Materiales de Construcción (75) 357
January-March 2025, e364
ISSN-L: 0465-2746, eISSN: 1988-3226
https://doi.org/10.3989/mc.2025.384024

Investigation of freeze-thaw performance for sustainable rubberized concrete composites with different water to cement ratios

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Received May 11, 2024
Accepted August 22, 2024
Available on line March 28 , 2025

ABSTRACT: This research aimed to evaluate the freeze-thaw performance of waste rubber substituted concretes with two different water/cement ratios. Different ratios of waste rubber were used in concrete by substituting fine and coarse aggregates. The weight and compressive strength losses of rubberized concrete and control concretes subjected to freeze-thaw were experimentally examined. The changes in the microstructure of the concrete were analyzed by using a Scanning Electron Microscope (SEM). Furthermore, ANOVA was used to test the significance of the selected parameters statistically. The control concrete with a 0.5 water/cement ratio had eight times higher mass loss compared to the rubberized concrete. The SEM analysis results were consistent with the freeze-thaw test results. ANOVA that the waste rubber substitution ratio had a significant effect on the freeze-thaw performance of rubberized concrete. Water/cement ratio, together with the waste rubber substitution ratio, is an effective parameter on the freeze-thaw resistance of rubberized concrete.

KEY WORDS: Rubberized concrete; Waste rubber; Freeze-thaw cycles; SEM; ANOVA.

Citation/Citar como: Alperen Bulut H, Kandil U. 2025. Investigation of freeze-thaw performance for sustainable rubberized concrete composites with different water to cement ratios. Mater. Construcc. 75(357):e364. https://doi.org/10.3989/mc.2025.384024.

RESUMEN: *Investigación del comportamiento de congelación y descongelación de compuestos de hormigón cauchutados sostenibles con diferentes proporciones agua/cemento.* Esta investigación tuvo como objetivo evaluar el rendimiento de congelación-descongelación de hormigones sustituidos con residuo de caucho con dos proporciones diferentes de agua/cemento. Se utilizaron diferentes proporciones de caucho de desecho en el hormigón sustituyendo áridos finos y gruesos. Se examinaron experimentalmente las pérdidas de peso y resistencia a la compresión del hormigón con caucho y de los hormigones de control sometidos a congelación-descongelación. Se analizaron los cambios en la microestructura del hormigón utilizando un microscopio electrónico de barrido (SEM). Además, se utilizó un análisis ANOVA para probar la significancia de los parámetros seleccionados estadísticamente. El hormigón de control con una proporción de agua/cemento de 0.5 tuvo una pérdida de masa ocho veces mayor en comparación con el hormigón con caucho. Los resultados del análisis SEM fueron consistentes con los resultados de la prueba de congelación-descongelación. El análisis ANOVA demostró que la proporción de sustitución de residuo de caucho tuvo un efecto significativo en el rendimiento de congelación-descongelación del hormigón engomado. La proporción de agua/cemento, junto con la proporción de sustitución de residuo de caucho, es un parámetro eficaz en la resistencia a la congelación-descongelación del hormigón con caucho.

PALABRAS CLAVE: Hormigón con caucho; Residuo de caucho; Ciclos de congelación y descongelación; SEM; ANOVA.

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1. INTRODUCTION

One of the most important concerns of environmental organizations and the scientific community is the recycling of end-of-life tires, which are non-biodegradable and have huge production volumes (1). This is because the disposal of waste tires worldwide poses a serious environmental problem (2-4). Very few of these tires are recycled; most are disposed of in landfills (5). Waste tires can leach toxic substances into the soil, valuable space in landfills can be consumed, a fire hazard can be created inadvertently, and a breeding ground for mosquitoes can be created (6). In the construction industry, these waste tires have been tried to be used in concrete production by substituting natural aggregate (7-12).

Recycled tires shredded for use as aggregates in concrete are divided into three categories (13, 14);

- Chipped rubber ranging in size from 13 mm to 76 mm and used as coarse aggregate,
- Crumb rubber used as fine aggregate with particle size ranging from 4.75 mm to 0.5 mm,
- Powder rubber with a particle size lower than 0.5 mm as a very fine aggregate.

Many advantages, such as sound insulation, lightweight, energy absorption, impact resistance and toughness improvement, have been revealed by adding waste tire rubber to concrete (15-17). It is stated that the use of waste tires in other construction applications such as sound and impact barriers on highways, roller-compacted concrete and asphalt mixtures has become quite widespread (18-20). The amount of research to develop rubberized concrete (RC) composed of recycled rubber particles is increasing day by day (21-27).

As a result of studies on the workability of rubberized concrete, however, numerous negative effects have also occurred with the increase in rubber (28, 29). The lower density of rubber compared to natural aggregates also reduced the density of rubberized concrete (30, 31). As a result of increasing the rubber ratio up to 30%, it was reported that compressive, tensile and flexural strengths decreased by up to 50% (32). Atahan and Yücel (33) explained that a 96% decrease in modulus of elasticity values was observed when rubber was added to concrete at a ratio of 100%. Li et al. (34) declared that chloride ion permeability improved at a ratio of 35% in rubberized concrete. Bravo and Brito (35) stated that carbonation resistance was significantly affected, especially when waste tires were used instead of coarse aggregates. In another study, it was emphasized that the sulfate resistance of concretes decreased as the rubber usage ratio increased (36). It was explained that reinforcement corrosion rates increased when waste tires were used in concrete instead of coarse aggregate (37).

Increases in energy absorption and impact resistance of rubberized concrete were emphasized in the studies (38, 39). In another study, it was stated that the abrasion resistance of rubberized concrete was higher than the control concrete (40). It was stated that adding rubber to concrete at a ratio of 20% to 25% reduced the average crack length, width and area in terms of plastic shrinkage (41). It was reported that rubberized concrete panels were lighter than conventional concrete panels and also had higher sound absorption and lower thermal conductivity (42). A study revealed that micro-sized rubbers induced less electrical conduction than nano-sized rubbers (43).

Especially construction structures such as ports and dams are exposed to serious damages caused by freeze-thaw in cold regions where wetting-drying cycles are intense (44, 45). These damages are also increased by climate changes caused by global warming (46). Thus, the mechanical and durability properties of the concrete are negatively affected and cracks and performance losses occur in the concrete (47).

When the studies in this field are examined in the literature, it is seen that the effect of crumb rubber on the mechanical properties of concrete is generally investigated. Studies on freeze-thaw, which is one of the most important durability properties of concrete, are extremely few (48, 49). In this study, the freeze-thaw performance of rubberized concretes with water/cement ratios of 0.4 and 0.5, in which chips, crumb and powder waste rubbers were used as aggregates, was investigated. In this study, unlike the studies in the literature, chips, crumb and powder rubber were used together instead of natural aggregate in waste rubber concrete. In addition, the presence of some steel wire in the waste tires increased the originality of the work.

The purpose of this study is to examine in detail the effect of waste rubbers used as aggregate in concrete on the freeze-thaw performance, which is one of the most important durability problems of concrete. For this purpose, not only freeze-thaw experiments were conducted on rubberized concretes with different water/cement ratios and different proportions of waste rubbers, but also changes in the microstructure were examined with SEM analysis and the obtained data were evaluated statistically. As a result of the study, it is thought that the behavior of rubberized concretes against freeze-thaw will contribute by filling the gaps in the literature on this subject.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials

In the study, Portland cement was classified as CEM I 42.5 R according to the TS EN 197-1 (50) standard. Technical information about the cement provided by the manufacturer is given in Table 1.

The properties of the limestone-based aggregates used in the study are presented in Table 2.

Mixed aggregate was obtained by using half the volume of coarse and fine aggregate in order to remain between the limit curves according to the TS 802 (51) standard. Accordingly, for example, the rubber aggregate ratios in rubberized concrete containing 20% waste rubber are: It is chips rubber instead of 10% coarse aggregate, and powder and crumb rubber instead of 10% fine aggregate. Granulometry curve of the aggregate is given in Figure 1.

Limit curves in the standard (A16, B16 and C16) are used to determine the ideal aggregate granulometry in concrete. Accordingly, the aggregate used in this study granulometry curve between the A16 and C16 limit curves is defined as a curve that can be ideally used in concrete. In the recycling facility, waste tires are first separated from their steel wires (some steel wire may remain inside the tires at this stage), and then they are mechanically shredded. Waste tire particles of different sizes resulting from this process are sifted and divided into groups. Chips were used instead of coarse aggregate, and crumb and powder rubber were used instead of fine aggregate. Additionally, waste rubbers contain 1% to 3% steel wire by volume. The length of these steel wires is between 5-10 mm and is embedded in the waste rubber. Waste rubber aggregates are given in Figure 2. The specific gravity of waste rubber aggregates is 1.05 g/cm^3. The average water absorption value of waste rubber aggregates used in concrete production was determined as 3.67%.

A polycarboxylate ether based superplasticizer was used in all concretes to keep the slump value constant.

2.2. Concrete production and parameters

Rubberized concrete production with seven different aggregate contents (0%, 4%, 8%, 12%, 16%, 20% and 24%) by volume instead of natural aggregates was carried out at water/cement ratios of 0.4 and 0.5. Therefore, a total of fourteen different concretes were produced, including seven concretes with 0.4 water/cement ratio and seven concretes with 0.5 water/cement ratio. In concrete production, first the aggregates (including waste rubbers) were poured into the mixer and mixed for 1 minute. Then, saturation water was added to the mixer and mixed for 2 minutes. Three-quarters of the mixing water and cement were poured into the mixer and the whole mixture was mixed for 2 minutes. Finally, superplasticizer was added to the

Table 1. Properties of cement.

	CEM I 42.5 R
Chemical Compositions (%)	
SiO_2	19.41
Al_2O_3	4.57
Fe_2O_3	3.32
CaO	62.94
MgO	2.48
SO_3	3.05
Na_2O	0.39
K_2O	0.78
Cl^-	0.006
Loss on ignition	2.88
Insoluble residue	0.59
Physical Characteristics	
Specific surface (cm^2/g)	3324
Specific gravity	3.10
Residue on a 32 micron sieve	7.36
Volume expansion (mm)	1.0
Beginning of setting	2hrs-27min
End of setting	3hrs-31min
Compressive strength (MPa)	
2nd day	28.5
28th day	54.7

Table 2. Physical properties of natural aggregates.

	Size (mm)	Specific Gravity (g/cm^3)	Water Absorption (%)
Fine agg.	0 - 4	2.65	0.64
Coarse agg.	4 - 16	2.67	0.61

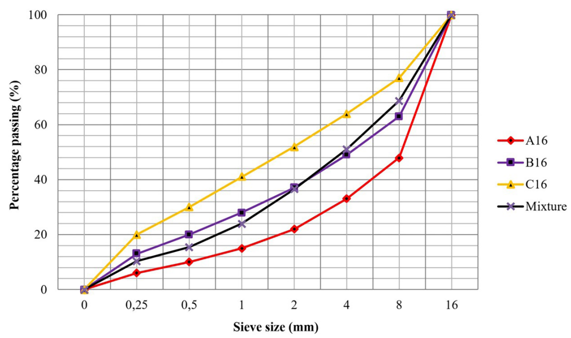

Figure 1. Granulometry curve of the aggregate.

remaining one-quarter of the water, poured into the mixer and mixed for 2 minutes, and then the concretes were produced. After the concretes for which slump tests were performed were kept in the molds for 24 hours, the molds were removed and water curing was applied to the samples until the 28 days. Cement was used in all concretes at a dosage of 400 kg/m^3. In the coding of mixtures, the numbers before "WR" indicate the water/cement ratio, and the numbers after indicate the waste rubber aggregate substitution ratio. In addition, in order to keep the slump values (8 ± 1 cm) of concrete constant, superplasticizer chemical additives were included in production at a rate of 0.15% to 0.8% in proportion cement. More detailed information on concrete mixture design is available in Kandil and Bulut (52).

2.3. Testing of specimens

Slump tests were conducted on concretes according to ASTM C143/C143M (53) standard. For each mixture, four cylindrical samples (diameter of 10 cm and length of 20 cm) were produced, and two of them were used in the freeze-thaw test and two in the compressive strength test. A total of 56 samples were produced. Within the scope of the study, the resistance of the concretes against freeze-thaw was evaluated according to their weight loss and compressive strength loss after 300 cycles. A visual evaluation of the samples was also made. Cylindrical samples with a diameter of 10 cm and length of 20 cm were used to examine the freeze-thaw performance of the concretes. At the end of the curing period, these samples were weighed in a saturated state and placed in the freeze-thaw chamber. The samples were subjected to freeze-thaw in a way to be subjected to 300 cycles in total. At the end of cycles of 0, 100, 150, 200, 250 and 300, the samples were weighed, and the weight changes compared to the initial condition were examined. ASTM C666 was taken as a basis for the freeze-thaw test (54). The test followed procedure B in ASTM C666 (54), i.e. freezing in air and thawing in water. The automatic device was programmed so that the applied temperature cycle was -18°C to 4°C, and the test was continued in this way. A photograph of the device in which the freeze-thaw test was performed and the samples placed in it is given in Figure 3. The changes in the microstructure of rubberized concrete and control concrete after exposure to freeze-thaw were examined by taking SEM (scanning electron microscope) images. SEM analysis was performed by means of a QUANTA FEG 450 brand device. ANOVA carried out statistical analysis to examine the level of contribution of the selected parameters to the results. The fact that the waste rubber substitution ratio and water/cement ratio factors have a significant effect on weight loss and compressive strength loss was examined by this method. As a general acceptance, if the p-value is lower than 0.05, it is accepted that the independent variables have a significant effect.

FIGURE 2. Waste rubber aggregates.

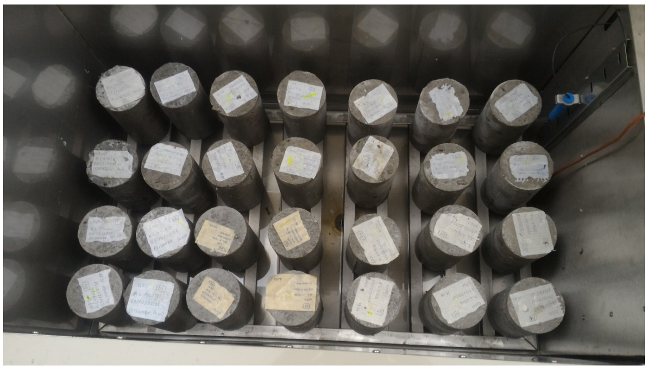

FIGURE 3. Freeze-thaw chamber and samples used in the experiment.

3. RESULTS AND DISCUSSION

3.1. Mass loss of rubberized concretes after freeze-thaw cycles

The change in mass of 0.4 water/cement ratio of the samples according to the number of freeze-thaw cycles applied is given in Figure 4. With the increase in the number of freeze-thaw cycles, it is seen that the mass loss of concretes with 12% and more waste rubber aggregate content decreases continuously; that is, their weight increases. It is thought that this weight increase occurs due to the growth of cracks as well as voids in the concretes as a result of the freeze-thaw effect and due to the filling of these voids by water. In addition, the steel wires, which are present in very small amounts in the rubber aggregate used, prevent exfoliation due to the freeze-thaw effect, causing a large number of voids to fill with water and play an important role in the weight increase. It's possible that a lot of the early mass increase is due to continued hydration of the concrete. The decrease in mass of concrete containing 4% waste rubbers (0.4WR4) up to 150 cycles and increase in mass in more than 150 cycles and the decrease in mass of control (0.4C) concrete without waste rubbers up to 200 cycles and increase in mass in 250 and 300 cycles support this idea. As a result, it was observed that the saturated masses of the samples increased with the increase in waste rubber content, and it was seen that more freeze-thaw-resistant samples could be produced with an increase in the waste rubber aggregate substitution ratio.

Figure 5 shows the changes in the masses of concretes with 0.5 water/cement ratio according to the number of freeze-thaw cycles applied.

From Figure 5, it was seen that at the end of 250 and 300 freeze-thaw cycles, the weight loss of concrete without waste rubbers (0.5C) increased significantly to 2.5% and 3.8%, respectively. On the other hand, the mass changes of all concrete containing waste rubber aggregate did not exceed 0.5% after 300 cycles. Here, the effectiveness of the use of waste rubbers in preventing mass loss is visible. For a 0.5 water/cement ratio, all concrete containing waste rubbers were not affected by the freeze-thaw number up to 300 cycles.

When the freeze-thaw test results of concretes with 0.4 and 0.5 water/cement ratios are analyzed together, while the mass change at the end of 300 cycles in 0.4C concrete without waste rubbers is about 0.1%, the said mass loss in 0.5C concrete is 3.8%. In terms of mass loss, significant reductions in freeze-thaw resistance were seen in conventional concretes as the water/cement ratio increased. However, it was observed that the water/cement ratio was not a very effective parameter in concretes containing waste rubber aggregate with a very small amount of steel wire. Different researchers have shown that recycled rubber aggregates reduce the mass loss of concretes due to the freeze-thaw effect and increase the freeze-thaw resistance (55, 56).

Turgut and Yesilata (57) reported that concretes containing crumb rubber as a natural sand substitute at levels exceeding 50% by volume had higher freeze-thaw resistance. As a result of this study, it was found that the use of waste rubbers reduced the mass loss of concretes, and parallel results were obtained with the literature. The reason for the increase in freeze-thaw resistance due to the use of waste rubbers can be explained in two ways. The first is that the ductile rubber aggregate can allow ice to expand (23). The second one is explained as the fact that the rubber aggregate increases the effective porosity, which increases the entrained air and, hence, the freeze-thaw resistance (58, 59). In addition, it is thought that the size and amount of waste rubber aggregate also affect the results (60). In the literature, it is seen that crumb rubber is used as aggregate in almost all studies, but there is no study in which fine and coarse rubber aggregate are used at the same time. It is thought that this study, which also examines the effect of different water/cement ratios, will fill an important gap in the literature. Figure 5 shows that the mass loss of concrete with a 16% waste rubber ratio increases dramatically after 200 cycles. As stated in the literature (60), especially when the waste rubber ratio exceeds 10%, rubberized concrete becomes more permeable and high weight loss may occur.

The decrease in the compressive strength of the samples at the end of 300 freezes and thaws compared to the compressive strength of 28-day concretes is given in Figure 6. According to Figure 6, compressive strength decreased in all concretes at the end of 300 freeze-thaw cycles. The lowest compressive strength losses were observed in concrete without waste rubbers (0.4C), with 35% compressive strength loss for 0.4 water/cement ratio, and in concrete with 8% waste rubber substitution (0.5WR8) with 13% compressive strength loss for 0.5 water/cement ratio. Moreover, the compressive strength loss of concrete with code 0.5WR8 was the lowest among all the concretes produced.

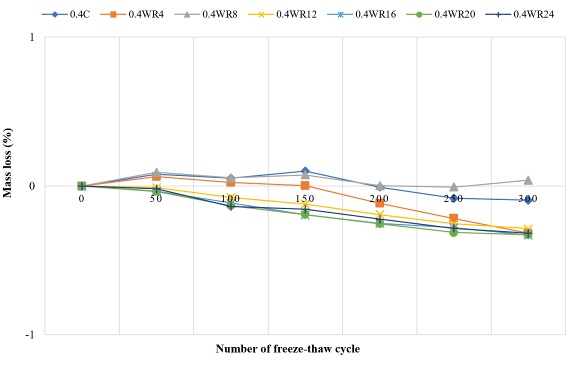

Figure 4. Mass loss (%) of concretes for 0.4 water/cement ratio according to the number of freeze thaw cycles.

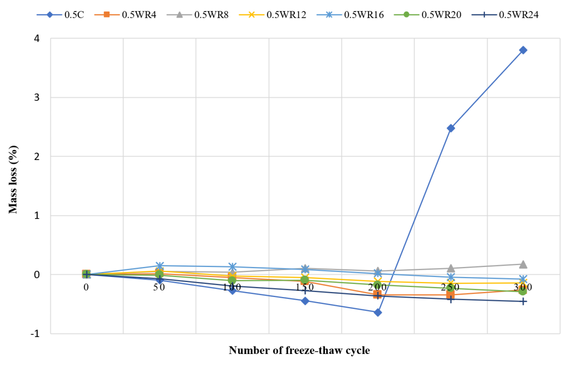

Figure 5. Mass losses (%) of concretes for 0.5 water/cement ratio according to the number of freeze thaw cycles.

3.2. Compressive strength loss of rubberized concretes after freeze-thaw cycles

Table 3 presents the compressive strength results of the concrete before the freeze-thaw test.

The compressive strength loss of concrete coded 0.5WR8 is lower at a ratio of about 1/8 than that of concrete coded 0.5C without waste rubbers. While concretes with a 0.4 water/cement ratio have smaller compressive strength losses than those with a 0.5 water/cement ratio for concretes without waste rubbers and 4% waste rubber, the opposite is true for concretes with other waste rubber substitutes. In other words, in general, for concretes containing waste rubbers, the compressive strength loss of concretes with 0.5 water/cement ratio is lower than that of concretes with 0.4 water/cement ratio. In a study, it was recorded that the compressive strength of concretes produced using 5% rubber aggregate by weight increased to 23% after 200 freeze-thaw cycles and decreased by 58% after 400 cycles (61).

In this study, the average compressive strength loss in all groups at the end of 300 cycles was approximately 55%, and the results conformed to the literature. It can be stated that the decrease in compressive strength due to the freeze-thaw effect is the further growth of cracks in the concretes at the end of each cycle and the existence of mass losses (61). As seen in Table 3, as the waste rubber replacement ratio increased, there was a decrease in compressive strength. However, compressive strength losses (Figure 6) compare the concrete before the freeze-thaw test. The minimum compressive strength loss is seen in rubberized concrete with a waste rubber ratio of 8%. It is thought that the internal strains that will arise from the freeze-thaw effect with the presence of rubber in the concrete are compensated to some extent by the waste rubber. In addition, the fact that the steel wire in the waste rubber absorbs the energy created by the stresses caused by the freeze-thaw effect is another reason that prevents the loss of compressive strength (62).

Finally, the sample images of the concrete containing the highest amount of waste rubbers (24%) at the end of 300 freeze-thaw cycles are given in Figure 7. Accordingly, it is clearly seen that concrete samples with a 0.4 water/cement ratio (0.4WR24) containing 24% waste rubbers were damaged more than concrete samples with a 0.5 water/cement ratio (0.5WR24) containing 24% waste rubbers. It was also revealed by the visual results that the water/cement ratio should be a clear parameter of the resistance to be shown by rubberized concretes against freeze-thaw.

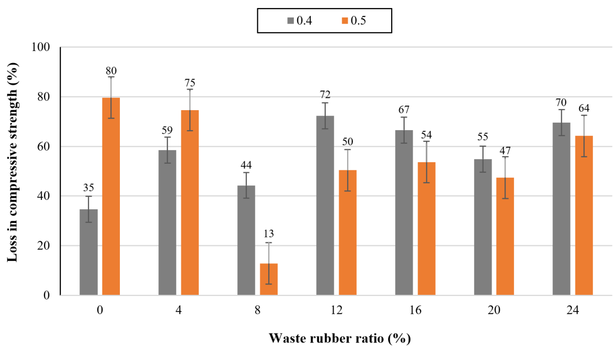

Figure 6. Compressive strength loss of concretes according to numbers of freeze-thaw cycle.

Table 3. Compressive strength results.

Code	Compressive strength (MPa)	Code	Compressive strength (MPa)
0.4C	60.7	0.5C	46.0
0.4WR4	50.3	0.5WR4	38.9
0.4WR8	43.4	0.5WR8	33.7
0.4WR12	36.2	0.5WR12	30.8
0.4WR16	32.1	0.5WR16	25.5
0.4WR20	29.7	0.5WR20	20.4
0.4WR24	28.0	0.5WR24	22.2

Figure 7. Image of rubber concretes with 24% waste rubber aggregate after 300 freeze-thaw cycles.

3.3. Microstructural analysis

The microstructures of the concrete subjected to the freeze-thaw test at the end of 300 cycles were analyzed by SEM analysis. The SEM analysis results of the control concrete with water/cement ratios of 0.4 and 0.5 and the concretes in which the highest waste rubber ratio (24%) is substituted are given in Figure 8. Figure 8(a) shows the microstructure of concrete without waste rubbers and a water/cement ratio 0.4. According to the results of the freeze-thaw test, obvious cracks appeared thoroughly in the cement paste. Figure 8(b) shows the internal microstructure of concrete with the highest waste rubber substitution (24%) and a water/cement ratio of 0.4. Figure 8(b) clearly shows that no cracks or large pores were formed between the rubber and the hydration products. Figure 8(c) shows the microstructure of waste rubber-free concrete with a water/cement ratio of 0.5. According to Figure 8(a), as the water/cement ratio increased from 0.4 to 0.5, the width of the cracks in the matrix increased and became clear. This indicates that the increase in water/cement caused significant damage to the microstructure with freeze-thaw cycles. The SEM analysis result of 24% waste rubber substituted concretes with a water/cement ratio of 0.5 (Figure 8(d)) revealed that no cracks were formed either in the rubber or in the interface region with the hydration products. This result proved that the use of waste rubbers in concrete increased the resistance to freeze-thaw. In Figure 8(b) and (d), the products (C-S-H and $Ca(OH)_2$) formed as a result of cement hydration can be seen. In addition, it was obtained that no significant cracks or voids were formed in the interfacial transition zone (ITZ) between the waste rubber/cement matrix. It is evaluated that these results are distinctive from the few studies in the literature (2, 63). When the SEM analysis results were evaluated in general, it was seen that the formation of cracks in the microstructure was significantly reduced with the use of waste rubbers as a result of freeze-thaw. In addition, as seen in Figure 8(b) and Figure 8(d), as a result of SEM analysis, it is thought that the compressive strength decreases due to non-homogeneous microstructures (64).

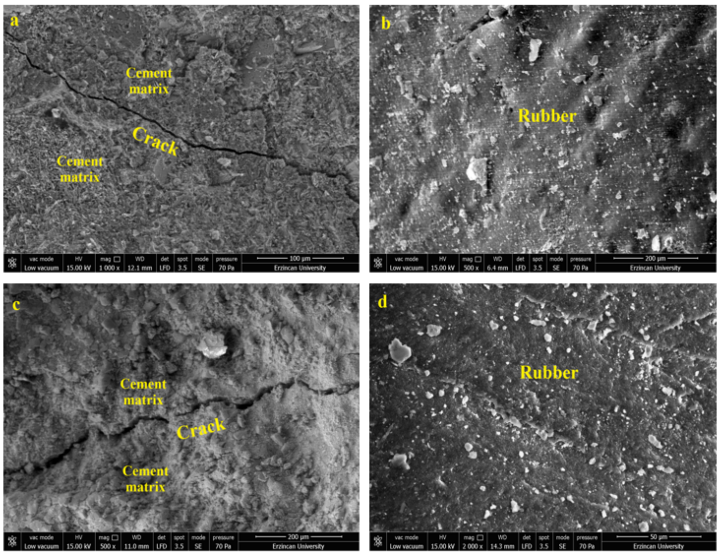

Figure 8. Structure of the concretes; (a) control concrete (0.4C) mag x1.000, (b) 24% waste rubber substituted concrete (0.4WR24) mag x500, (c) control concrete (0.5C) mag x500, (d) 24% waste rubber substituted concrete (0.5WR24) mag x2.000.

3.4. ANOVA analysis

At the end of 300 freeze-thaw cycles, with the ANOVA analysis performed, it was determined whether the waste rubber substitution ratio and water/cement ratio had a significant effect on the percentage changes in weight loss and compressive strength loss of the concrete. The results of the analysis were interpreted in a way to be within a 95% confidence interval. The fact that p values obtained here are lower than 0.05 means that the examined parameter has a significant effect on the target result. Table 4 shows the ANOVA analysis performed on the percentage weight and compressive strength losses at the end of 300 cycles. From Table 4, it is seen that the p-value for the effect of the water/cement ratio on weight loss is 0.0502. Since the p-value is higher than 0.05, it is seen that the difference in water/cement ratio is not a significant parameter in the mass loss amounts of the samples at the end of the freeze-thaw test. However, since the value found (0.0502) is very close to the limit value (0.05), it is not very accurate to say that the water/cement ratio is insignificant on concrete mass losses. On the other hand, since the p-value found for the waste rubber substitution ratio is 0.0087, it is seen that the waste rubber substitution ratio is an effective parameter on the mass loss of the concretes at the end of the freeze-thaw test. Since both the effect of the water/cement ratio (p-value = 0.8869) and the effect of waste rubber substitution ratio (p-value = 0.0937) were higher than the limit p-value (0.05) for the compressive strength loss, it is seen that these two parameters are not effective parameters on the compressive strength loss of concretes after 300 cycles of freeze-thaw.

Table 4. The result of ANOVA analysis.

For mass loss (%)					
Source	Sum of Squares	Degree of Freedom	Mean Squares	F-value	p-value
Effect of water/cement ratio	2.7707	1	2.77075	4.34	0.0502
Effect of waste rubber ratio	15.2813	6	2.54688	3.99	0.0087
Error	12.7649	20	0.63825		
Total	30.8169	27			
For compressive strength loss (%)					
Source	Sum of Squares	Degree of Freedom	Mean Squares	F-value	p-value
Effect of water/cement ratio	7	1	7	0.02	0.8869
Effect of waste rubber ratio	4329.2	6	721.536	2.14	0.0937
Error	6748.5	20	337.425		
Total	11084.7	27			

4. CONCLUSIONS

The following findings can be concluded regarding the performance of rubberized concrete against the freeze-thaw effect;

1. In rubberized concretes with a water/cement ratio of 0.4, mass losses decreased with an increased waste rubber substitution ratio. In concretes with a 0.5 water/cement ratio, the mass loss in the control concrete increased up to 3.8%. In rubber-containing concretes, this mass loss percentage did not exceed 0.5%.
2. As a result of the freeze-thaw test, compressive strength loss occurred in all concretes. The minimum compressive strength loss was obtained with 13% in 8% waste rubber substituted concrete (0.5WR8) with a water/cement ratio of 0.5. The compressive strength losses of rubberized concrete with a 0.5 water/cement ratio were lower than the 0.4 water/cement ratio.
3. As a result of the visual evaluation, the damage on the surface of the 24% waste rubber substituted concretes with a 0.4 water/cement ratio was found to be much higher than the 0.5 water/cement ratio.
4. Freeze-thaw test results and SEM analysis results were found to be very consistent with each other. The use of waste rubber in concrete up to 24% resulted in high resistance to freeze-thaw. Serious cracks in concrete without waste rubbers support this conclusion. Increasing the water/cement ratio in rubberized concrete did not cause any significant difference in the microstructure and did not cause any cracks or damage.
5. At the ANOVA analysis, it was observed that the waste rubber replacement ratio had a significant effect on the mass loss of concretes as a result of freeze-thaw. The p-value for the effect of the water/cement ratio on weight loss was found to be 0.0502. Since this value is very close to the limit value of 0.05, it can be said that it is not an insignificant parameter.
6. It was observed that the use of waste rubbers as aggregate in concrete increased the freeze-thaw resistance. It can be clearly stated that the use of waste rubbers in concretes that will be exposed to these conditions will be beneficial within the framework of the principle of sustainability.
7. This experimental study revealed that the water/cement ratio should be considered an important parameter along with the waste rubber substitution ratio on the behavior of rubberized concretes subjected to freeze-thaw.

Authorship contribution statement

Halit Alperen Bulut: Conceptualization, Methodology, Investigation and Writing-original draft.
Ufuk Kandil: Conceptualization, Methodology, Investigation and Writing-original draft.

Declaration of competing interest

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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