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Research Article

Freeze-thaw and drop-weight impact resistance of fiber-reinforced pervious concretes produced using recycled pervious concrete aggregate

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ABSTRACT

Pervious concrete can rapidly drain stormwater from the top layer to the sublayer. However, the porous structure of this concrete also results in low mechanical properties, which prevent the widespread use of pervious concrete around the world. This study investigated the freeze-thaw and drop-weight resistances of pervious concrete produced with recycled pervious concrete aggregate. Two different aggregate types (limestone and recycled) and two different aggregate size fractions (15/25 mm and 5/15 mm) were used to examine the effect of aggregate type and gradation. Additionally, for improving mechanical and durability properties, polypropylene fibers were used at three different dosages by the volume of mixtures (0.1%, 0.2%, and 0.3%). Within the scope of the study, compressive, splitting-tensile, and flexural strengths, effective porosity, freeze-thaw, abrasion, and impact resistance of pervious concrete were determined. The results showed that concrete produced with recycled aggregate had some advantages in terms of porosity; however, its mechanical properties, freeze-thaw, and impact resistance were lower than those of pervious concretes produced with limestone aggregate. Additionally, fiber addition decreased the compressive strength and effective porosity of pervious concrete. However, up to a certain point (0.2%), fiber addition improved abrasion, freeze-thaw, and impact resistance, as well as splitting tensile and flexural behavior of pervious concrete.

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1. Introduction

With the industrial revolution, there was a mass migration to urban areas. Over the years, more and more people settled in cities, causing an excessive increase in urban area populations and a scarcity of natural resources (Liu et al. 2018). Concrete is the most widely used building material in the world due to its many advantages and its versatility in different applications (Yıldızel 2023; Khan et al. 2020). Although traditional concrete is widely used in urbanization, it is known to be inadequate and disadvantageous in some applications. For instance, when conventional concrete is used in pavement production, the water accumulated on the concrete surface cannot drain at a sufficient speed, leading to puddles and causing various problems. Contrary to traditional concrete, pervious concretes can drain storm water from top layer to sublayer. Hence, averting any accumulated water on surfaces (Gesoglu et al. 2014). The use of a special type of concrete named pervious concrete in areas such as parking lots, pedestrian walkways, and low-traffic zones offers various advantages. In the production of this concrete, either fine aggregates are not used or low amount of fine aggregates are utilized. This results in a pervious structure that is interconnected and allows the transmission of water (Teymouri et al. 2023). Porosity in the range of 15% to 35% in pervious concrete provides the rapid transmission of water, and this situation is affected by various factors like aggregate shape, aggregate gradation, and conductivity (Merten et al. 2022).

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Aggregates are one of the basic components of concrete and constitute approximately 70% to 80% of the concrete volume (Mo et al. 2020). As a result of the increasing demand for concrete, the need for aggregate is growing day by day (Marinković et al. 2010). In the process of natural aggregate production, not only is nature harmed, but also effects such as dust emissions, visual pollution, and noise are created (Yavan and Bozbey 2023). In general terms, it is possible to say that the same materials are used in the production of pervious concrete as those used in traditional concrete production. Studies have been carried out on the production of pervious concrete using aggregates with different properties, such as limestone, basalt, granite, dolomite and river aggregate (Mahboub et al. 2009; Ćosić et al. 2015; Zaetang et al. 2013; Agar-Ozbek et al. 2013; Neptune and Putman 2010).

There are concerns about sustainability in aggregate production like many other areas. Social and environmental demands have led to the increasing use of recycled waste materials as partial substitutes for natural resources (Abuellella and Elmalky 2023; Maciej et al. 2023). Using recycled aggregate produced from waste concrete in concrete production will both protect natural resources and support the solution of the waste storage problem by disposing of waste concrete (Monika et al. 2023). Especially earthquakes and renewals practices cause an increase in the waste concrete issue and create a large amount of waste concrete. The use of these wastes in concrete production -both traditional concrete and special type of concretes like pervious concrete- has been investigated for years (Yan and Huang 2005; Vintimilla and Etxeberria 2023; Yap et al. 2018; Aliabdo et al. 2018; Zhang et al. 2018; Barnhouse et al. 2016). However, recycled aggregates (RA) contain old cement pastes attached to their surfaces; therefore, pervious concretes made with these types of aggregates show lower mechanical properties compared to natural aggregates. Nevertheless, due to indented surface texture of RA, pervious concretes produced with RAs can percolate water faster (El-Hassan et al. 2019; Zhu et al. 2020). Consequently, researchers suggest that with an adequate concrete mix design, RAs can be useful in the production of pervious concrete (Yavuz and Gultekin 2024). Although many studies have been conducted on the properties of RA-bearing pervious concretes, there is a need for research on pervious concretes produced using RA whose parent concrete is pervious concrete. It is thought that the RA obtained from pervious concrete has different properties than the RA obtained from conventional concrete because of thinner adhered mortar/paste.

The pervious concrete is generally used for pavement applications. Exposing to atmospheric conditions makes freeze-thaw (F-T) resistance of pervious concrete as a crucial durability parameter (Taheri et al. 2021). Pervious concretes, due to their highly porous structure, can store excessive amount of water. As the temperature of saturated pervious concrete decreases, the water in the pores of the pervious concrete freezes, causing an internal pressure resulted in detrimental effects. When the temperature rises, thawing follows freezing. With increasing cycles, damage occurs and the extent of damage increases (Neville 1995). While the degree of saturation and pore structure of pervious concrete affect F-T resistance, it was reported (Gesoglu et al. 2014) that the addition of sand and microfibers could increase the strength and F-T performance of pervious concrete.

In this study, the impact resistance, compressive, flexural and splitting tensile strength, and freeze-thaw resistance of pervious concrete produced with recycled pervious concrete aggregate were determined. Two different sieve fractions of aggregate, 5/15 mm and 15/25 mm, were used in this context. Additionally, 0.1%, 0.2%, and 0.3% polypropylene fibers by volume were added to examine the effect of fiber addition on these properties. The results were compared with concrete produced using natural limestone crushed aggregate within the same size fractions.

2. Experimental Program

2.1. Materials

CEM I 42.5 R type ordinary Portland cement in accordance with TS EN 197-1 2012 was used. The specific gravity and specific surface area of the cement were 3.15 and 3220 cm^2/g, respectively. To determine the effect of fiber inclusion on the properties of pervious concrete mixtures, 54 mm long polypropylene fibers were used. Some properties of the fibers obtained from the manufacturer are given in Table 1.

Table 1. Properties of polypropylene fiber.

Property	Value
Density	0.91 g/cm^3
Length	54 mm
Diameter	0.95 mm
Tensile strength	530 MPa
Modulus of elasticity	7.2 GPa
Melting point	160 °C

Two different coarse aggregates (i.e., limestone and recycled pervious concrete aggregate) and tap water were utilized for the preparation of mixtures. Natural coarse aggregate, designated as “L”, was provided by a local ready-mix concrete plant. The recycled aggregate was obtained from pervious concrete produced in the laboratory using limestone aggregate. The limestone aggregate in the parent concrete, from which the recycled aggregate is obtained, is the same limestone used as natural aggregate in this study. Thus, the research aimed to be independent of different factors such as type, surface roughness, and shape. The production process of recycled aggregate is shown in the Fig. 1.

Recycled aggregate was coded as “R”. Moreover, to improve strength, concrete residue with gradations of 0-3 mm was used as fine aggregate (6% by volume of total aggregates). This fine aggregate is the waste produced after using a jaw crusher. Size fractions and some physical properties of the aggregates are listed in Table 2. To attain proper workability and freeze-thaw (F-T) resistance, a superplasticizer (SP) and an air-entraining agent (AEA) were used, respectively. Physical and chemical properties of cement is given in Table 3. Appearances of fibers are shown in Fig. 2.

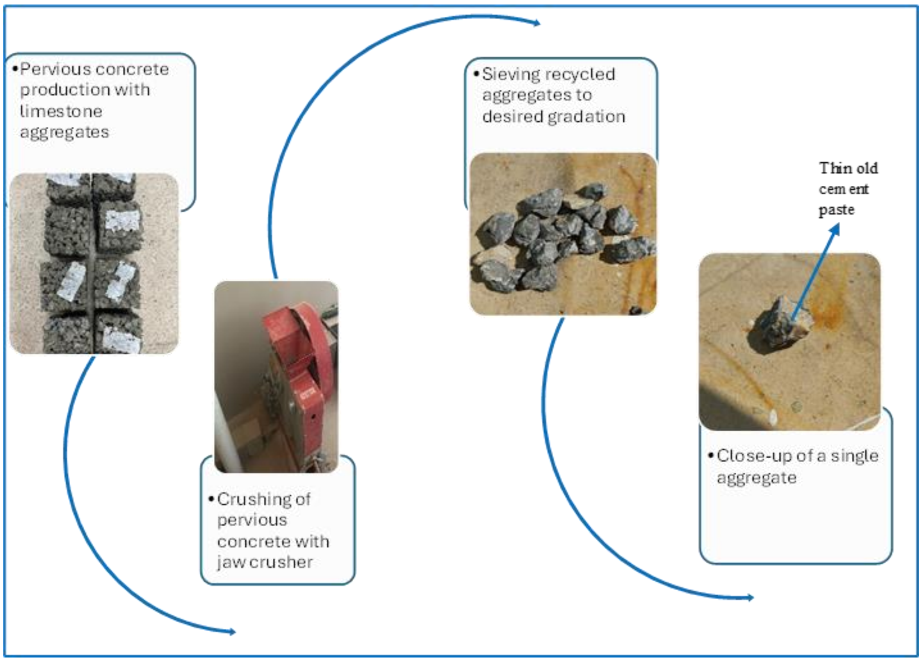

Fig. 1. Production steps for obtaining pervious concrete recycled aggregate.

Table 2. Physical properties of aggregates.

Property	Limestone aggregate		Recycled aggregate		
	5-15 mm	15-25 mm	0-3 mm	5-15 mm	15-25 mm
Specific gravity	2.67	2.71	2.55	2.65	2.61
Water absorption (%)	0.30	0.23	11.26	8.92	5.39

Table 3. Chemical and physical properties of cement.

Property	Value
SiO_2 (%)	18.18
Al_2O_3 (%)	4.70
Fe_2O_3 (%)	3.41
CaO (%)	63.17
MgO (%)	1.22
Na_2O (%)	0.58
K_2O (%)	0.74
SO_3 (%)	3.57
Loss in ignition (%)	3.28
Cl (%)	0.006
Insoluble matter (%)	0.03
Free CaO (%)	0.94
Specific gravity	3.14
Specific surface (cm²/g)	3220

Fig. 2. Appearance of fibers.

2.2. Mixture design and proportion

The study focused on investigating the effects of aggregate type (natural or recycled), aggregate size fraction (5/15 mm and 15/25 mm), and fiber dosage (0%, 0.1%, 0.2%, and 0.3% by total volume) on the properties of pervious concrete. To achieve this, a total of 16 concrete series were produced. The water/cement ratio and target void were maintained constant at 0.33 and 15%, respectively. Concrete series were coded based on the type and size fraction of the aggregate, as well as the fiber dosage, as illustrated in the Fig. 3.

First, cement and aggregates (coarse+fine) were mixed in dry form for 2 minutes and then the fibers were added to the mixture in dry form and the mixing was continued for another minute. Then, AEA additive was added to half of the water and mixed for another minute. Then, the plasticizer additive was added to the remaining mixing water and mixed for another minute. After total of 5 minutes, the mixer was stopped, and the samples were placed in the relevant molds. Total mix proportions of 16 concrete series are given in Table 4.

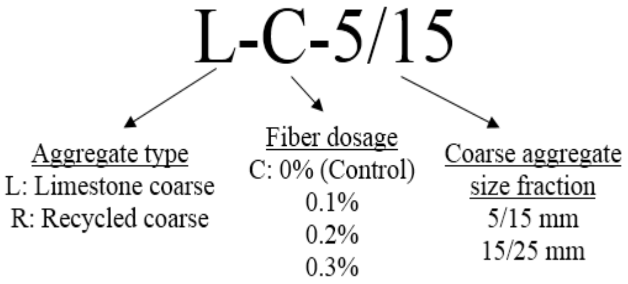

Fig. 3. Nomenclature of concrete mixtures.

Table 4. Mix proportions (1 m^3).

Mixture	Ingredient (kg)					
	Cement	Aggregate (mm)			Water	Fiber (%)
		0/3	5/15	15/25		
L-C-5/15	350	95.3	1564	-	155.5	-
L-C-15/25	350	95.3	-	1588	155.5	-
R-C-5/15	350	95.3	1547	-	155.5	-
R-C-15/25	350	95.3	-	1523	155.5	-
L-0.1-5/15	350	95.3	1564	-	155.5	0.1
L-0.1-15/25	350	95.3	-	1588	155.5	0.1
R-0.1-5/15	350	95.3	1547	-	155.5	0.1
R-0.1-15/25	350	95.3	-	1523	155.5	0.1
L-0.2-5/15	350	95.3	1564	-	155.5	0.2
L-0.2-15/25	350	95.3	-	1588	155.5	0.2
R-0.2-5/15	350	95.3	1547	-	155.5	0.2
R-0.2-15/25	350	95.3	-	1523	155.5	0.2
L-0.3-5/15	350	95.3	1564	-	155.5	0.3
L-0.315/25	350	95.3	-	1588	155.5	0.3
R-0.3-5/15	350	95.3	1547	-	155.5	0.3
R-0.3-15/25	350	95.3	-	1523	155.5	0.3

Only one compaction method, standard rodding compaction, was used in this study. A total of three-stage compacting method was used, with each stage being rodded 25 times. After demolding, pervious concretes were kept in water for 27-day (total of 28-day) and related tests were performed.

2.3. Testing

In the scope of this study, compressive, splitting tensile, and flexural strengths were determined. 150×150×150 mm cube samples, 100×200 mm cylindrical samples and 100×100×400 mm prismatic samples were used to determine compressive, splitting-tensile and flexural strengths, respectively. All mechanical tests were performed in accordance with standards (TS EN 12390-3 2019; TS EN 12390-5 2019; TS EN 12390-6 2010).

Since it has been reported that effective porosity is the key factor for the strength and service functions of pervious concrete, effective porosity was determined instead of total porosity. Effective porosity was measured using the volumetric method, as described by Eq. (1) (Liu et al. 2019).

$$P_e = \left(1 - \frac{m_1 - m_0}{V \times \rho}\right) \times 100\% \qquad (1)$$

In the equation P_e represents effective porosity, m_0 and m_1 are the submerged specimen mass (g) and is surface dry mass of the specimen (g), respectively. ρ is the density of water (g/cm^3) and V is the volume of the sample (cm^3).

Freeze-thaw durability of pervious concretes was determined in accordance with ASTM C666-97 (2017). During F-T cycles freeze-thaw cabinet was kept between -18 °C and 10 °C and after freezing samples were bathed with water for 70 minutes for deicing.

Impact resistance is determined with drop-weight impact test procedure in accordance with ACI 544.9R-17 (1999). The setup is presented in Fig. 4. Specimens were fixed in the cabin and a steel ball with a diameter of 63.5 mm was placed on top of it as shown as Fig. 4, then 10 kg steel hammer was dropped repeatedly from 470 mm of height. The test was started, and number of blows were recorded at first crack. After that, tests were carried out until the complete fracture.

Abrasion resistance was determined with Los Angeles abrasion test device due to its ease of application. Test was conducted without steel balls and the weight loss of specimens were measured after 300 revolutions (Wu et al. 2011). Abrasion resistance test setup is given in Fig. 5.

Fig. 4. Impact resistance test setup.

Fig. 5. Abrasion resistance test setup.

3. Results and Discussion

3.1. Mechanical properties

The compressive strengths are presented in Fig. 6. As expected, the compressive strength of concretes produced with limestone aggregate is higher than those produced with recycled aggregate. While the use of recycled aggregate in the 5/15 mm size fraction reduced the compressive strength by 30–39%, this reduction range was 43–48% for the 15/25 mm sieve range. While the porous and weaker structure of the recycled aggregate is the main reason for this situation, the reduced workability due to the use of recycled aggregate also has an effect on phenomenon. When the effect of aggregate particle size on compressive strength is examined, it is observed that compressive strength decreases with decreasing size fraction, regardless of the aggregate type. For the fixed cement content, smaller aggregate size fraction led to a larger surface area, and inadequate cement paste cannot fully cover the aggregates, resulting in low compressive strength. Among the control specimens, the highest compressive strength was obtained with 15/25 mm limestone aggregates at 12.8 MPa. Fiber addition caused a decrease in compressive strength, as previous studies suggested (Gesoglu et al. 2014; Liu et al. 2018). The lowest compressive strength was detected at a 0.3% fiber dosage with 5/15 mm recycled aggregates, measuring 4.6 MPa.

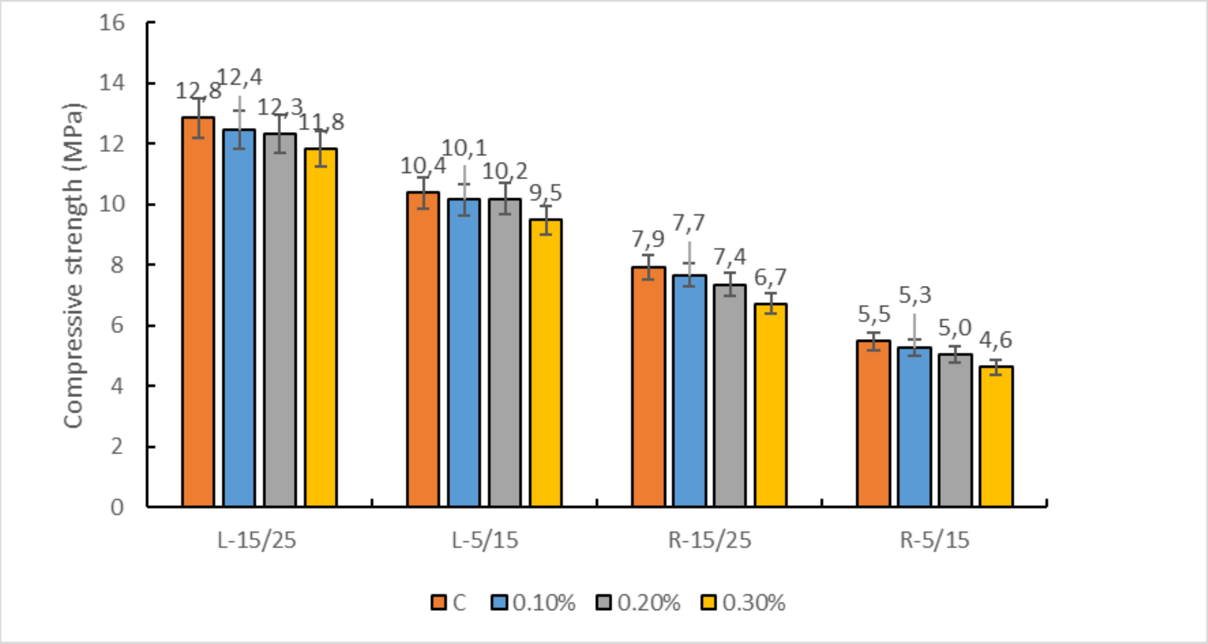

Fig. 6. The compressive strength of concretes.

Figs. 7 and 8 show the splitting tensile and flexural strength results, respectively. It is observed that splitting tensile strengths increase for all aggregate gradations up to 0.2% fiber content, but the strength decreases when fiber dosage is higher than this. This result may be caused by the difficulty of mixing the fibers homogeneously as the fiber amount increases.

Like the compressive strength results, flexural strengths decreased with the use of recycled aggregate. Regardless of the aggregate type and size fraction, fiber inclusion increased the flexural strengths to an optimum point (0.2%), followed by a decrease. Among the control specimens, the highest result was obtained with 15/25 mm limestone aggregates, followed by limestone 5/15 mm, recycled 15/25 mm, and recycled 5/15 mm. Excessive fiber dosage (0.3%) adversely affected recycled aggregate-bearing concretes more than those of concretes produced with limestone aggregates. The fact is associated with adhered cement paste (Hua et al. 2021; Chen et al. 2023).

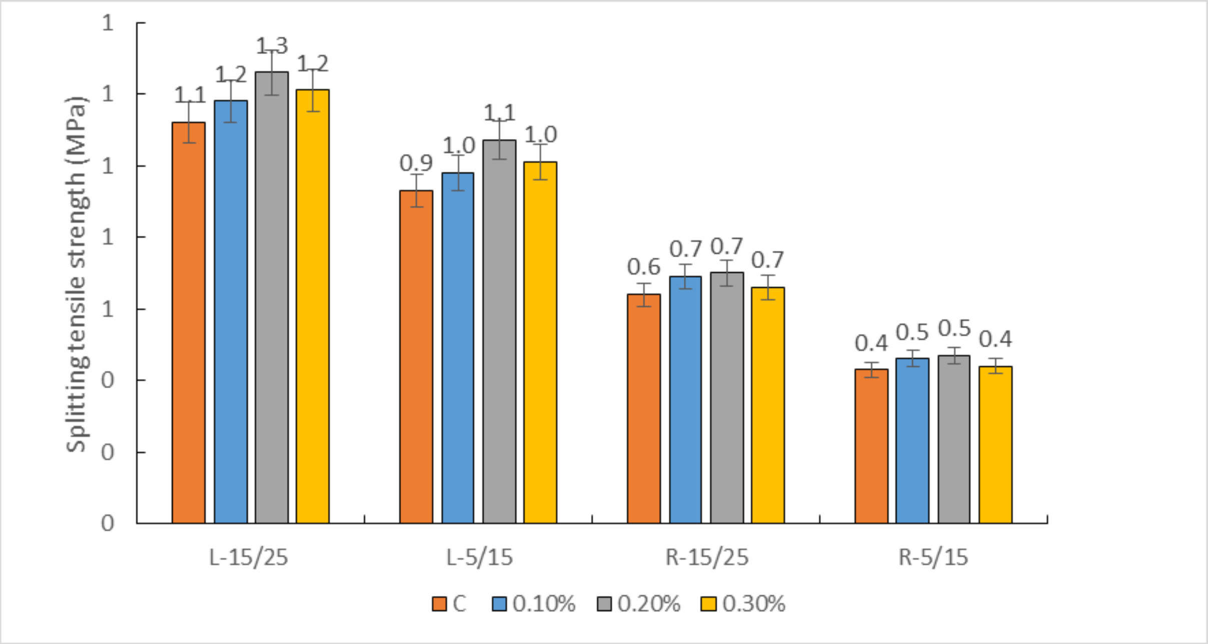

Fig. 7. The splitting tensile strength test results.

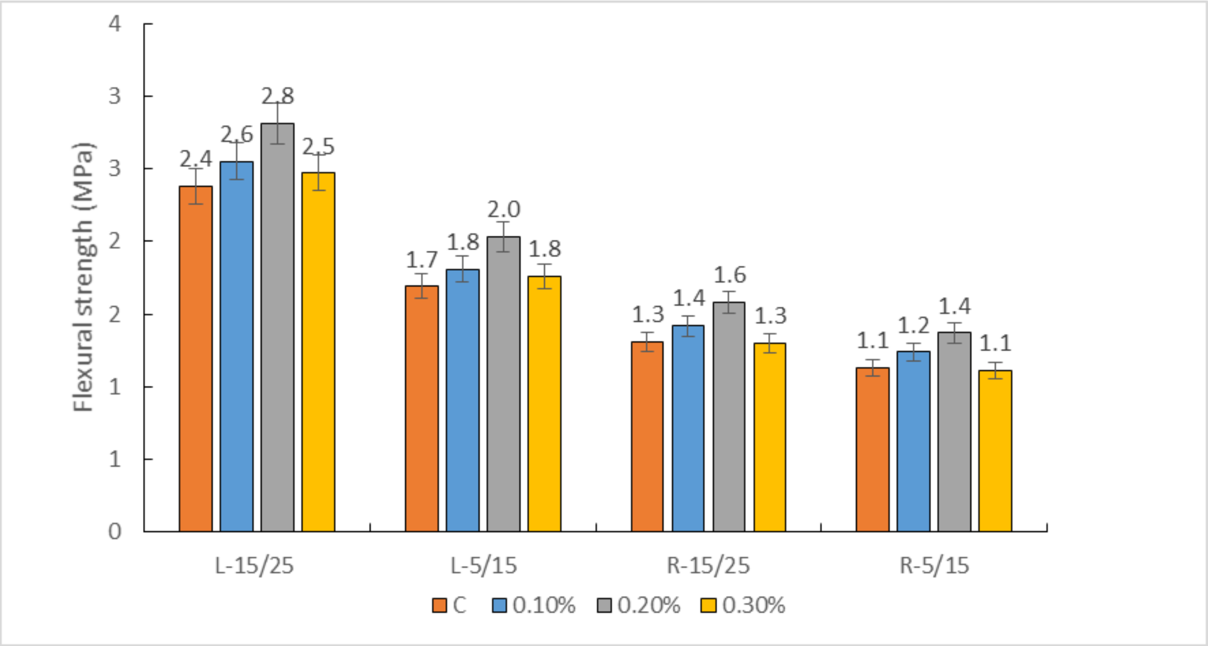

Fig. 8. The flexural strength test results.

3.2. Effective porosity

The effective porosities of concretes are presented in Fig. 9. In contrast to the mechanical properties, effective porosities increased with the use of recycled aggregate. It is evident that the use of fiber has a negative effect on the effective porosity. Effective porosity values vary between 15.8% and 16.6%, which are considered acceptable values (Wu et al. 2016). It is observed that pervious concretes produced using recycled aggregates have higher effective porosity values compared to those produced using limestone aggregates. It is known that the old cement paste present on the surfaces of recycled aggregates causes this result. Such aggregates create larger and continuous voids within the pervious concrete and improve the effective porosity of the concrete (Yavuz and Yazıcı 2023). It has been observed that the effective porosity of pervious concretes increases when coarser aggregate gradations are used in both aggregate origins used. There are studies in the literature where similar results are obtained, and researchers have attributed the obtained results to the fact that although more voids are formed when finer aggregates are used, these voids are not always connected to each other and therefore do not positively affect the effective porosity (Li et al. 2021; Shan et al. 2022).

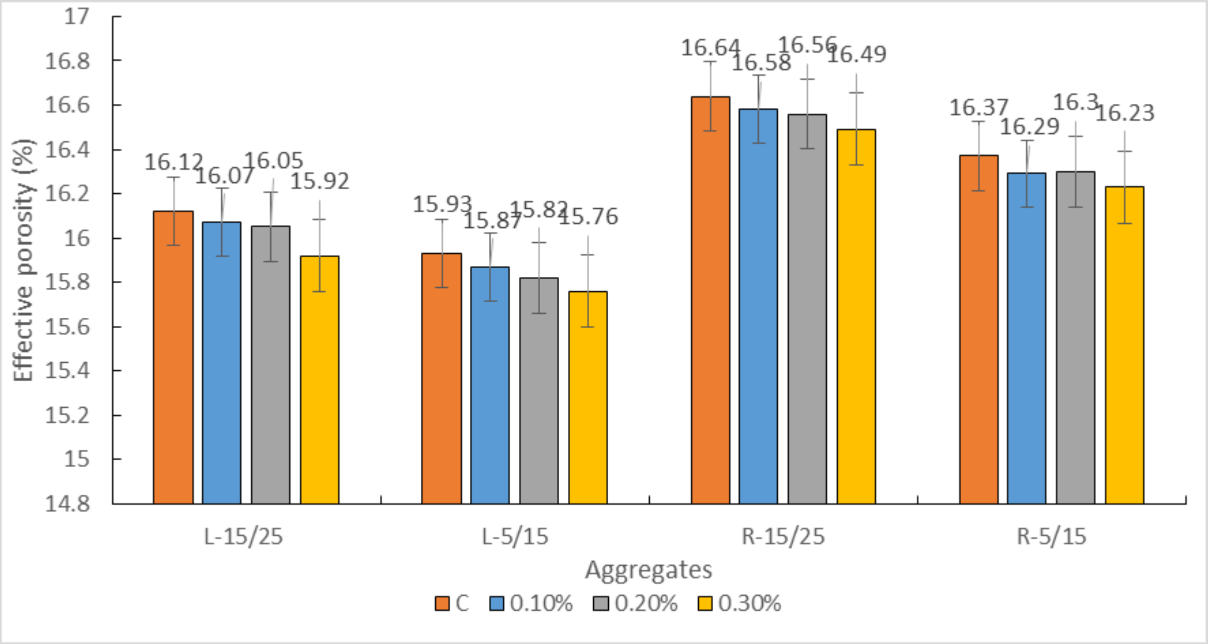

Fig. 9. Effective porosity results.

3.3. Abrasion resistance

Fig. 10 illustrates the weight losses after abrasion tests. The control series produced without fiber exhibited higher abrasion weight loss, ranging between 63-85%. As fibers were introduced into the mixture, weight loss due to abrasion decreased. The abrasion resistance for mixes with 0.1% fiber dosage ranged between 49-66%. A fiber dosage of 0.2% resulted in the lowest weight loss, between 37-58%. These results are consistent with the findings of (Yap et al. 2018), as almost the entire concrete specimen tends to be loss much weight due to the lower strength of pervious concrete (Dong et al. 2012).

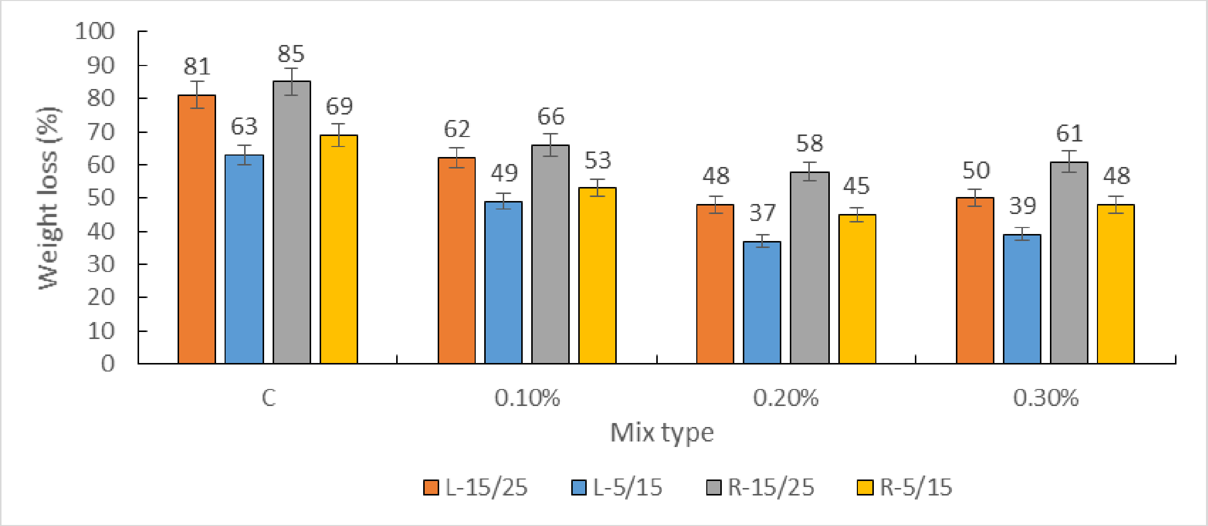

Fig. 10. Weight loss due to abrasion.

3.4. Freezing-thawing resistance

During the first 20 cycles, only slight mass loss was observed as aggregates separated from the cement paste. Notably, after 40 cycles, deterioration around the aggregates increased rapidly, and aggregates separate from the matrix. As shown in Fig. 11, up to around 20 cycles, pervious specimens maintained their integrity and did not lose significant mass. Particularly after 80 cycles, pervious specimens nearly lost half of their weight. Fiber addition had a positive effect on freeze-thaw performance. A 0.2% fiber content proved to be the best option among the dosages considered in this study. However, it should be noted that after a certain number of cycles, even fiber addition cannot markedly affect freeze-thaw resistance. The freeze-thaw performance of pervious concretes produced with recycled aggregates was ineffectual due to their low compressive strength. It was concluded that after 40 cycles, pervious concretes deteriorate massively, and these findings are consistent with those of (Leiva et al. 2019; Tan et al. 2023). The remaining mass after certain freeze-thaw cycles are presented in Figs. 12 and 13.

3.5. Impact resistance

The impact resistance of pervious concretes at initial crack and at failure is summarized in Table 5. Based on the average results of 9 samples first crack impact resistance of control specimens was as follows for mixes L-15/25 mm, L-5/15 mm, R-15/25 mm and R-5/15 mm 9, 7, 4 and 3 respectively. Fiber addition improved drop weight impact resistance of pervious concretes as expected. Fiber-free samples exhibited brittle failure while mixes with fiber dosage of 0.1% and 0.2% exhibited more ductile behavior (Abid et al. 2020; Liu and Wei 2022). Crack propagation did not occur the way traditional concrete, instead some of the specimens smashed under steel hammer as shown in Fig. 14.

Fig. 11. F-T failure characteristics of pervious concrete for L-15/25 mm control specimen.

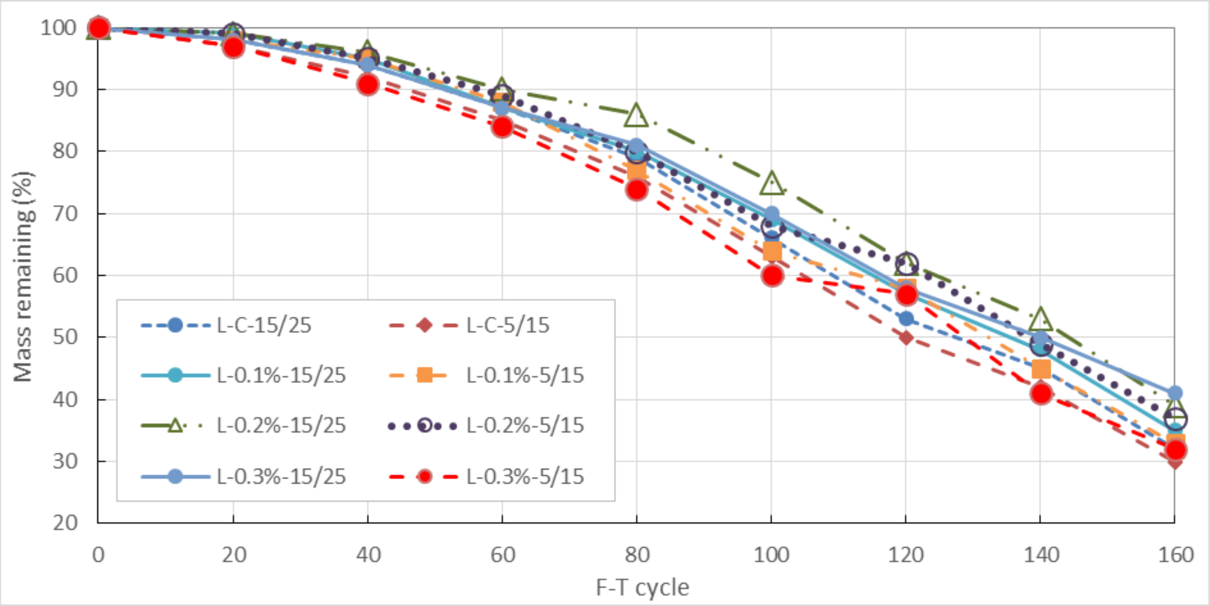

Fig. 12. Results of mass remaining after F-T cycles (limestone aggregates).

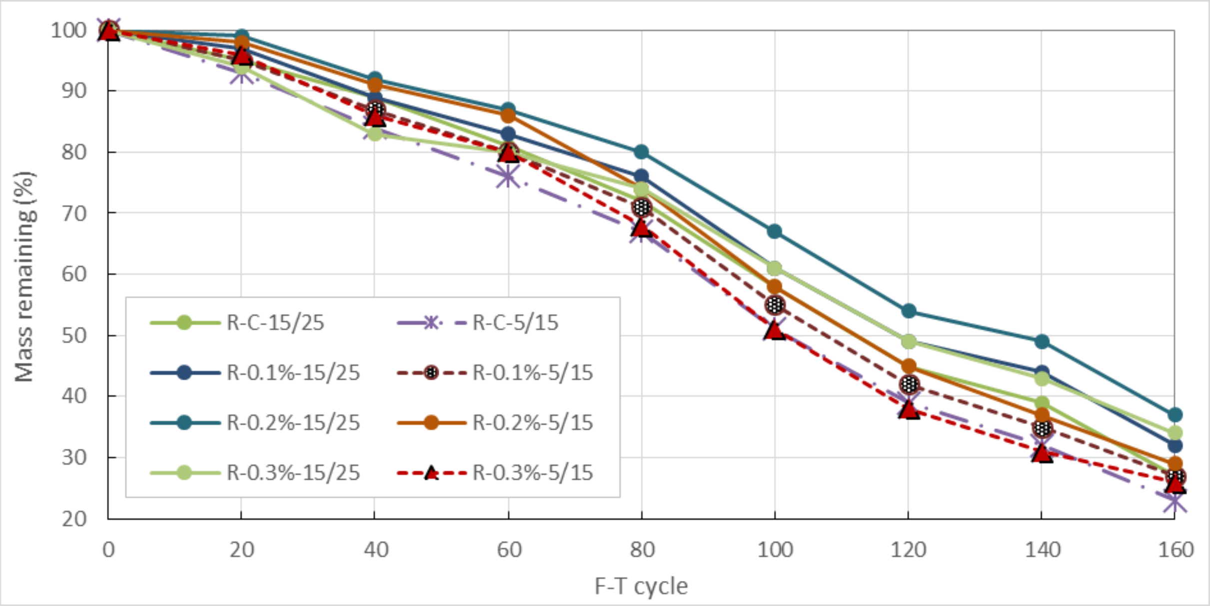

Fig. 13. Results of mass remaining after F-T cycles (recycled aggregate).

Table 5. Impact resistance (number of drops) of pervious concretes.

Mixture	Number of drops at		Mixture	Number of drops at	
	Initial crack	Total fracture		Initial crack	Total fracture
L-C-5/15	7	9	L-0.2-5/15	17	21
L-C-15/25	9	12	L-0.2-15/25	20	26
R-C-5/15	3	4	R-0.2-5/15	11	15
R-C-15/25	4	5	R-0.2-15/25	14	17
L-0.1-5/15	13	16	L-0.3-5/15	6	7
L-0.1-15/25	15	19	L-0.3-15/25	10	12
R-0.1-5/15	7	9	R-0.3-5/15	3	4
R-0.1-15/25	10	12	R-0.3-15/25	4	5

Fig. 14. Crack pattern at total fracture.

4. Conclusions

In this study the properties of recycled pervious concrete aggregate-bearing fiber-free and fiber-reinforced pervious concretes were investigated. Based on used materials and methods following conclusions were drawn:

- Limestone aggregates, compared to recycled pervious concrete aggregates, were superior in terms of mechanical strength, abrasion, impact, and freeze-thaw resistance, except for porosity.
- In general, fiber inclusion enhances the abrasion and freeze-thaw resistance of pervious concretes. Increased fiber dosage improved abrasion and freeze-thaw resistance up to a certain point. Beyond the optimum content, increased the fiber dosage had no positive effect; in some cases, it even led to decreased abrasion and freeze-thaw resistance.
- Although all pervious concretes were designed to have the same porosity, those produced with recycled pervious concrete aggregates had higher effective porosity compared to those of limestone aggregate-bearing mixtures. Additionally, smaller aggregate size fraction resulted in decreased effective porosity.
- The compressive strength of the pervious concretes ranged from 4.62 to 12.84 MPa. The lowest compressive strength results were observed with the highest fiber dosage (0.3%). In contrast, fiber addition improved the splitting tensile and flexural strength of pervious concrete. However, beyond the dosage of 0.2%, fiber addition did not significantly affect the tensile and flexural strength.
- The impact resistance of pervious concretes improved with the addition of fibers. Similar improvements were observed in other properties such as tensile and flexural strength, abrasion, and freeze-thaw resistance. Among the fiber dosages considered in this study, a dosage of 0.2% proved to be the optimum.

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Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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