The effect of recycled crumb rubber and steel fibers on durability of roller-compacted concrete pavement

Morteza Madhkhan*[1], Farshid Heidary[2]

1. Professor, Corresponding Author, Department of Civil Engineering, Isfahan University of Technology (IUT), Isfahan, Islamic Republic of Iran
madhkhan@iut.ac.ir

2. MSc. Graduate, Department of Civil Engineering, Isfahan University of Technology (IUT), Isfahan, Islamic Republic of Iran
farshid.heydari@cv.iut.ac.ir

Abstract

The low cost, good initial strength, and high execution speed of roller-compacted concrete pavements make them an excellent alternative to conventional pavements in many road construction projects. This concrete can be made with recycled rubber granules instead of natural aggregates to preserve natural aggregate resources and contribute to rubber waste recycling. Recycled steel fibers can also be added to this concrete to improve its mechanical properties. This study investigates the effect of using different amounts of crumb rubber instead of aggregates both alone and in combination with recycled steel fibers on the mechanical properties and durability of roller-compacted concrete in pavements, including freeze-thaw resistance, water penetration, and water absorption. Moreover, the amount and size of rubber crumbs play an important role in the compressive strength of specimens under the freeze-thaw cycles. The designs with higher rubber contents had better compressive strength reduction under the freeze-thaw action, as the designs containing 14% cement and 0, 5, 10, 15, and 20% crumb rubber showed respectively 3.1, 16.8, 12.4, 9.5, and 7.9% strength reduction after 300 freeze-thaw cycles. Water absorption and water penetration depth increased in the specimens containing more crumb rubber. Adding recycled steel fibers did not positively impact the durability of specimens, as the designs containing 14% cement and 0, 30, and 45 kg/m^3 of recycled steel fibers showed respectively 3.1, 4.7, and 4.9% strength reduction after 300 freeze-thaw cycles. Adding crumb rubber increases water penetration and water absorption. Also, durability parameters improved as cement content increased from 14% to 17%.

Keywords: roller-compacted concrete, crumb rubber, recycled steel fibers, mechanical properties, durability

1. Introduction

By definition, roller-compacted concrete pavement is a pavement that is made with zero-slump concrete composed of a relatively dry blend of aggregates, cementitious materials and water, which is placed by conventional paving machines and then compacted by a roller to turn into hard concrete. Since the compaction operation is done with a roller (unlike in ordinary concrete, where it is done by vibration), this concrete is known as roller-compacted concrete (ACI 309.5R-99 (2004), Aghaeipour and Madhkhan, 2020). On the other hand, to reduce the use of aggregates and sustainability of natural resources, and problems associated with the disposal of waste rubber, many researchers are using waste rubber to replace aggregates with crumb rubber and steel fibers to improve mechanical properties. The performance of concrete containing crumb rubber has been studied since the early 1990s. This type of concrete is known to have higher flexibility, impact resistance, and energy dissipation capability than conventional concrete (Moustafa, and El Gawady, 2016; Liu et al., 2013). Eldin and Senouci (1993) were the first to study the effect of rubber on concrete. They found that crumb rubber reduces workability and compressive and tensile strength but increases durability and ductility. In a study by Raffoul et al (2016), they reported that replacing the entire sand with crumb rubber results in a 90% reduction in strength, and replacing 60% of coarse aggregate with crumb rubber leads to an 80% strength reduction. The main cause of this strength reduction was reported to be reduced adhesion at the interface of the hardened matrix with cement. According to Torres et al. (2018), there exists an optimal combination of rubber particle size and ratio that improves the performance of concrete under cyclic load stresses. In a study carried out by Ganjian et al. (2009), they reported that replacing aggregates with crumb rubber increased the water penetration depth, replacing coarse aggregates with crumb rubber increased the water absorption, and replacing a percentage of cement with rubber powder decreased the water absorption of concrete. Zhang et al. (2018) investigated the effect of rubber particles and steel fibers on the frost resistance of roller-compacted concrete in potassium acetate solution. In this study, all specimens showed increasing mass reduction with the increasing number of freeze-thaw cycles, especially in the first 100 cycles. Since all specimens also showed signs of micro-cracking after 300 freeze-thaw cycles in potassium acetate solution, it was concluded adding rubber particles and steel fibers does not effectively reduce cracking induced by the freeze-thaw process in potassium acetate solution. Zarei et al. (2022) considered the effect of crumb rubber and recycled steel fiber on the mechanical properties, and abrasion and freezing–thawing resistance of conventional concrete pavement. They showed even the crumb rubber's inclusion reduces the mechanical strength significantly and durability resistance, but the most appropriate way to benefit from the desirable characteristics of rubberized concrete while minimizing the crumb rubber inclusion's adverse effects is through the addition of fibers into the concrete mixtures. Modarres and Ghalehnovi (2023) did an overview of the recent research on the effect of recycled steel fibers from waste tiers on the mechanical characteristics and durability properties of concrete. They showed that using recycled steel fibers to strengthen concrete can be a suitable alternative to industrial steel fibers, which have fewer adverse effects on the environment and reduced recycling costs. Liu et al. (2016) showed that surface-treated rubber particles can improve the adhesion of the rubber matrix, which has a positive effect on the mechanical properties and durability of crumb rubber concrete. A 20% replacement of fine aggregate and a 5% replacement of the total mixture with crumb rubber after pretreatment met the safety strength requirements of concrete and had excellent durability. Mohammed and Adamu (2018) reported that the replacement of fine aggregates with crumb rubber in roller-compacted concrete pavement reduced the Vebe time. This effect was attributed to the hydrophobic nature of crumb rubber, as it increases free water in the mixture and reduces compaction time. However, the addition of nano-silica slightly improved the Vebe time. They also found that the addition of crumb rubber reduces the compressive strength. The Vebe test is a common method for measuring the workability of roller-compacted concrete. In a study by Sukontasukkul et al. (2019) the Vebe time of roller-compacted concrete increased with the amount of steel fibers added to its mixture. This means that it takes more time to compact the fiber-containing mixture than ordinary roller-compacted concrete. In this study, ordinary roller-compacted concrete had a brittle behavior, but the one containing steel fibers was soft and ductile. Keles et al. (2024) showed that as the proportion of waste rubber added to the RCC mixes increased, so did the optimal water content, necessitating additional water for the mixture. For RCC mixes containing 30% waste rubber additive, the water required was about 7% greater. Abed et al. (2024) indicated that using 10% crumb rubber and 0.6% recycled steel fibers results in a notable increase in impact energy compared to reference RCC specimens. The addition of CR and RSF enhances the abrasion resistance of RCC, making it well-suited for pavement applications. Juveria et al., (2023) noted that when recycled concrete aggregate (RCA) is mixed with waste tire rubber (TR) for use as pavement material, the TR content should not exceed 15% of the total weight of RCA to satisfy the criteria required for pavement base material. According to Adhikari et al. (2000) the use of crumb rubber improves sound insulation and increases the resistance of concrete to temperature gradients and freeze-thaw cycles, which leads to reduced maintenance costs. In this study, the authors investigated the effect of crumb rubber and recycled steel fibers on several durability parameters, including water absorption, water penetration, and freeze-thaw resistance, and also the compressive strength of roller-compacted concrete.

There are many studies about using crumb rubber in place of natural aggregates and also using recycled steel fibers in conventional concrete. However, the studies conducted on the impact of using these recycled materials on the durability of rolled-compacted concrete pavement are very limited and still need more study. The main focus of the present study is the durability of roller-compacted concrete pavement containing different sizes and amounts of crumb rubber combined with different contents of recycled steel fibers on parameters such as water absorption, water penetration, and compressive strength of the specimens after applying freeze and thaw cycles.

2. Test plan

In this study, first, a series of preliminary tests were performed to determine the properties of materials and the results were compared with the relevant standards. Then, mix designs were developed accordingly and the test specimens made with these mix designs were subjected to freeze-thaw, water penetration, and water absorption tests.

2.1. Properties of materials

The materials used in this research were aggregates (coarse and fine), cement, crumb rubber, recycled steel fibers, microsilica, and superplasticizer. The fine-grained aggregate used in the study was sand with a maximum size of 5 mm. The coarse-grained aggregates were of two types: crushed rock with a maximum size of 19 mm and pea gravel with a maximum size of 12 mm. For the roller-compacted concrete mixtures that contained 14% cement, the aggregate composition was 25% crushed rock (12-19 mm), 15% pea gravel (5-12 mm), and 60% sand. For the mixtures containing 17% cement, the aggregate composition was 19% crushed rock (12-19 mm), 16% pea gravel (5-12 mm), and 65% sand. Specifications of coarse and fine aggregates were determined according to ASTM C33 (2003). Fig. 1 shows the grading of aggregates and the corresponding allowable range as per ACI 325 (2004). The cement used in the study was ordinary type 1 Portland cement (type 425-1) produced by the Shahrekord cement factory. The chemical analysis of this cement is given in Table 1. The microsilica used in the study was produced by Iran Ferroalloys Industries Co. Specifications of this microsilica according to the manufacturer are given in Table 2. The crumb rubber (produced by grinding worn tires) and the recycled steel fibers were acquired from the Daneshfar Factory in Dolatabad, Isfahan. In this research, crumb rubber was used as a partial replacement for fine-grained aggregate (sand). The grading of crumb rubber to be used in this study was selected according to ASTM C33 (2003). This grading is shown in Table 3 and Fig. 2. The Fig. 3 shows an image of crumb rubber used in this research. The specifications of the recycled steel fibers are given in Table 4 and their image is shown in Fig. 4.

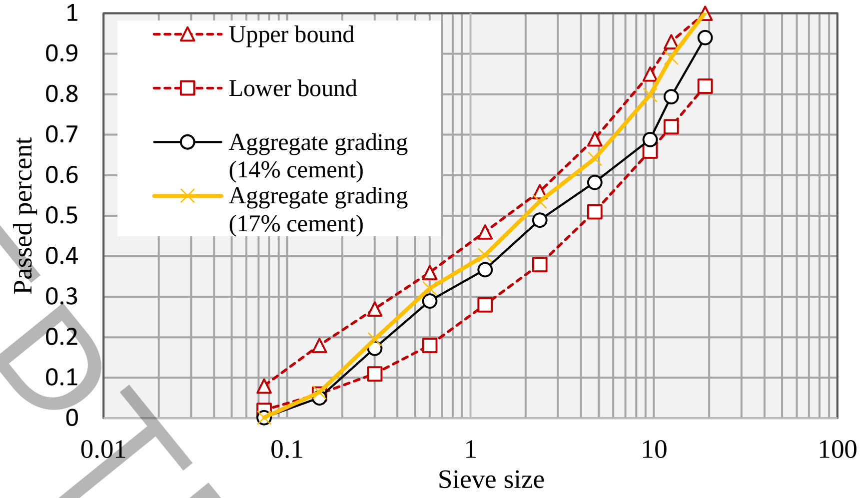

Fig. 1. Grading chart of coarse and fine aggregates for the mix design containing 14% and 17% cement and the corresponding limits in ACI 325

Table 1- Chemical composition of the cement (type 425-1)

Combination	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
Percentage	63.25	21.24	5.1	3.65	1.96	2.55	0.6	0.25

Table 2- Specifications of the microsilica

Combination	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Cl	K_2O+Na_2O	C
microsilica	90-95	1.0-2.6	1.1-8.2	-	1.0-2.6	0.0-7.05	0.0-9.7	0.8-2.0

Table 3- Grading of the granules

Granule composition	powder granules	1-3 mm granules	3-5 mm granules	Sieve size, mm
100	100	100	100	9.5
100	100	100	100	4.75
85	100	100	38	2.36
52	100	29	0	1.18
45	100	8	0	0.6
26	63	0	0	0.3
2	4	0	0	0.15

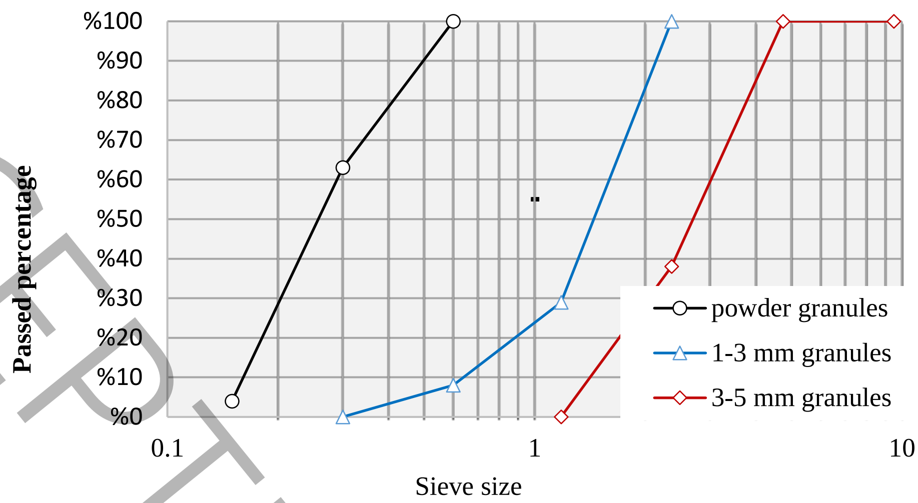

Fig. 2. Grading of the crumb rubber

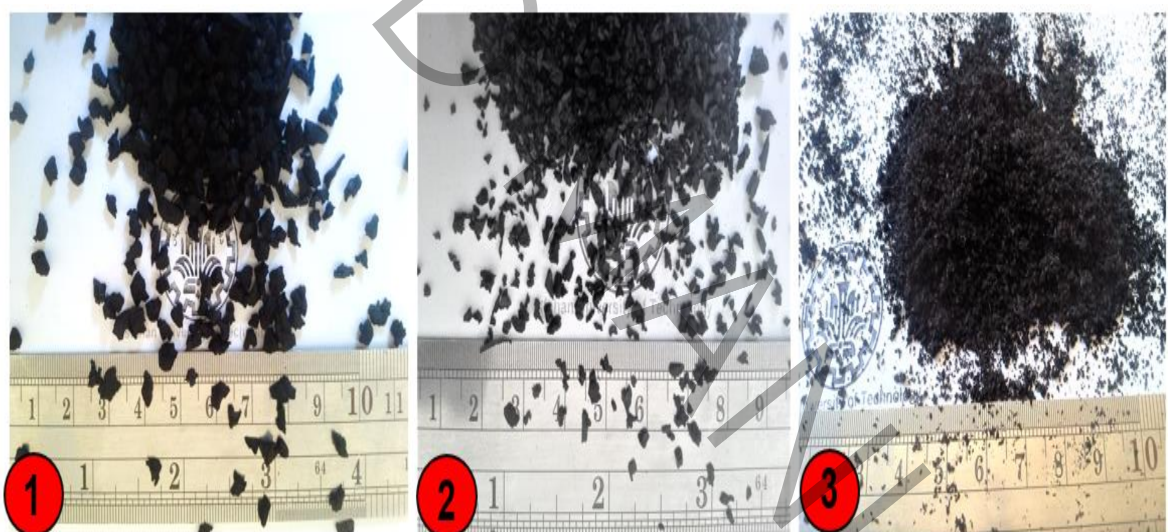

Fig. 3. Crumb rubber: 1) 3-5 mm granules 2) 1-3 mm granules 3) powder

Table 4- Specifications of the recycled steel fibers

Properties	Density (kg/m^3)	Length (mm)	Diameter (mm)	elongation increase in rupture (percent)	Ultimate strength (MPa)
steel fibers	7800	5-35	0.3	10	1800-2000

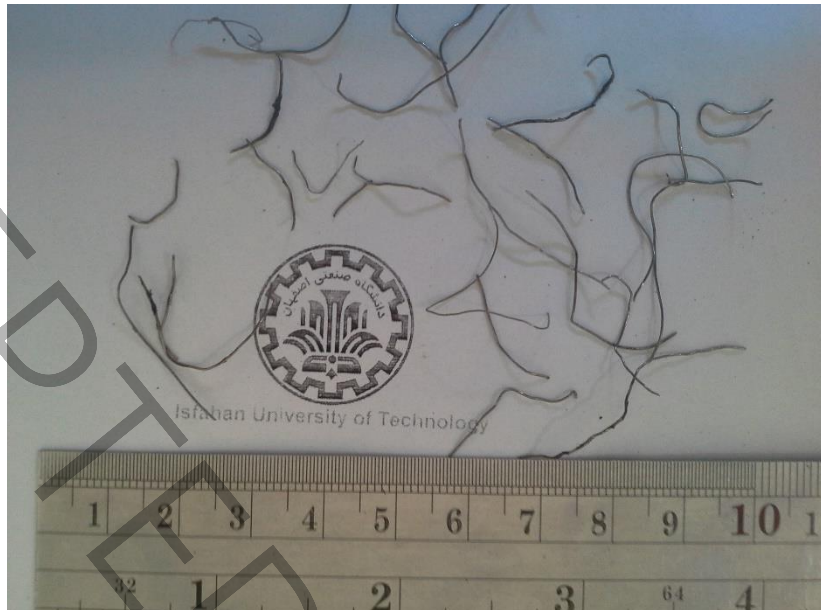

Fig. 4. Recycled steel fibers

2.2. Specimen preparation

In this study, 30 different roller-compacted concrete mix designs were developed using the soil method. The developed mix designs were labeled in the form of CxGyFz, where C stands for cement and x is the cement content of the mixture (14 or 17% by dry weight of aggregates), G stands for granule (rubber) and y is the amount of rubber granule used in the mixture (0, 5, 10, 15 or 20% by volume of aggregates), and F stands for steel fibers and z is the amount of steel fibers used in the mixture (0, 30 or 45 kg/m^3). To make the specimens, the materials were mixed inside a cylindrical mixer with a capacity of 40 liters at a speed of 60 RPM. Each of the resulting mixtures was placed in three 150×150×150mm cube molds and then compacted in three stages according to ASTM D1557 (1991). Since adding crumb rubber to concrete reduces its mechanical properties, microsilica was also used in the mix design to reduce this negative effect. Since adding microsilica and steel fibers to the roller-compacted concrete mixture reduces its workability, a superplasticizer was also added to make the mixture easier to mix, place, and compact. Finally, the optimum moisture for each mix design was determined as explained in section 3.1.

2.2.1. Determination of microsilica content

As mentioned, microsilica can be used to reduce the negative impact of adding crumb rubber to the mixure of rolled-compacted concrete on the properties of this pavement. In this study, the amount of microsilica to be used in place of cement was selected by checking how compressive strength is affected by adding microsilica in amounts of 5, 10, and 15% by weight of cement. Table 5 shows the 28-day compressive strength obtained for the mix design containing 14% cement. As can be seen, the design containing 15% microsilica had higher compressive strength than those with 5% and 10% microsilica, but there was a very small difference between the designs containing 15% and 10% microsilica. But the construction cost of RCC containing 10% and 15% microsilica was increased 4.5 and 7% respectively compared to the one without microsilica. Since it is not economical to use 15wt% microsilica instead of cement and it also reduces the workability and increases the Vebe time of the mixture (Siddique, 2011). So all roller-compacted concrete mix designs of this study were made with 10% microsilica by weight of cement.

Table 5- Compressive strength and Construction cost ratio of RCC containing microsilica

Microsilica Percentage	Average compressive strength (MPa)	Construction cost increase compared to without microsilica (percent)
0	45.6	0
5	51.6	2.4
10	56.3	4.5
15	56.9	7.0

2.2.2. Determination of superplasticizer concentration

Since adding 10% microsilica and 30 or 45 kg/m^3 steel fiber inevitably reduces the workability of roller-compacted concrete mixtures, it is common to use superplasticizers to make these mixtures easier to mix, place, and compact. The suitable amount of superplasticizers to be used for this purpose can be determined by the Vebe test. According to ACI325.10R (2004), the Vebe time of roller-compacted concrete mixtures should be between 30 and 40 seconds. Although adding crumb rubber reduces the Vebe time (Mohammed and Adamu, 2018), this reduction is often not great enough to merit using superplasticizer. In this study, Vebe time measurements were performed on the mix designs with 14% cement. First, the Vebe time of the mix design containing only 0, 5, 10, 15, and 20vol% rubber was measured to determine how the Vebe time is impacted by the rubber content. The Vebe times of the mix designs with 14% cement with rubber (without steel fiber) are shown in Fig. 5. As can be seen, adding crumb rubber reduces the Vebe time by 7 seconds. Next, to determine the amount of superplasticizer needed to keep the Vebe time in the allowable range, the Vebe time of the mixtures containing 14% cement, 0, 30, and 45 kg/m^3 steel fiber, and 0.5, 0.75, 1, and 1.25% (by weight of cement) plasticizer was measured. The results of these measurements are presented in Fig. 6. The target VB time for these mixtures was considered to be 38 seconds so that the final Vebe time in the presence of rubber would fall within the standard range of 30 to 40 seconds. Based on Fig. 7, the amount of superplasticizer needed to reach the Vebe time of 38 seconds for the mixtures with 0, 30, and 45 kg/m^3 steel fiber was estimated to be 0.6, 0.9, and 1.1%, respectively. Therefore, these were considered as suitable amounts of superplasticizer for mix designs with 14% and 17% cement, 0, 5, 10, 15, and 20% crumb rubber, and 0, 30, and 45 kg/m^3 steel fiber.

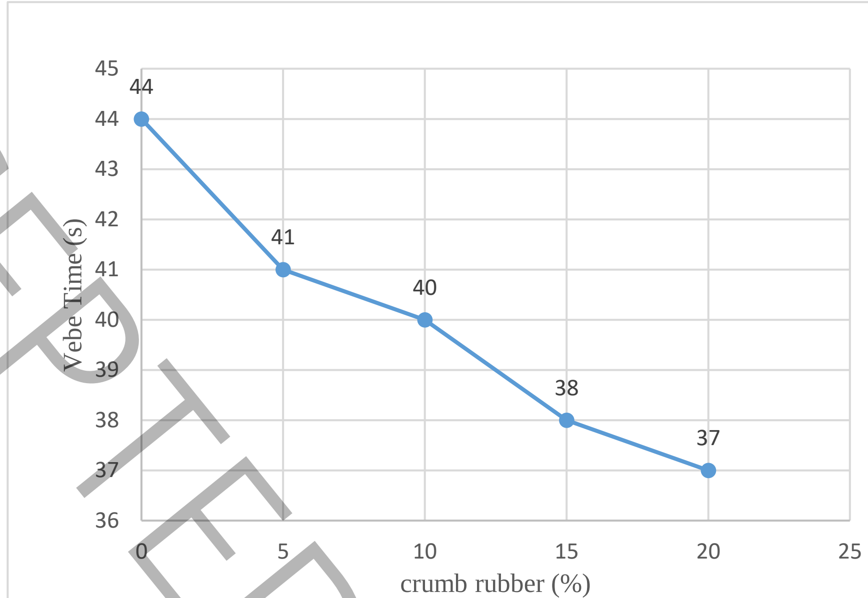

Fig. 5. Vebe time of mix designs with 14% cement and crumb rubber (without steel fibers)

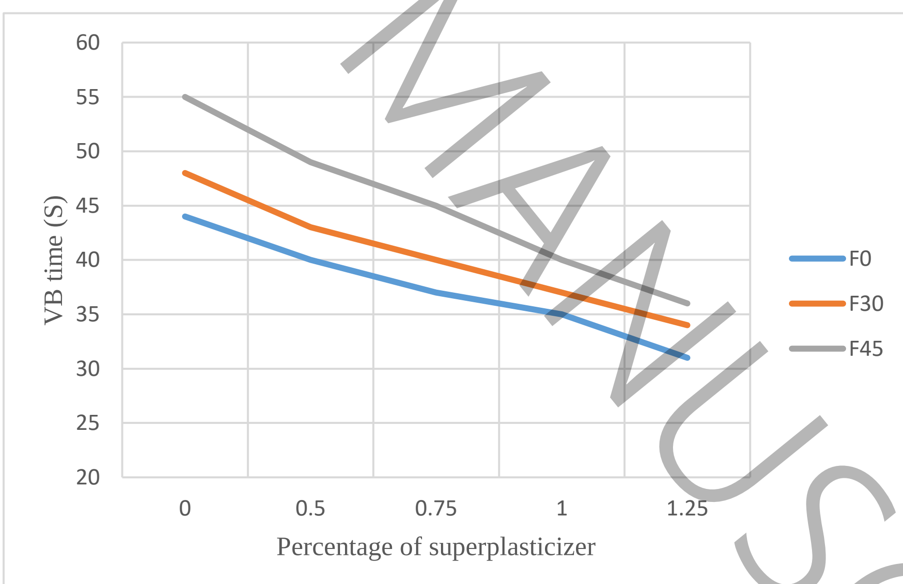

Fig. 6. Vebe time of mix designs with 14% cement and steel fibers (without crumb rubber)

3. Test results and analysis

3.1. Determination of optimum moisture content

To determine the optimum moisture content, a total of 450 cube specimens of size 150×150×150 mm with cement contents of 14 and 17%, steel fiber contents of 0, 30, and 45 kg/m^3, crumb rubber contents of 0, 5, 10, 15 and 20vol% (as a substitute for sand), and moisture contents of 4, 4.5, 5, 5.5 and 6% (by dry weight of aggregates) were created in triplicates using the microsilica and superplasticizer concentrations determined in the previous phase. After determining the dry density of each mixture and plotting the results, the optimum moisture content to be used for the primary designs was estimated. For this purpose, immediately after placing the mixture in a 150×150×150 mm cubic mold, the specimens were weighed and their dry density was obtained using Equation (1):

$$\rho_{dry} = \frac{W_{total} - W_{mold}}{V(1+\omega)} \tag{1}$$

where ρ_{dry} is the dry density of the specimen, W_{total} is the total weight of the specimen and its mold immediately after compaction, W_{mold} is the weight of the empty mold, V is the volume of the specimen, ω is the moisture content of the specimen.

For each mix design, dry density was plotted versus moisture content, and the resulting diagram was used to determine the moisture content that gives the highest dry density. In Fig. 7, the diagram obtained for the mix design C14G5F30 is illustrated as an example.

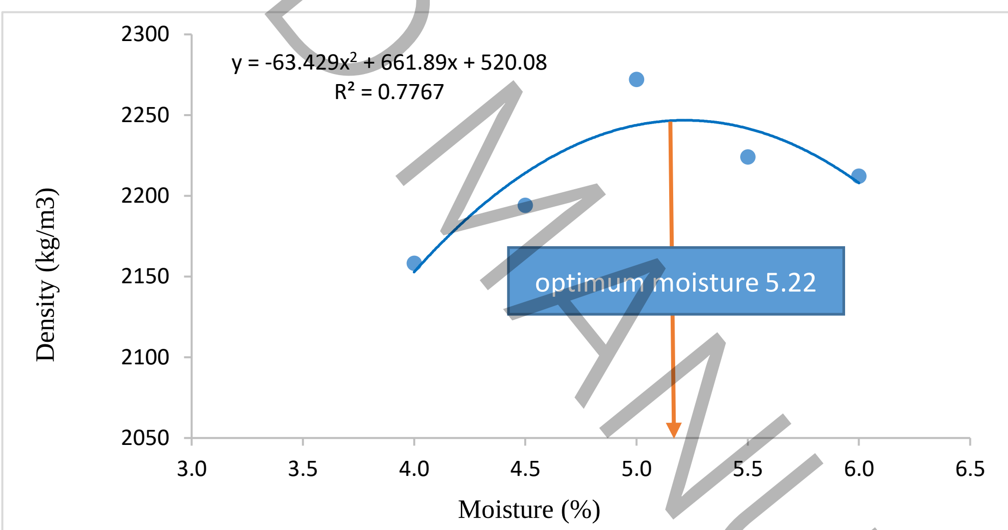

Fig. 7. Optimum moisture content of the mix design C14G5F30

In all mix designs, as moisture content increased, density increased up to a certain point and then started to decrease. The moisture content corresponding to the best density for each mix design is provided in Table 6. These results show that:

- As the cement content increases (from 14% to 17%), the moisture content needed to reach the maximum dry density also increases.
- Adding crumb rubber to the mix design reduces the moisture content needed to reach maximum dry density.
- As the steel fiber content increases (from 0 to 30 and then to 45 kg/m^3), so does the moisture content needed to reach maximum dry density.

Table 6- Results of preliminary tests for the determination of optimum moisture content

mix design	optimum moisture	mix design	optimum moisture
C14G0F0	5.25	C17G0F0	5.32
C14G5F0	5.14	C17G5F0	5.12
C14G10F0	4.81	C17G10F0	5.05
C14G15F0	4.75	C17G15F0	5.01
C14G20F0	4.63	C17G20F0	4.86
C14G0F30	5.37	C17G0F30	5.39
C14G5F30	5.22	C17G5F30	5.26
C14G10F30	4.97	C17G10F30	5.14
C14G15F30	4.87	C17G15F30	5.10
C14G20F30	4.74	C17G20F30	4.87
C14G0F45	5.44	C17G0F45	5.57
C14G5F45	5.20	C17G5F45	5.29
C14G10F45	5.04	C17G10F45	5.17
C14G15F45	4.94	C17G15F45	4.91
C14G20F45	4.71	C17G20F45	4.88

After determining the optimum moisture content, 360 cube specimens of size 150×150×150 mm were made based on the 30 primary mix designs developed based on the results of preliminary tests. The resulting specimens were subjected to water absorption test, water penetration test, and compressive strength test after 150 and 300 freeze-thaw cycles.

3.2. Water absorption test

A total of 90 cube specimens of size 150×150×150 mm were made based on the 30 primary mix designs (Table 6) to measure water absorption. After 28 days of curing in water, specimens were taken out of the water and tested according to ASTM C642 (2002). The following subsections discuss the effect of cement content, rubber cement, and steel fiber cement on water absorption, and also the simultaneous impact of crumb rubber and recycled steel fibers on this parameter.

3.2.1. Effect of cement content on water absorption

The effects of 14% and 17% cement contents on the water absorption of the specimens with different mix designs are plotted in Fig. 8.

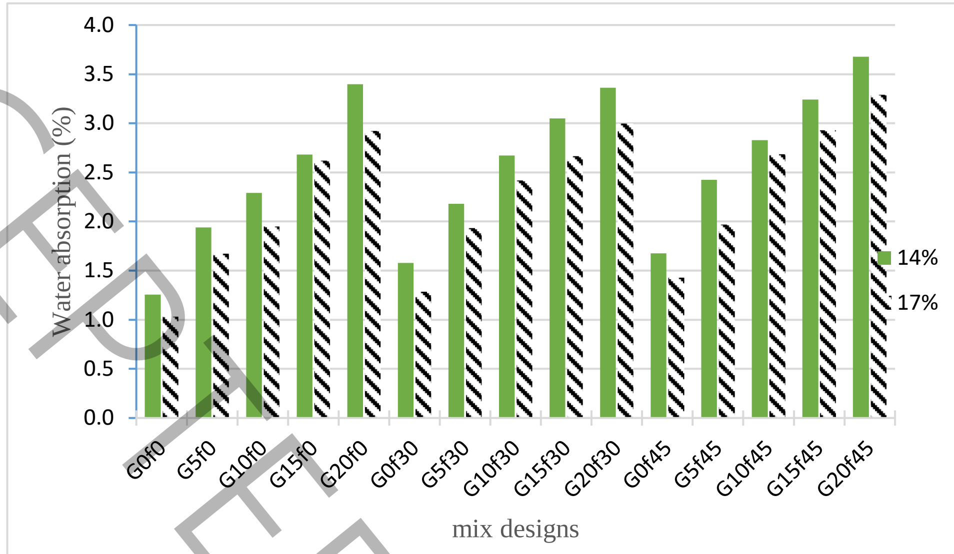

Fig. 8. Water absorption of the specimens with 14% and 17% cement contents

As shown in Fig. 8, in general, as cement content increases from 14 to 17%, water absorption decreases. The lowest water absorption (1.03%) belongs to the mix design C17G0F0 and the highest (3.68%) belongs to the specimen C14G20F45. As can be seen, the water absorption of all designs is less than 4%.

3.2.2. Effect of recycled steel fiber content on water absorption

The results of adding 0, 30, and 45 kg/m^3 of recycled steel fibers to the mix design with 14% and 17% cement content are presented in Fig. 9. In general, as the amount of recycled steel fiber increases, so does water absorption. In the mix design containing 14% cement, adding 30 and 45 kg/m^3 of steel fiber increases the water absorption by 25.4% and 33.4%, respectively, (compared to the control specimen). Similarly, in the mix design with 17% cement content, adding 30 and 45 kg/m^3 of steel fiber to the design increases the water absorption by 24.5% and 38.5%, respectively (compared to the control specimen). The water absorption of all these mixtures is less than 2%.

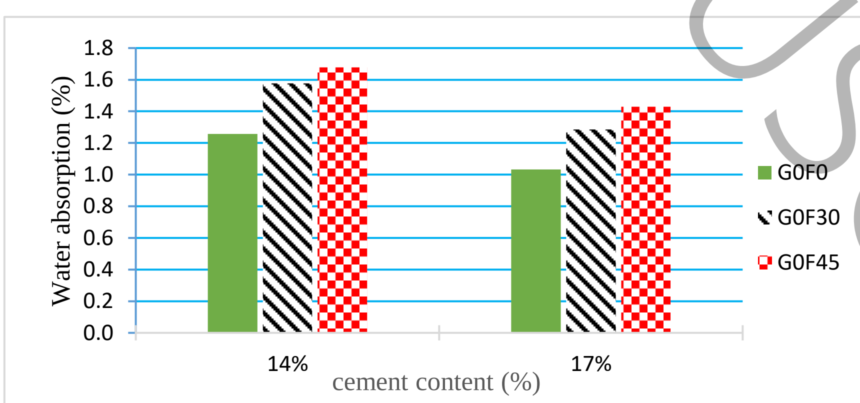

Fig. 9. Water absorption of the specimens containing recycled steel fibers

3.2.3. Effect of crumb rubber content on water absorption

As the amount of crumb rubber added to the mix design increases, the water absorption of the specimen also increases. In the designs containing 14% cement, adding 5, 10, 15, and 20vol% crumb rubber increases water absorption by 0.68, 1.03, 1.43, and 2.14%, respectively. In the designs containing 17% cement, adding the same amounts of crumb rubber increases water absorption by respectively 0.64, 0.92, 1.6, and 1.9% (compared to the control specimen). The water absorption diagram for the mix designs with crumb rubber contents of 0, 5, 10, 15, and 20vol% is shown in Fig 10.

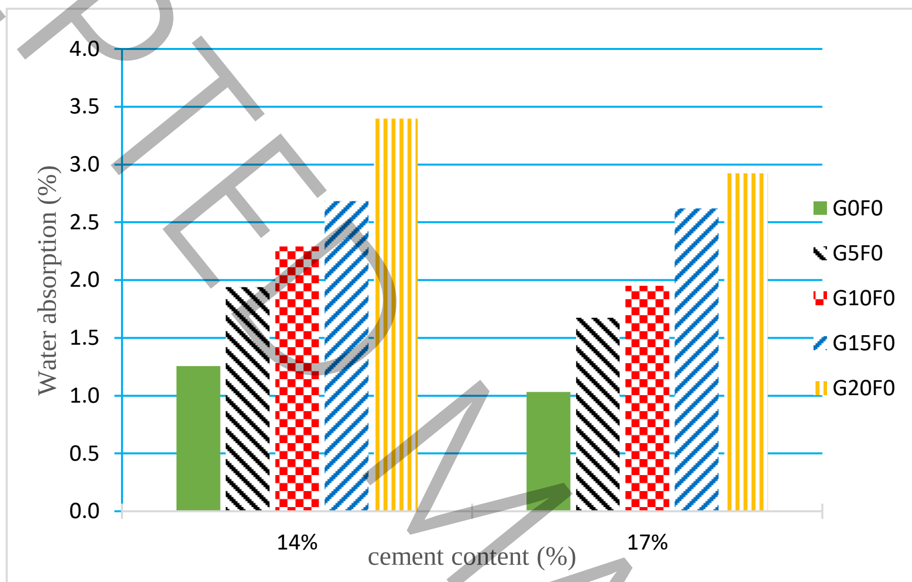

Fig. 10. Effect of crumb rubber on water absorption in the mix designs containing 14% and 17% cement

3.2.4. Simultaneous effect of recycled steel fibers and crumb rubber on water absorption

Adding both crumb rubber and steel fibers to the roller-compacted concrete mixture increases water absorption. The highest water absorption amount in all mix designs (3.68%) was observed in specimen C14G20F45. The increase in water absorption seems to be more influenced by the amount of crumb rubber added to the mixture rather than the amount of steel fibers. The diagram of the simultaneous effect of recycled steel fibers and crumb rubber in the mix designs with 14% and 17% cement contents is illustrated in Fig. 11.

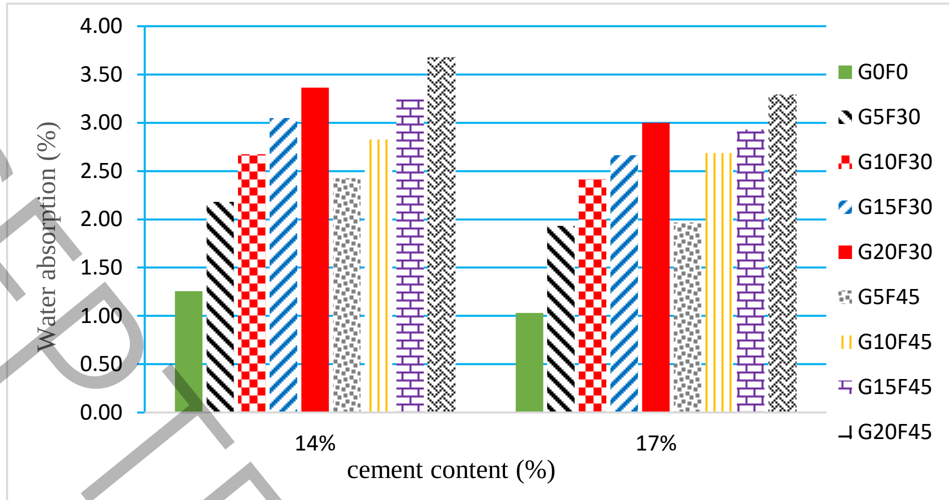

Fig. 11. Simultaneous effect of crumb rubber and recycled steel fibers on water absorption in the mix designs containing 14% and 17% cement

3.3. Water penetration test

A total of 90 prism specimens of size 120×200×200mm were made based on the 30 primary mix designs to examine the water penetration. The specimens were cured for 28 days in water and then tested according to EN 12390-8 (2000) by being subjected to a water pressure of 5 bars for 3 days and then measuring water penetration depth in millimeters. Fig. 12 shows the water penetration test apparatus and the specimens fractured by the Brazilian method to determine the water penetration depth.

Fig. 12. Stages of water penetration test according to EN 12390-8: 1) subjecting the specimens to water pressure, 2) loading and fracture, 3) fractured specimen, 4) measuring the water penetration depth with a digital caliper

In the following, the impact of cement, rubber, and steel fiber on water penetration, and also the simultaneous effect of crumb rubber and recycled steel fibers on this parameter are discussed.

3.3.1. Effect of cement content on water penetration

The results of the water penetration test of mix designs with 14% and 17% cement contents are shown in Fig. 13. It can be seen that in all of the specimens, as cement content increases from 14% to 17%, water penetration decreases. The lowest penetration depth (6.6mm) was observed in C17G0F0 and the highest (48.43 mm) was in C14G20F45.

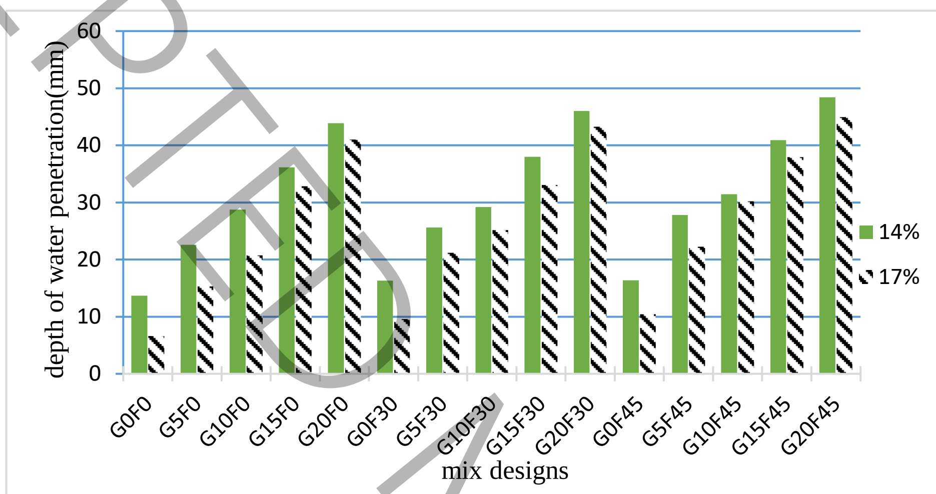

Fig. 13. Water penetration depth for the specimens containing 14% and 17% cement

3.3.2. Effect of recycled steel fibers on water penetration

The results of using 0, 30, and 45 kg/m^3 of steel fibers in the roller-compacted concrete mix design on the water penetration depth are shown in Fig. 14. As can be seen, the penetration depth increases with the amount of steel fiber added to the mix design. For example, in the mix design containing 14% cement, adding 30 kg/m^3 of steel fiber increases the penetration depth by 19% (compared to the control specimen), and adding 45 kg/m^3 of steel fibers increases this depth by 19.5% (compared to the control specimen).

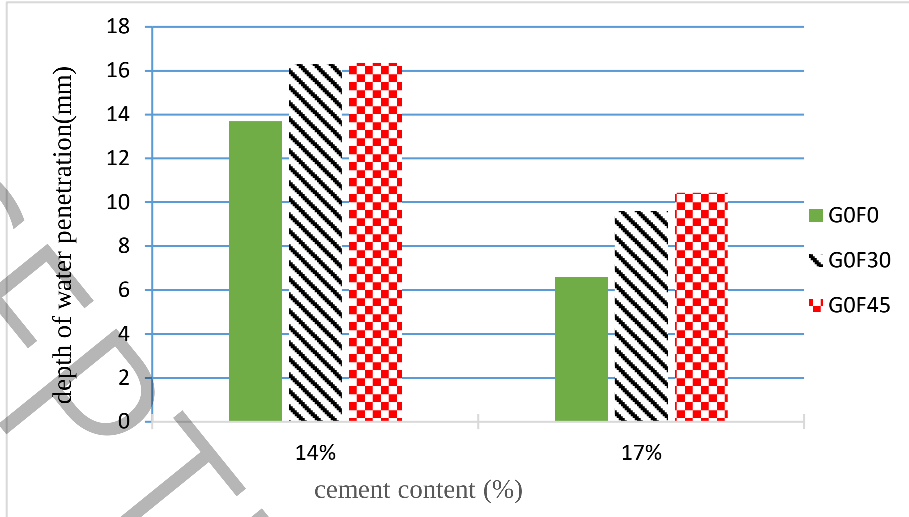

Fig. 14. Effect of recycled steel fibers on water penetration depth in the mix designs containing 14% and 17% cement

3.3.3. Effect of crumb rubber on water penetration

The results obtained by using 0, 5, 10, 15, and 20vol% crumb rubber in the mix designs with 14% and 17% cement contents are presented in Fig. 15. In all mix designs, the penetration depth increases with the increase in crumb rubber content. The lowest penetration depth (6.6 mm) belongs to the control specimen containing 17% cement and the highest penetration depth (43.87mm) belongs to the mix design with 14% cement and 20vol% crumb rubber.

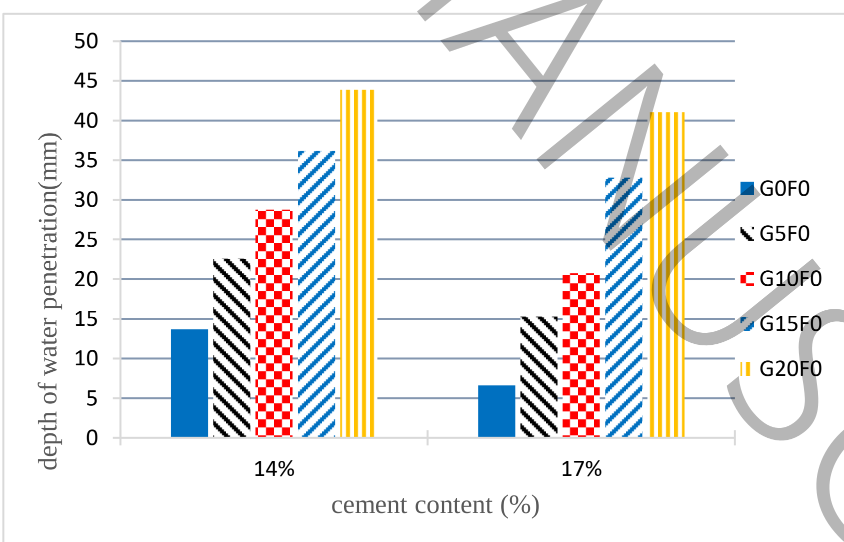

Fig. 15. Effect of crumb rubber content on the water penetration depth in the mix designs containing 14% and 17% cement

3.3.4. Simultaneous effect of recycled steel fibers and crumb rubber on water penetration

The simultaneous effect of using 5, 10, 15, and 20vol% crumb rubber and 30 and 45 kg/m^3 steel fibers in the mix designs with 14 and 17% cement contents is shown in Fig. 16. As with water absorption, water penetration depth too appears to be more affected by the addition of crumb rubber than steel fiber. When used together, crumb rubber and steel fibers have a greater impact on water penetration depth than when they are used individually. The highest penetration depth (48.4mm) was observed in the mix design C14G20F45.

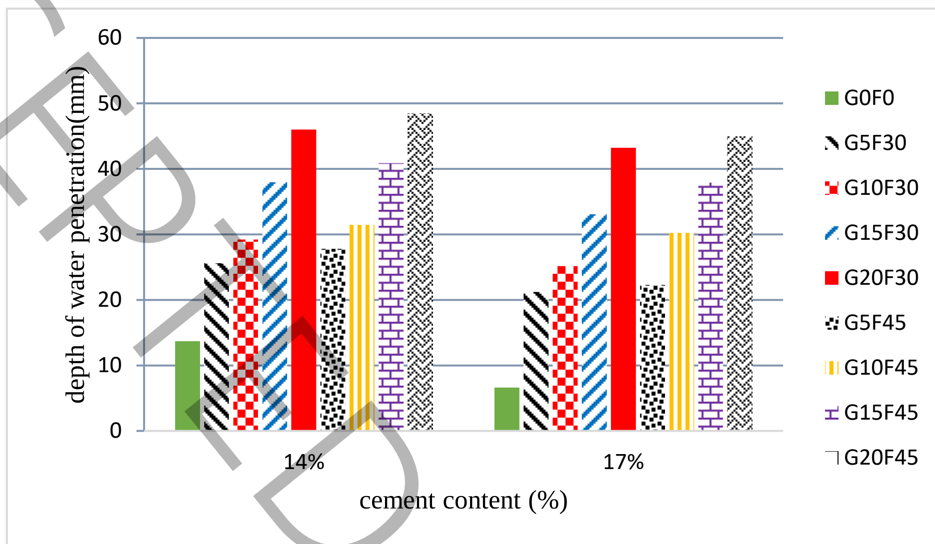

Fig. 16. Simultaneous effect of crumb rubber and steel fibers on water penetration depth in the mix designs with 14% and 17% cement

3.4. Freeze-thaw test

A total of 180 cubic specimens of size 150×150×150 mm with cement contents of 14% and 17% were made based on the 30 primary mix designs (Table 6) for compressive strength measurements. After 28 days of curing in water, the specimens were subjected to 150 and 300 freeze-thaw cycles according to ASTM C666 (2000) and then tested according to BS 1881 (1970) to measure the compressive strength. Fig. 17 shows the freeze-thaw machine used in this study and how the specimens were placed inside it. Fig. 18 shows the fractured specimens after the compressive strength test. The effects of using crumb rubber and recycled steel fibers alone and simultaneously on the compressive strength of roller-compacted concrete after 150 and 300 freeze-thaw cycles are discussed in the following subsections.

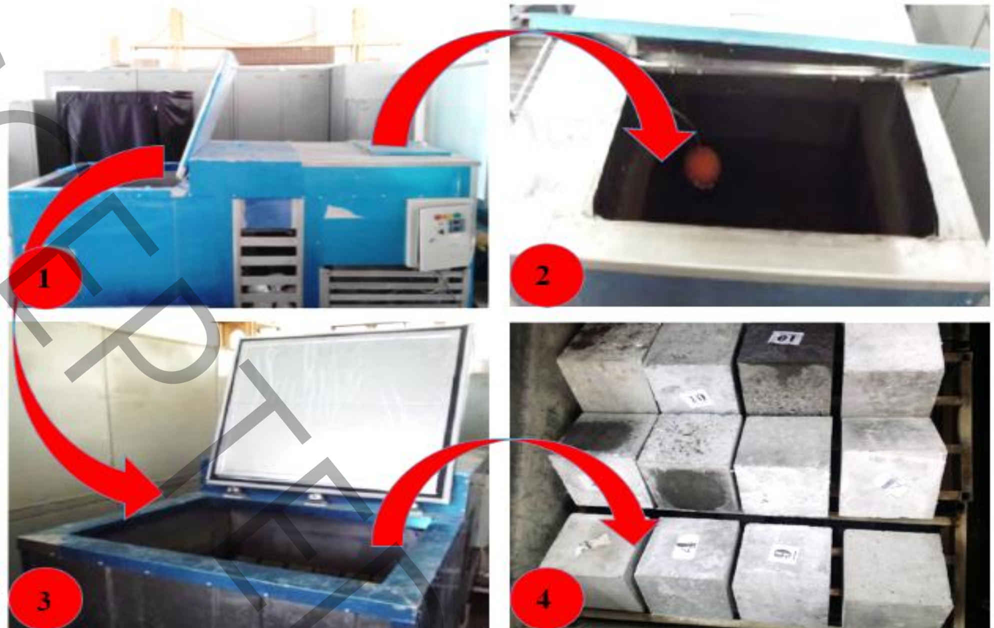

Fig. 17. Placement of cube specimens inside the freeze-thaw machine

Fig.18. Specimens fractured in the compressive strength test after the freeze-thaw cycles

3.4.1. Effect of recycled steel fibers on compressive strength after 150 and 300 freeze-thaw cycles

The results of adding 30 and 45 kg/m^3 of steel fibers to the mix designs with 14% and 17% cement contents on their compressive strength after 150 and 300 freeze-thaw cycles are presented in Figs. 19 and 20. As can be seen, the mix designs containing 14% cement and 0, 30, and 45 kg/m^3 of steel fibers showed respectively 0.01, 3.1, and 3.4% compressive strength reduction after 150 freeze-thaw cycles and 3.1, 4.7, and 4.9% strength reduction after 300 freeze-thaw cycles. Similarly, the mix design containing 17% cement and 0, 30 and 45 kg/m^3 of steel fibers showed respectively 2.6, 3.5 and 4.1% strength reduction after 150 freeze-thaw cycles and 3.7, 5.1 and 6.7% strength reduction after 300 freeze-thaw cycles (compared to 28-day of the specimens not subjected to freeze-thaw cycles).

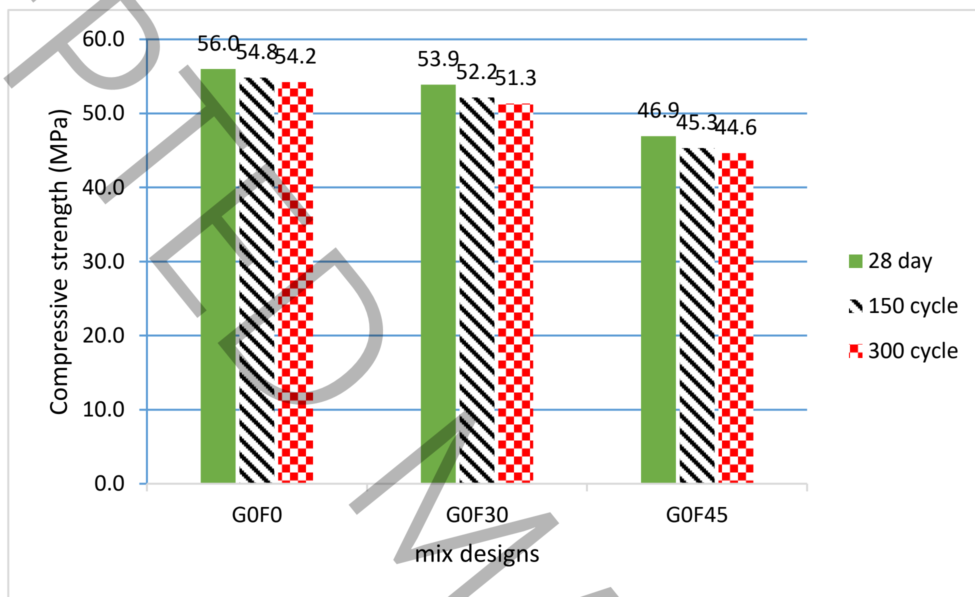

Fig. 19. Compressive strength of specimens containing recycled steel fibers after 150 and 300 freeze-thaw cycles in the mix designs containing 14% cement

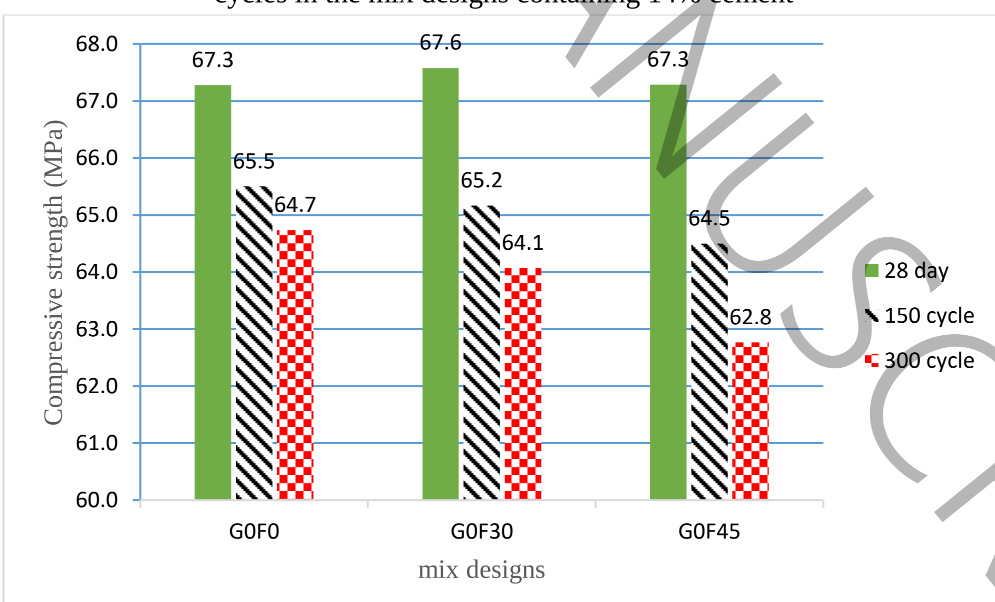

Fig. 20. Compressive strength of specimens containing recycled steel fibers after 150 and 300 freeze-thaw cycles in the mix designs containing 17% cement

3.4.2. Effect of crumb rubber on compressive strength after 150 and 300 freeze-thaw cycles

Figs. 21 and 22 show the compressive strength after 150 and 300 freeze-thaw cycles of the mix designs that contained 0, 5, 10, 15, and 20vol% crumb rubber but not steel fiber. It can be seen that for mix designs with both 14% and 17% cement content, adding crumb rubber generally mitigates the compressive strength reduction that takes place during the freeze-thaw cycles. For example, the design containing 14% cement and 0, 5, 10, 15 and 20vol% crumb rubber showed respectively 2.08, 10.7, 7.9, 6.7, and 6.0% compressive strength reduction after 150 freeze-thaw cycles and 3.1, 16.8, 12.4, 9.5 and 7.9% strength reduction after 300 freeze-thaw cycles.

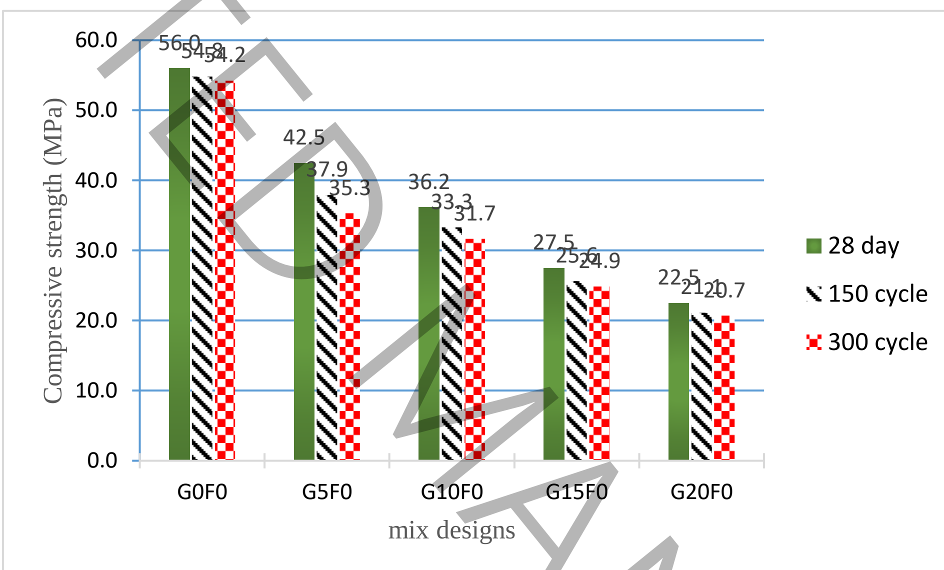

Fig. 21. Effect of crumb rubber on the compressive strength of specimens after freeze-thaw cycles in the mix designs containing 14% cement

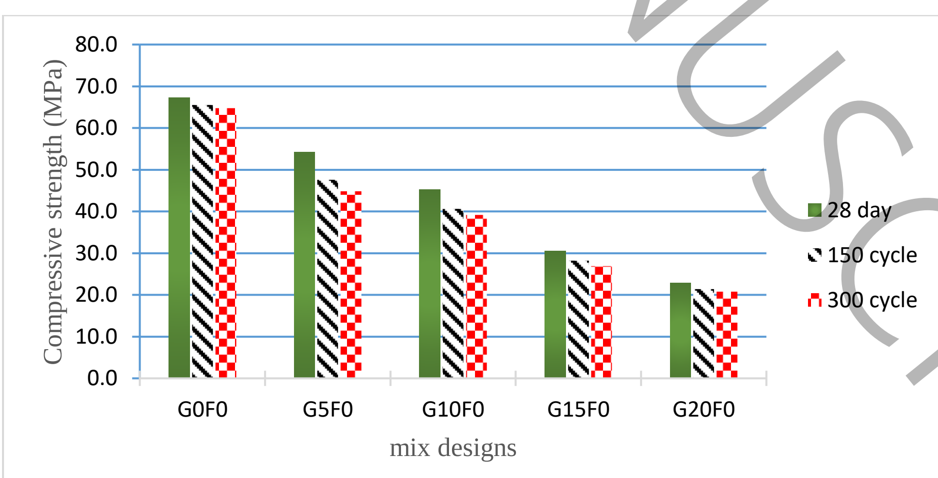

Fig. 22. Effect of crumb rubber on the compressive strength of specimens after freeze-thaw cycles in the mix designs containing 17% cement

3.4.3. Simultaneous effect of crumb rubber and recycled steel fibers on compressive strength after 150 and 300 freeze-thaw cycles

The test results for the specimens containing both crumb rubber and recycled steel fibers suggest that, when used together, these materials make a better improvement in compressive strength reduction after freeze-thaw cycles. As in the previous subsection, using more crumb rubber further mitigates the said compressive strength reduction. For example, for the mix design with 14% cement and 45 kg/m^3 of steel fiber, using a crumb rubber content of 5, 10, 15, and 20vol% has resulted in respectively 19.3, 14.2, 10, and 7.25% strength reduction. Among all mix designs, the design G5F45 has the highest strength reduction (19.3%). The simultaneous effect of having 30 and 45 kg/m^3 of steel fibers and 5, 10, 15, and 20vol% crumb rubber in the mix designs with 14% and 17% cement contents is shown in Figs. 23 and 24.

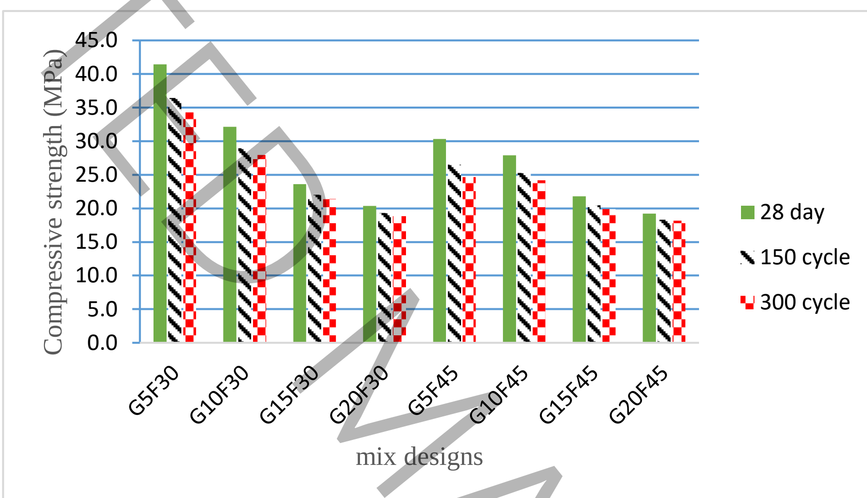

Fig. 23. Simultaneous effect of 30 and 45 kg/m^{3}of steel fibers and 5, 10, 15 and 20vol% crumb rubber on the compressive strength of specimens after freeze-thaw cycles in the mix designs with 14% cement

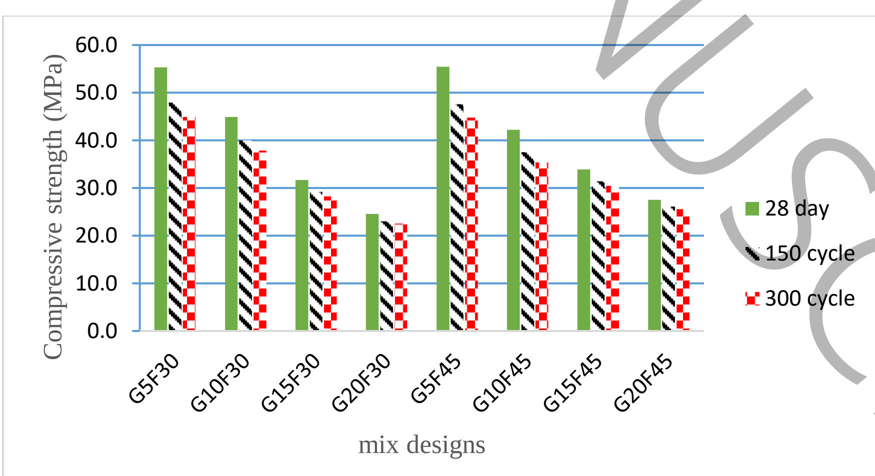

Fig. 24. Simultaneous effect of 30 and 45 kg/m^{3}of steel fibers and 5, 10, 15 and 20vol% crumb rubber on the compressive strength of specimens after freeze-thaw cycles in the mix designs with 17% cement

4. Analysis of results

4.1. Effect of cement content

As the cement content of the mix design increases, the amount of cement paste present in the concrete mixtures also increases. This results in better adhesion of the constituents of concrete and lower porosity of the matrix compared to when less cement is present in the environment. As the volume of pores in the concrete matrix decreases, concrete becomes harder and materials adhere better to each other, which results in decreased water absorption. The reduced number of pores because of higher cement content also makes it more difficult for water to infiltrate the concrete, thereby leading to lower water penetration depth. The degradation of concrete under successive freeze-thaw cycles is due to the penetration of water into concrete pores, where it undergoes a 9% volume increase during phase change to ice. When the concrete matrix is so saturated that there is no space for this volume expansion, it will cause significant hydraulic pressures and tensile stresses, which help create larger pores. These large pores allow more water inside which exacerbates the situation in the next freezing phase, and the continuation of this cycle leads to concrete deterioration. Hence, the rate and level of damage caused by the freeze-thaw action are controlled by the pore structure. As the cement content of the roller-compacted concrete mixture increases, dry aggregates gain better access to cement paste, which results in the development of fewer pores in the specimens. As the porosity of the specimens decreases, so does the space available for water to expand during phase change, which is why high-cement specimens experience greater stresses than low-cement specimens, and therefore, undergo greater degradation.

4.2. Effect of crumb rubber

Given the rough and non-polar surface of rubber particles, adding crumb rubber to the roller-compacted concrete mixture increases the amount of air mixed in the mixture, which increases the volume of cavities and pores in the hardened matrix, ultimately leading to higher water absorption (Mohammed and Adamu, 2018). The increased water penetration depth in the crumb rubber-containing mixture is probably due to the lack of proper bonding between rubber particles and cement paste, as it acts as bedding for pressurized water to flow into concrete (Ganjian, 2009; Alsaif, 2019). Since damage done to concrete during freeze-thaw cycles is due to the formation of ice in concrete pores, controlling these pores plays an essential role in controlling the damage. The freeze-thaw resistance of concrete can be improved by using air entertainment agents to create empty bubbles at close distances to act as receptors of excess water. Adding air entertainment agents reduces the pressure created in the concrete during the ice formation. It has been shown that crumb rubber can produce pores of the same quality as those created by air entertainment agents. The air entrapment property of crumb rubber can be attributed to the hydrophobic nature and rough surface of rubber particles, which retain air during the mixing process. It has been reported that to achieve acceptable durability in cement mortars and concretes, the rubber content should remain below 10-30% by volume of fine aggregates (Kardos and Durham, 2015; Mohammed, 2012). The addition of crumb rubber also increases the air mixed into the roller-compacted concrete mixture, which can reduce the freezing-induced stress in the hardened product. In addition, the excellent damping properties of rubber particles allow them to absorb internal stresses due to freeze-thaw action as well as deformations.

4.3. Effect of recycled steel fibers

Adding recycled steel fibers to the roller-compacted concrete mixture prevents it from becoming sufficiently compacted, which leads to reduced internal friction. Adding recycled steel fibers to this mixture also increases the water needed for the product to reach maximum density. The high water-to-cement ratio increases the water content per unit weight of cement in the roller-compacted concrete mixture, which has a negative impact on the strength of the product. The slight increase in water absorption and water penetration depth after adding steel fibers is probably due to the increase in the water content of the resulting mixture (compared to the control specimen). The increased water-to-cement ratio increases the pore creation and consequently the capillary property, which leads to increased penetrability and water absorption of the specimens containing steel fibers. Another reason behind the high penetration depth of fiber-containing specimens compared to the control specimen could be their poor density. After adding recycled steel fibers to the mix designs with both 14 and 17% cement contents, the resulting specimens showed a slightly greater strength reduction during the freeze-thaw cycles. This suggests that the freeze-thaw action mainly affects the surface of the concrete rather than endangering its internal integrity.

5. Conclusion

This study investigated the effect of recycled steel fibers and crumb rubber on water absorption, water penetration, and freeze-thaw resistance of roller-compacted concrete used in pavement applications. The results of this study are summarized below:

1) Increasing the cement content from 14% to 17% increased the amount of moisture needed to reach the maximum dry density. Also, in both groups of mix design with 14% and 17% cement content, increasing the amount of steel fibers added to the mix from 0 to 30 and then to 45 kg/m^3 increased the moisture content required to reach maximum dry density.

2) Adding recycled steel fibers to the mix design slightly increased the compressive strength reduction of the product under freeze-thaw action. In the mix designs with 14% and 17% cement content and containing 45 kg/m^3 of steel fibers, the greatest strength reductions after 300 freeze-thaw cycles were 4.9% and 6.7%, respectively.

3) Adding crumb rubber to the mix design generally improved the compressive strength reduction due to freeze-thaw action. This is because crumb rubber can produce pores of the same quality as those created by air entertainment agents. This air entrapment property can be attributed to the hydrophobic nature and rough surface of rubber particles, which retain air during the mixing process. Therefore, the amount and size of rubber particles play an important role in the compressive strength of specimens under the freeze-thaw process.

4) Water absorption and water penetration depth of the specimens increased with the amount of crumb rubber added to the mix design. The highest observed water absorption and penetration depth were respectively 3.4% and 43.87 mm, which belonged to the specimen with 14% cement content and 20vol% crumb rubber.

5) Adding recycled steel fibers to the roller-compacted concrete mix designs increased the water absorption and water penetration depth of the resulting specimens. This is because adding recycled steel fibers to the roller-compacted concrete mixture prevents it from becoming sufficiently compacted, which leads to reduced internal friction, and furthermore, it increases the amount of water needed to reach the maximum density.

Acknowledgements

The authors wish to thank the Isfahan University of Technology for funding and supporting the project.

References

[1] ACI 309.5R-99, Compaction of Roller Compacted Concrete Pavements. ACI Manual of Concrete Practice, USA, (2004).

[2] Aghaeipour, A. and Madhkhan, M. Mechanical properties and durability of roller compacted concrete pavement (RCCP)–a review. Road Materials and Pavement Design. 21(7), (2020). 1775-1798.

[3] Zhang, W. Gong, S. and Zhang, J. Effect of rubber particles and steel fibers on frost resistance of roller compacted concrete in potassium acetate solution. Construction and Building Materials. 187, (2018). 752-759.

[4] Zarei, A. Rooholamini, H. and Ozbakkaloglu, T. Evaluating the Properties of Concrete Pavements Containing Crumb Rubber and Recycled Steel Fibers Using Response Surface Methodology. International Journal of Pavement Resources and Technologies. 15(2), (2022). 470–484.

[5] Modarres, Y. and Ghalehnovi, M. The Effect of Recycled Steel Fibers from Waste Tires on Concrete Properties. Civil Engineering Infrastructure Journal. 56(1), (2023). 1-18.

[6] Liu, H. Wang, X. Jiao, Y. and Sha, T. Experimental investigation of the mechanical and durability properties of crumb rubber concrete. Journal of Materials. 9(3), (2016). 172.

[7] Mohammed, B.S. and Adamu, M. Mechanical performance of roller compacted concrete pavement containing crumb rubber and nano silica. Construction and Building Materials. 159, (2018). 234-251.

[8] Sukontasukkul, P. Chaisakulkiet, U. Jamsawang, P. Horpibulsuk, S. Jaturapitakkul, C. and Chindaprasirt, P. Case investigation on application of steel fibers in roller compacted concrete pavement in Thailand. Case Studies in Construction Materials. 11, (2019). p.e 00271.

[9] Keles, Ö. F. Osman Ü. B. and Halim F. B. Experimental investigation on mechanical properties of sustainable roller compacted concrete pavement (RCCP) containing waste rubbers as alternative aggregates. Construction and Building Materials. 424, (2024). 135930.

[10] Abed, Z. M. Wasan I. K. and Hisham K. A. Effect of waste tire products on some characteristics of roller-compacted concrete. Open Engineering. 14 (1), (2024). 20220559.

[11] Juveria, F. Pathmanathan R. Piratheepan J. and Jay S. Impact of stabilization on mechanical properties of recycled concrete aggregate mixed with waste tire rubber as a pavement material. Case Studies in Construction Materials. 18, (2023). e02001.

[12] Moustafa, A. and El Gawady, M.A. Strain rate effect on properties of rubberized concrete confined with glass fiber–reinforced polymers. Journal of Composites for Construction. 20(5), (2016). 04016014.

[13] Liu, F. Zheng, W. Li, L. Feng, W. and Ning, G. Mechanical and fatigue performance of rubber concrete. Construction and Building Materials. 47, (2013). 711-719.

[14] Eldin, N.N. and Senouci, A.B. Observations on rubberized concrete behavior. Cement, Concrete and Aggregates. 15(1), (1993). 74-84.

[15] Raffoul, S. Garcia, R. Pilakoutas, K. Guadagnini, M. and Medina, N.F. Optimization of rubberized concrete with high rubber content: An experimental investigation. Construction and Building Materials. 124, (2016). 391-404.

[16] Torres, R. P. Cerro-Prada, E. Escolano, F. and Varela, F. Fatigue performance of waste rubber concrete for rigid road pavements. Construction and Building Materials. 176, (2018). 539-548.

[17] Ganjian, E. Khorami, M. and Maghsoudi, A. A. Scrap-tire-rubber replacement for aggregate and filler in concrete. Construction and Building Materials. 23(5), (2009). 1828-1836.

[18] Adhikari, B. De, D. and Maiti, S. Reclamation and recycling of waste rubber. Progress in polymer science. 25(7), (2000). 909-948.

[19] ASTM C33-03, Standard Specification for Concrete Aggregates, ASTM International, Philadelphia, (2003).

[20] ACI 325. 10R-04, State of the Art Report on Roller Compacted Concrete Pavements. ACI Manual of Concrete Practice, USA, (2004).

[21] ASTM D1557, Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort. American Society for Testing and Materials, Philadelphia, (1991).

[22] Siddique, R. Utilization of silica fume in concrete: Review of hardened properties. Resources, Conservation and Recycling. 55(11), (2011). 923-932.

[23] ASTM C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete Annual Book of ASTM Standards, ASTM International, Philadelphia, (2002).

[24] EN 12390-8, Testing Hardened Concrete – Part 8: Depth of Penetration of Water under Pressure. European Committee for Standardization, (2000).

[25] ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, Philadelphia, (2017).

[26] BS 1881: part 5, Testing Concrete: Methods of Testing Hardened Concrete for Other Than Strength0 British Standard Institution, London, (1970).

[27] Alsaif, A. Bernal, S. A. Guadagnini, M. and Pilakoutas, K. Freeze-thaw resistance of steel fiber reinforced rubberized concrete. Construction and Building Materials. 195, (2019). 450-458.

[28] Kardos, A. J. and Durham, S. A. Strength, durability, and environmental properties of concrete utilizing recycled tire particles for pavement applications. Construction and Building Materials. 98, (2015). 832-845.

[29] Mohammed, B. S. Hossain, K. M. A. Swee, J. T. E. Wong, G. and Abdullahi, M. Properties of crumb rubber hollow concrete block. Journal of Clean Production. 23(1), (2012). 57-67.