standard. During the experiments, eight different mortar mixtures were produced by replacing waste rubber aggregate with river sand at 0%, 3%, 6%, 9%, 12%, 15%, 18%, and 21% by volume. In the codes, WR, the abbreviation of waste rubber, is given first, and then the replacement rate is written. For instance, WR6 refers to 6% waste rubber replacement mortar. The control mortar is denoted as C.

2.3. Experimental methods

Preparation of the mixtures and execution of the ASR experiments were conducted under ASTM C 1260 [45]. Sand and waste rubbers separated into different grain classes by sifting through the sieves specified in the standard were weighed in the specified amounts. Subsequently, the mortar mixtures were prepared following the relevant standard. Samples of 25x25x285 mm dimensions were taken for ASR from the prepared mortar mixtures. Besides, samples of 40x40x100 mm dimensions were taken to determine mortar specimens' compressive and flexural strength. After being retained in the molds for 24 hours, the mortar samples were demolded. The samples produced for the ASR test were kept in 80^{o}C water for 24 hours and subsequently, their lengths were measured (L_o).

Afterward, the specimens were held in 1 mol NaOH solution at 80^{o}C. Then, their lengths were again measured at the end of the 3rd, 7th, 14th, 21st, and 28th days. The length changes were calculated in percentage. The samples produced to determine the compressive and flexural strength of the mortar samples were removed from the mold 24 hours later, and they were kept in water in curing pool for 28 days. The mechanical effect of the waste rubber replacement on the mortars was determined by subjecting the samples taken from the curing to compressive and flexural strength tests. Correspondingly, the changes in the internal structure were examined by taking SEM (scanning electron microscope) images on the samples. SEM analysis was performed via the QUANTA FEG 450 brand device. With the help of SEM analysis, the density of the ASR gel in the mortars and the density and structure of the cracks were determined.

3. Results and Discussion

3.1. Alkali-silica reaction (ASR)

The expansion results depending on the time (3, 7, 14, 21, and 28 days) of the mortar samples containing waste rubber at different rates are in Figure 3. The findings of the measurements show that, regardless of the replacement ratio, the mortars' expansion values increased compared with the control mortar sample when waste rubber was substituted into the mixture. For example, when the results at 14-day regarding the expansion due to ASR are assessed, the mortar sample containing 3% waste rubber (WR3) expanded by 21%, and the sample containing 15% waste rubber (WR15) enlarged by around 100% compared to the control mortar sample.

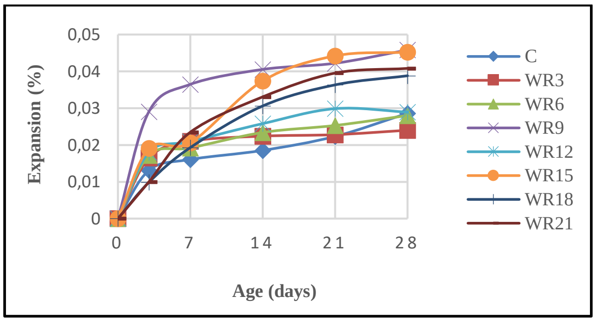

Figure 3. The changes in ASR expansion of mortars depending on waste rubber substitution

For instance, investigating the 28-day expansion results indicates the samples having 9% waste rubber (WR9) stretched 60% more than the control sample. Likewise, the samples accommodating 21% waste rubber (WR21) extended approximately 43% of the control sample. Although the expansion value of 3% waste rubber mortar was higher than the control mortar in the 14-day results, these expansion values were equalized in 21 days and much lower expansion values than the control mortar were obtained at the end of 28 days. A few studies investigating the ASR of samples whose aggregates were replaced by waste rubber reveal that the expansions in samples increased compared with the control sample owing to the increase in the substitution ratio [26].

The hydrophobic structure of waste rubbers may have caused a weak adhesion at the interface between the cement paste and waste rubber, thus providing more opportunity for ASR gel formation [46]. Although the rubber particles with high deformability can release some of the internal stress caused by the ASR gel brought about during the process, it is thought that the mixture stiffness declines along with the rising rubber ratio. This way, a more significant deformation occurs by a similar magnitude of internal stress [1, 47].

Therefore, it is concluded that mortars with low hardness and high waste rubber ratio show more expansion. When each sample whose aggregates were substituted is compared to one another, the expansion rates increased linearly with the rising waste rubber proportions, especially on the 14th day and its aftermath. Two special exceptions are observed in samples that do not fit the trend mentioned above (WR9, WR15). The experiments show that the mortar samples holding 9% and 15% waste rubber reached the highest ASR expansion values compared to the others. As will be discussed further in the following sections, observing this phenomenon in the SEM analysis results indicates the experimental outcomes are consistent. Although the expansion values increased as the substitution rate of waste rubber in the mortar mixes changed, the expansions for all samples dwelled within limits set by ASTM C1260 [45] (for harmful reactive aggregates, the maximum expansion of the samples should be less than 0.2%).

3.2. Compressive strength

The compressive strength rates of the prepared samples by ratios of waste rubber aggregate replacement are in Figure 4.

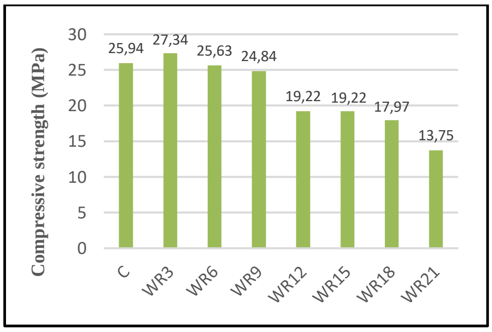

Figure 4. The changes in compressive strength of mortars depending on waste rubber substitution

The graph shows that the highest compressive strength value is achieved in the sample containing 3% waste rubber (WR3). On the other hand, the lowest compressive strength value was reached in the sample with 21% waste rubber (WR21). When using 3% of the waste rubber in the mortar, the compressive strength increased by 5% compared to the control sample. Besides, when 6% and 9% of waste rubber were replaced with aggregate in samples, the compressive strength rates did not remarkably decline.

The compressive strength decline has become particularly critical when the waste rubber substitution rate exceeds 9%. The reduction in compressive strength of the sample containing 21% waste rubber is 47% compared to the control sample.

It is thought that the properties of waste rubber, such as deformability, softness and low hardness, are effective on the decreases in compressive strength results observed with the increase in the waste rubber ratio [48, 49]. Previous studies demonstrated that the compressive strengths declined as the waste rubber replacement ratio used in the mortar samples increased. Afshinnia and Poursaee [26] revealed that the compressive strength of samples with 16% and 20% waste rubber substitution declined by 20% and 48%, respectively. This study's experimental outcomes show similar compressive strength reductions when the waste rubber replacement ratio is 15% and 21%. The 3% waste rubber replacement ratio led to the highest compressive strength in samples (27.34 MPa). Therefore, it can be deemed as the ideal ratio for this study.

3.3. Flexural strength

The results of the flexural strength test performed on the mortar samples are displayed in Figure 5.

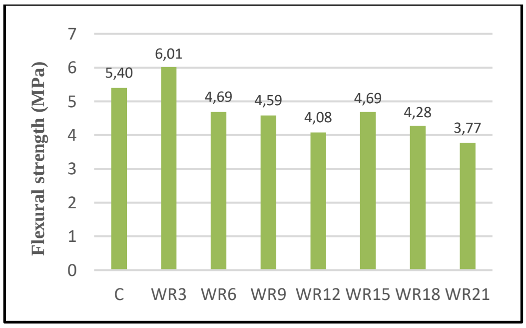

Figure 5. The changes in flexural strength of mortars depending on waste rubber substitution

The figure shows that the highest flexural strength is 6.01 MPa, which is achieved when the waste rubber substitute mortar (WR3) is 3%. On the other side, the lowest flexural strength is 3.77 MPa, which occurs with the sample of 21% waste rubber replacement (WR21). The flexural strength of the waste rubber sample with a 3% substitute is 11% higher than the control sample. A decreasing trend was observed in flexural strengths of samples when the replacement ratio was greater than 3%. The reduction in flexural strength of the samples containing 21% waste rubber is approximately 30% compared to the control sample. The 3% waste rubber replacement ratio was ideal, giving rise to the highest flexural strength value (6.01 MPa). The results are in the same trend as the compressive strength results. Waste rubber aggregate used up to a certain rate (3% for this study) positively affected the strength values by acting as a filling material in the mortar. It has been observed that when waste rubbers are used at higher rates than this ratio, the amount of voids in the internal structure of the mortars increases and mechanical performances decrease [50, 51].

3.4. Microstructural analysis

The microstructure of the mortar bars subjected to the ASR test after 28 days was investigated using SEM. SEM images of the mortar samples having the maximum highest ASR expansion, along with the control samples are in Figure 6.

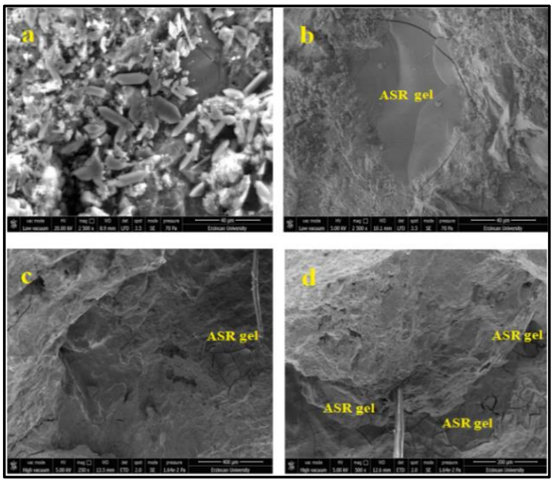

Figure 6. SEM images from (a) control sample, (b) sample of 9% waste rubber replacement, (c) and (d) samples of 15% waste rubber replacement sample after 28 days

The SEM image of the control mortar is given in Figure 6 (a), the SEM image of the mortar with 9% waste rubber is given in Figure 6 (b), and the SEM images of the mortar with 15% waste rubber are given in Figure 6 (c, d). Figure 6 (a) displays structures such as CH, CSH, and ettringite, which are hydration products. At this point, it is important to remark that ASR gel formation barely exists in the control sample. In Figure 6 (b), the ASR gel's intensity was slightly higher than the control sample. In Figure 6 (c-d), the intensity of the ASR gel and the map-shaped cracks in the ASR gel were more apparent. Figure 6 (d) mainly presents the ASR gel formation and cracks observed around the crumb rubber containing steel wire. The tensile stress caused by the presence of ASR gel and the soft material of rubbers developed these microcracks in the mortars [52].

The ASR gel formed around the waste rubber caused expansion in the matrix, creating a cracked structure in the mortar, which negatively affected the mechanical performance [49, 53]. The images are obtained from the SEM image of the mortar sample containing 15% waste rubber replacement. Subsequently, the study has determined that these microstructure formations are parallel with the results of ASR expansion.

4. Conclusion

The main conclusions drawn from the evaluation of the findings obtained from this study are as follows:

1. ASR expansions increased with the rising substitution rate of waste rubbers. The mortar samples containing 9% and 15% waste rubber replacement expanded significantly more than the others, especially on the 14th day and its aftermath.

2. The ASR expansion values of the control sample and the 3% waste rubber replacement mortar were very close, and the expansion rates were the lowest for both mortars. It can be said; when utilized in mortar production, a 3% waste rubber ratio will not pose a problem in ASR terms.

3. The compressive and flexural strength values of the 3% waste rubber substitution sample were significantly higher than the control sample and others with varying waste rubber replacement rates.

4. The microstructure of the ASR gel and cracks in the microstructure of the samples having 9% and 15% waste rubber replacement rates had the highest ASR expansion. The considerably higher expansions in these two groups of samples were seen in the images obtained through SEM. It has been determined that the SEM analysis results are similar to the ASR expansion results.

5. The least adversely affecting rate in terms of ASR and mechanical properties is 3%, but it is concluded that using waste materials as a positive contribution is important in terms of sustainability and environmental effect.

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Authors' Contribution

The authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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