



# The impact of recycled coarse aggregates obtained from waste concretes on lightweight pervious concrete properties

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## Abstract

Significant environmental damage can result from the use of natural resources such as cement, aggregate, and water in concrete production. Thus, more sustainable alternatives for concrete production are needed to protect the environment and natural resources. In this study, lightweight pervious concrete production involving recycled coarse aggregates (RCAs) with potential to cause environmental pollution was investigated. First, RCAs were produced from concretes possessing low compressive strength and were classified. Second, pervious concretes were produced from these RCAs. Third, the mechanical properties, permeability, and abrasion strength of the pervious concretes were determined. The water/cement (w/c) ratios of the mixtures were determined to be 0.32, 0.34, and 0.36, and the aggregate/cement (a/c) ratios were selected to be 3.5 and 4. Twelve different pervious concretes were produced and tested in total. The bulk densities (BD) of the mortars varied over an interval of 1160–1080 kg/m<sup>3</sup>. The aim was to design pervious concretes with lightweight bulk densities. When the w/c ratio was 0.34, the compressive, splitting tensile and abrasion strengths were high. The compressive strength of the pervious concretes varied over an interval of 1.50–2.00 MPa. It was determined that for optimal permeability, the most appropriate w/c ratio was 0.36, and the best a/c ratio was 4. When the a/c ratio was 4, the strength values were high, and as a result, the mechanical properties were poor. With respect to aggregate gradation, it was determined that a grain size distribution of 9.50–12.50 mm was most suitable for this pervious concrete. Recycled aggregates with low strength produced low strength concrete. Therefore, the pervious concrete produced in this study is most suitable for pedestrian roads where heavy vehicle traffic does not exist.

**Keywords** Sustainability · Ecology · Pervious concrete · Abrasion strength · Porosity

## Introduction

In the last 10 years, due to the growth in the construction sector, concrete production and consumption have significantly increased. The annual average concrete production is nearly 1 t per person globally (Marie and Quiasrawi 2012). Furthermore, due to population increases, industrial development, urban transformation, and infrastructure construction, considerable amounts of construction and demolition waste (CDW) are generated, which causes environmental pollution

(Xiao et al. 2012; Qin et al. 2018; Tam et al. 2018). Hence, due to the extreme consumption of natural resources, resource shortages and ecological damage have begun to create serious problems on a global scale (Li et al. 2016; Shi et al. 2016; Huang et al. 2019). Consciousness about sustainable waste management and natural resource protection has been increasing. The recycling of CDW in construction engineering projects has been recognized as a significantly effective and beneficial method for resource and environmental protection (Shi et al. 2016; Xuan et al. 2016, 2018; Tam et al. 2018; Iqbal et al. 2020). Currently, construction activities cause the consumption of a high amount of materials produced from natural resources, and a large amount of waste is generated by such production. With the development of waste management and recycling processes, materials such as asphalt, ceramic, rubber, glass, plastic, and concrete can be used in the production of building materials again (Bignozzi and Saccani 2012; Nassar and Soroushian 2012; Cetin 2013a, b, 2015a, b; Chakravarthi et al. 2019; Kavussi et al. 2019; Ajam et al.

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2020; Sereewatthanawut and Prasittisopin 2020; Yin 2020). According to Eurostat data, nearly 36% (891 million tons) of waste produced in the European Union in 2014 was CDW (EEA 2017; López-Uceda et al. 2019). CDW contains ceramic and brick particles, mortar, concrete, and, to a lesser extent, asphalt, gypsum, wood, metals, paper, and plastics (López-Uceda et al. 2019). With the recycling of these wastes into new materials that can be reused, sustainable development is achieved. CDW is primarily used as recycled aggregate (RA). RA is used as a foundation and filling material in roads as aggregate in concrete and mortars (López-Uceda et al. 2018; Barbudo et al. 2020).

RA is an important material for reducing the usage of natural aggregates in concrete production to protect the environment and natural resources (Shi et al. 2016). It has been considered that concrete production is the most effective way to dispose of RA obtained from CDW, and a considerable amount of research has been conducted on this subject. In these studies, when,  $w/c_{\text{eff}}$ , the proportion of RCA added in concrete was unity, mechanical features such as the compressive strength, tensile strength, and elasticity module decreased with respect to those of traditional concrete (Gómez-Soberón 2002; Poon et al. 2004; Topçu and Şengel 2004; Xiao et al. 2005; Etxeberria et al. 2007). Generally, as the RCA content increased, the compressive strength of concrete decreased. Despite this, there are design directives and application rules allowing for RCA to be used for structural purposes (Lamond et al. 2002; Lima et al. 2013; McNeil and Kang 2013; Khan et al. 2020), but RCA properties such as poor adherence, high water absorption, porosity, and low density due to old mortar on its surface (de Juan and Gutiérrez 2009; Marinković et al. 2010) have limited the use of RCAs in concrete (Li et al. 2017b). The cause of poor adherence involves microcracks and pores within old mortar on the aggregate surface (Faysal et al. 2020). This porosity and microcrack network of RCA increases the water needed for workability. In proportion to the increase in water content, the strength and durability of concrete decrease (Ali et al. 2020). Some researchers have shown that by reducing the water requirement of concretes containing RCA, concrete properties such as workability, mechanical properties, and durability features could be improved (Kurad et al. 2017; Kurda et al. 2018; Pedro et al. 2018). In addition, as RCA accumulates in waste storage fields, it increases the pH of leakage water due to rain, and water with a high pH damages stream ecosystems (Han et al. 2020). For this reason, to protect ecosystems and the environment, it is necessary to expand the application scope of RCAs.

Underground water is an important natural resource worldwide. Underground water supplies fresh water necessary for drinking, agriculture, and industry (Margat and van der Gun 2013). However, nitrate ( $\text{NO}_3^-$ ) concentrations in water resources have exceeded acceptable levels in various regions of the world. The excessive use of fertilizers and pollution

caused by humans and animals are the two main causes of this problem (Kendall et al. 2008). Water pollution has long-term impacts on human health. The WHO has stated that the nitrate level permitted in drinking water is nearly 50 mg/L (World Health Organization 2011). Permeable reactive barriers (PRBs) constitute an innovative technology for cleaning up polluted underground water. One of the best materials used in PRB design is pervious concrete. Pervious concrete is a special type of concrete that can easily discharge liquids due to its porosity of 15–30% and consists of cement paste and coarse aggregate (American Concrete Institute 2013; Alighardashi et al. 2018). Many studies have been conducted on the mechanical features, permeability, and porosity of pervious concrete over the years (Zaetang et al. 2013; Li et al. 2017a). Pervious concrete is a type of concrete that can also be used in regions with heavy rainfall to control overflow. In addition, pervious concrete is preferred in applications related to infrastructures such as pavement. Pervious concrete is widely used in green infrastructure applications in roads, parking lots, walking areas, and cycling routes to allow rainwater to pass through pavement or road surfaces (Chandrupa and Biligiri 2016; Kamali et al. 2017; Lu et al. 2019; Liu et al. 2020b). Furthermore, while pervious concrete enables air and water flow for trees and plants, it also eliminates environmental problems such as heat island impacts that form in cities (Tennis et al. 2004; Lu et al. 2019). The difference between pervious concrete and traditional concrete is that it does not contain fine aggregates, and less cement paste is used to fill in the gaps between the grains. As a result, open cells (pores) form within the structure of pervious concrete, and due to its high porosity, it allows drainage and filtration (American Concrete Institute 2010; Lu et al. 2019). In addition, in recent years, some researchers have studied reductions in pollutants in water by pervious concrete (Jo et al. 2007; Shabalala et al. 2017). The compressive strength requirement of pervious concrete is lower than that of traditional concrete, which creates an alternative opportunity for the use of waste materials in the production of pervious concrete (Lu et al. 2019). When the binder material content of a pervious concrete mixture is 180–355 kg/m<sup>3</sup>, its coarse aggregate content is 1420–1600 kg/m<sup>3</sup>, and its w/c ratio varies between 0.27 and 0.43. The 28-day compressive strength of pervious concrete varies between 5.6 and 21.0 MPa, and its permeability coefficient ranges between 0.25 and 6.1 mm/s (Henderson and Tighe 2012; Sriravindrarah et al. 2012). Although pervious concrete has low compressive strength, due to its environmental benefits, it is currently a type of concrete that is frequently preferred (Singh and Singh 2020). The strength, endurance, and permeability features of pervious concrete are primarily related to its pore structure (Liu et al. 2020a).

In this study, we aimed to design pervious concrete with RCAs obtained from concrete with low compressive strength. Sustainable concrete production has been aimed at the use of

**Table 1** Chemical and physical features of CEM I 42,5 R cement

Chemical composition (%)							Physical properties	
CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub>	MgO	LOI	Specific gravity	Blain specific surface area (cm <sup>2</sup> /g)
63.98	19.45	4.11	3.61	2.96	1.11	3.43	3.12	3300

RCAs posing an environmental pollution risk. For this purpose, the mechanical and permeability features of pervious concrete with different w/c and a/c ratios were examined. By using RCAs with different grain sizes in pervious concrete, which is beneficial for the environment and ecosystem, many proposals are put forward herein.

## Material and method

### Material

In this experimental study, cement, coarse aggregate, and water were used as materials. The chemical and physical properties of the materials used are described in the sections below.

### Cement

To produce pervious concrete, binder CEM I 42,5 R cement complying with the EN 197-1 standard was used. The chemical and physical features related to CEM I 42,5 R cement are given in Table 1.



**Fig. 1** Concrete samples from which RCA was obtained

### Aggregate

RA was used in the production of pervious concrete. The w/c ratios of concretes from which RA was obtained varied in the interval of 0.70–0.80. Because the wastes were obtained from old structures, low concrete strengths were chosen. The concrete samples from which the RA was obtained are given in Fig. 1. Fine aggregates were not used in the mixtures.

The concrete samples shown in Fig. 1 were broken with a stone crusher to produce coarse aggregates with two different gradations: (A) 4.75–12.50 mm and (B) 9.50–12.50 mm. The results of a sieve analysis of the aggregates are given in Fig. 2. The physical properties of the aggregates, such as specific gravity and water absorption, are given in Table 2.

### Mixture designs

The w/c ratios of the mixtures were selected as 0.32, 0.34, and 0.36. For pervious concretes, the a/c ratios were determined to be 3.5 and 4.0. Two classes of aggregate gradation were prepared: 4.75–12.50 (A)/9.50–12.50 (B) mm. Variables related to the experimental study are given in Table 3.

Twelve different mixtures were produced according to the variables shown in Table 3. The amount of cement in the mixtures was 450 kg, and 100% of the RCA produced was used in the mixtures. Segregation occurred in the concretes when water (> 170 kg) was in excess. Pervious concretes are very sensitive to segregation. In the presence of excess water, the cement paste moves towards the base of the mold, resulting in segregation. The amounts of materials used in the experimental study are presented in Table 4.

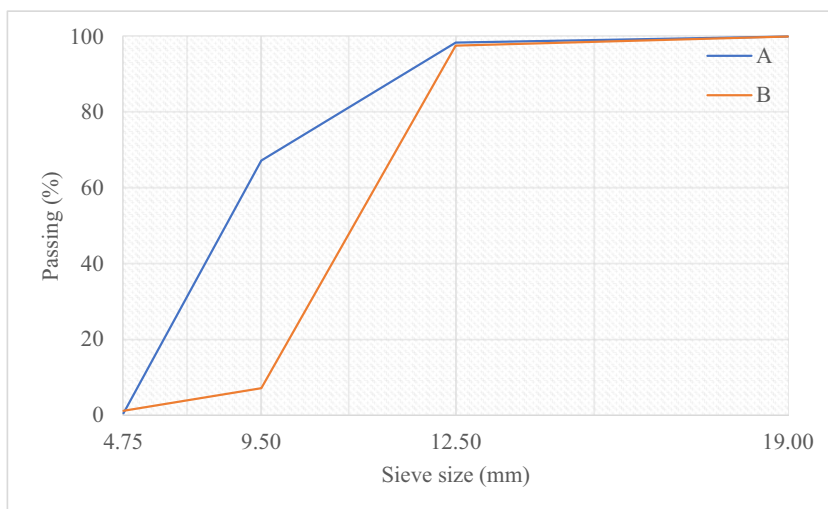
### Preparation and curing of pervious concretes

RCAs were obtained from concretes with a high w/c ratio of 0.7–0.8, as stated in the “Aggregate” section. The concretes

**Table 2** Physical features of the aggregates

Aggregate	Aggregate size (mm)	Specific gravity	Water adsorption (%)
A	4.75–12.50	2.43	6.2
B	9.50–12.50	2.40	5.6

**Fig. 2** Sieve analysis results for the aggregates



**Table 3** Variables related to the experimental study

	Level 1	Level 2	Level 3
Water/cement (w/c)	0.32	0.34	0.36
Aggregate/cement (a/c)	3.50	4.00	N/A
Gradation and size	A (4.75–12.50 mm)	B (9.50–12.50 mm)	N/A

N/A not applicable

were first crushed with a hammer, and then the size was adjusted to that of coarse aggregate with a stone crusher. To produce pervious concrete, a portable laboratory mixer (with a vertical axis) was used to mix the fresh concrete. The concrete mixing process constituted 3 stages. In the first stage, cement was mixed with half of the water for 1 min. In the second stage, water was added to the cement paste; the mixture was allowed to rest for 1 min and then mixed for 3 min. In the third stage, RCA was added, and mixing was performed for 3 min. For the pervious concrete mixtures, it was important

to prepare the cement paste first because it was observed that the concrete samples did not set when the consistency of the cement paste was not sufficient. Adding water to RCA causes coarse aggregates to absorb water since the water absorption capacity RCA is high. Because fine aggregate is not used in pervious concrete and the paste is insufficient, the friction among the coarse aggregate grains is high. For this reason, more attention needs to be paid to the compaction process for pervious concretes. In this study, fresh concrete was placed in 10-cm cubic molds in two layers and in three in-cylinder

**Table 4** Mixing properties and material quantities of the pervious concrete

Mix. no.	Mix. ID	w/c	a/c	Gradation	Materials (kg)			Paste/aggregate (by weight)
					Cement	Aggregate	Water	
1	3A32	0.32	3.5	A	450	1575	144	0.377
2	3A34	0.34			450	1575	153	0.383
3	3A36	0.36			450	1575	162	0.389
4	4A32	0.32	4.0		450	1800	144	0.330
5	4A34	0.34			450	1800	153	0.335
6	4A36	0.36			450	1800	162	0.340
7	3B32	0.32	3.5	B	450	1575	144	0.377
8	3B34	0.34			450	1575	153	0.383
9	3B36	0.36			450	1575	162	0.389
10	4B32	0.32	4.0		450	1800	144	0.330
11	4B34	0.34			450	1800	153	0.335
12	4B36	0.36			450	1800	162	0.340

**Table 5** Standard and sample features used in the experimental study

Testing method	Standard	Time (day)	Sample size	Number of samples
Workability (cement paste)	ASTM C230 (ASTM C230 2010)	Fresh paste	–	–
Bulk density (fresh concrete)	ASTM C1688 (ASTM C1688 2014)	Fresh concrete	10 × 10 × 10 cm (cube)	–
Bulk density (hardened concrete)*	ASTM C1754 (ASTM:C1754/C1754M-12 2012)	28	10 × 10 × 10 cm (cube)	–
Porosity		28	10 × 10 × 10 cm (cube)	3
Compressive strength	ASTM C109 (ASTM C109 2000)	28	10 × 10 × 10 cm (cube)	3
Splitting tensile strength	ASTM C496 (ASTM C496 2011)	28	10 × 20 cm (cylinder)	3
Abrasion strength	ASTM C944 (ASTM C944 2019)	28	10 × 10 × 10 cm (cube)	3
Permeability	ASTM C1701** (ASTM C1701 2017)	28	10 × 10 × 10 cm (cube)	3

\*Bulk density, porosity, and permeability tests were performed on the same samples

\*\*The permeability test was modified based on ASTM C 1701

molds with a height of 20 cm. Each layer was compacted for 30 s with a vibrating table. Water curing was applied to the pervious concretes for 28 days. The tests performed in the experimental study and the sample sizes are given in Table 5.

As shown in Table 5, in the experimental study, 108 pieces of 10 × 10 × 10-cm cubic samples and 36 pieces of 10 × 20-cm cylindrical samples were produced.

### Test methods

#### Determining the workability of cement pastes

The consistency of the cement pastes was determined with a spreading table in mortar experiments. The ASTM C230 standard was taken as the basis for determining the consistency of the cement pastes.

#### Determining the bulk densities of fresh and hardened concretes

The bulk densities (BDs) of fresh and hardened pervious concretes were determined with 10 × 10 × 10-cm cubic samples. The BDs of fresh concretes were determined according to the ASTM C1688 standard. The BDs of hardened concretes were determined after being dried in a 50 °C oven for 3 days following a curing process. Afterwards, permeability tests were conducted for concrete samples whose BDs had been measured.

#### Determining the porosities of pervious concretes

The porosities of pervious concretes were determined according to ASTM C1754. The BD and the porosities of the hardened concretes were determined on the same samples. Three samples were used for the porosity test.

#### Determining the compressive strength of pervious concretes

Cubic samples with sizes of 10 × 10 × 10 cm were used to determine the compressive strength of the pervious concretes. The compressive strength experiment was performed on 28-day concrete samples. The compressive strength experiment was realized by considering the criteria given in the ASTM C109 standard. Since the roughness is high on the surfaces of the pervious concrete due to the presence of aggregates, medium-soft rubber was used in the loading directions. In the compressive strength experiment, the loading speed (0.05 MPa/sn) was selected to be lower than that for ordinary concrete (Fig. 3).

#### Determining the splitting tensile strength of pervious concrete

The ASTM C496 standard was used to determine the splitting tensile strength. The splitting tensile strength of the pervious concretes was determined in 10 × 20-cm cylindrical samples. The splitting tensile strength experiment and the relevant samples are given in Fig. 4.



**Fig. 3** Compressive strength test applied to pervious concretes

**Fig. 4** Pervious concrete samples for the splitting tensile strength test



### Determining the abrasion strength of pervious concrete

The abrasion strength of the pervious concretes was determined on  $10 \times 10 \times 10$ -cm cubic samples. The abrasion strength was determined according to the ASTM C944 standard. In Fig. 5, the abrasion experiment performed in accordance with ASTM C944 and the relevant samples are depicted.

### Determining the permeability of pervious concrete

A permeability test was applied to cubic samples with sizes of  $10 \times 10 \times 10$  cm. In the permeability tests, the ASTM C1701 standard was followed as the basis, but certain modifications were made during the testing process. A thin film layer was formed from plaster to prevent water leakage on the side surfaces of the pervious concrete. After the side surfaces were coated, water could generally move vertically. A schematic illustration of the experimental setup is given in Fig. 6.

A glass pipe (scaled) with a diameter of 5 cm was placed at the center of the top surface of the pervious concretes. Glazier's putty was used to ensure impermeability at the bottom edges of the pipe. As the water flowed out from the bottom surface, the number of seconds required for  $100 \text{ cm}^3$  of water to accumulate in the graduated container was determined. The permeability test was administered in triplicate. The flow rate was calculated by

inputting the obtained measurements into Eq. 1.

$$\Phi = V_w / A \times t \quad (1)$$

Here,

- $V_w$  volume of water passing through the sample during the holding period ( $100 \text{ cm}^3$ )
- $\Phi$  water flow per unit surface
- $A$  sample area
- $t$  time required for  $100 \text{ cm}^3$  of water to accumulate

## Results and discussion

### Workability of cement pastes

In Fig. 7, the consistencies of the pastes used in the preparation of pervious concretes are given. It was determined that the flow diameters of the pastes with w/c ratios of 0.32, 0.34, and 0.36 were 148, 177, and 198 mm, respectively. As the water content of the paste increased, the workability of the cement-based composites increased. In addition, the increase in water also increased the paste volume. In traditional concrete, with an increase in the w/c ratio, the compressive strength decreases. However, since an increase in paste volume in

**Fig. 5** Pervious concrete sample for the abrasion test according to ASTM C 944



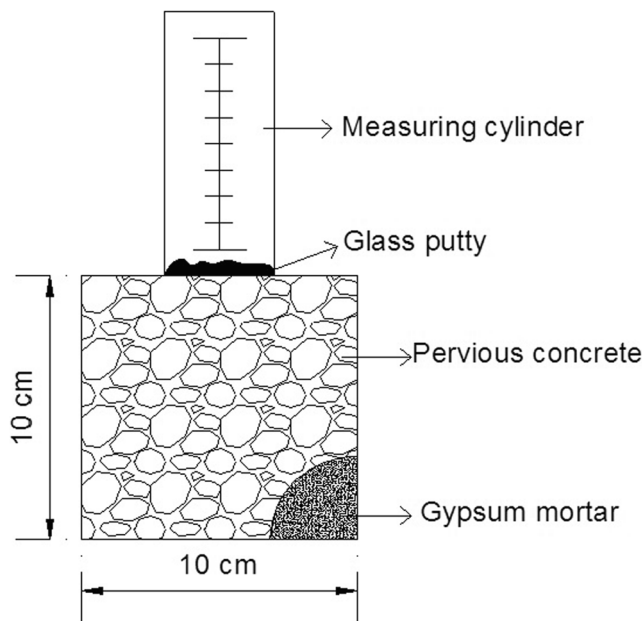


Fig. 6 Schematic illustration of the modified ASTM C1701 setup

pervious concretes reduces the friction between aggregates, this increase can also increase the workability.

### Fresh and hardened bulk densities

The bulk densities of fresh and hardened concretes are given in Fig. 8. The BDs of fresh concretes varied in the range of 1120–1191 kg/m<sup>3</sup>, while the BDs of hardened concretes varied in the range of 1076–1162 kg/m<sup>3</sup>. In the fresh concretes, the highest BD was obtained for the 3A34 samples, which had an a/c ratio of 3.5 and a w/c ratio of 0.34 and contained aggregates with gradation A. A similar result was obtained when aggregates with gradation B were used. Figure 8 reveals that, for both gradations, when the a/c ratio is 3.5, it is most appropriate for the w/c ratio to be 0.34. With gradation B, the BD was somewhat increased when the w/c ratio was 0.34 or 0.36 compared with that for the other w/c ratios. The reason for this is because in gradation B, where the friction between aggregates is greater than that in gradation A, the increase in the w/c

Fig. 7 Consistencies of the cement pastes

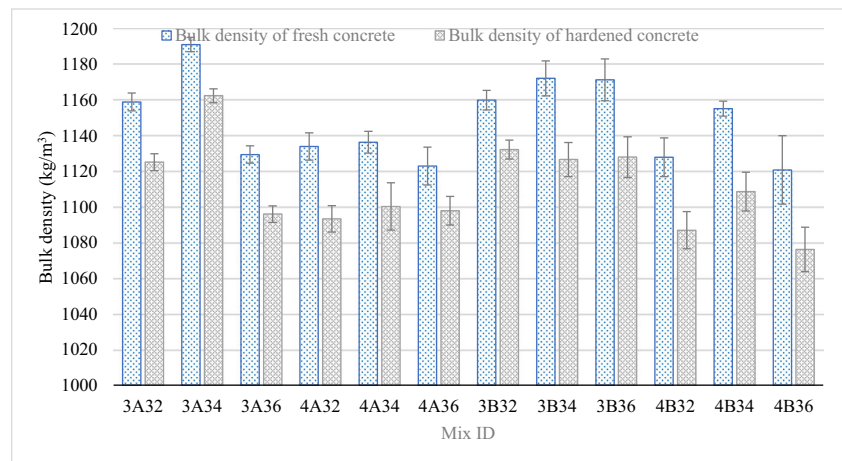


ratio reduces friction and contributes to even slight workability.

In Fig. 9(a), the impact of three different w/c ratios on BD is shown. When the w/c ratio was 0.36, the BD of fresh concrete increased by approximately 20 kg/m<sup>3</sup>. This increase was determined to be 15 kg/m<sup>3</sup> for the hardened concrete samples. When the w/c ratio was 0.36, the BD values of fresh concrete had an approximate value of 1145 kg/m<sup>3</sup>. This is very close to that of pervious concretes with a w/c value of 0.32. When the BD value of hardened concrete was examined, it could be seen that when the w/c ratio increased from 0.32 to 0.36, the BD decreased by nearly 10 kg/m<sup>3</sup>. With the increase in the w/c ratio, the BD values generally increased.

Similar results were obtained in the relevant literature. In many studies conducted by various researchers, an increase in the w/c ratio increased the BD of pervious concretes (Lian and Zhuge 2010; Lian et al. 2011; Bhutta et al. 2012; Ibrahim et al. 2014; Kant Sahdeo et al. 2020). In the experimental study conducted by Chindaprasirt et al. (2008), similar results were also reported. Chindaprasirt explained that this impact was a result of the continuity provided by coarse aggregates within cement paste. The paste/aggregate ratio of pervious concrete is important for the workability for this reason. In addition, as the w/c ratio increases, its impact on the paste increases even more. An increase in the w/c ratio causes the paste content to increase, and in this way, the surrounding part of the coarse aggregate grains is wrapped more completely. Friction among coarse aggregates surrounded by cement paste decreases compared with that around fine aggregates. Hence, the workability and compressibility increase (Chandruppa and Biligiri 2016). The results obtained in this study are similar to those in the literature. It has been determined that to achieve the maximum BD, the optimum w/c ratio was 0.34. In Fig. 9(b), the effects of the a/c ratio on the BD are shown. As seen in Fig. 9(b), as the a/c ratio increased, the BD decreased. When the a/c ratio was 4, the fresh BD decreased below 1150 kg/m<sup>3</sup>, whereas the hardened BD decreased below 1100 kg/m<sup>3</sup>. Furthermore, when the a/c ratio was 4, fresh BD decreased by nearly 30 kg/m<sup>3</sup>, whereas the hardened BD decreased by nearly 35 kg/m<sup>3</sup>. There was less of a difference between the BDs because the a/c ratios were similar.

**Fig. 8** Fresh and hardened BD values for pervious concrete



The results obtained, as shown in Fig. 9(b), are similar to the results in other studies in the literature. In the study conducted by Hariyadi (2015), if the  $a/c$  ratio was increased from 4 to 8, the densities of pervious concretes were reduced. In the study conducted by Liu et al. (2019), as the  $a/c$  ratio increased from 2.2 to 3.4, the BDs of concretes decreased. Therefore, the reason for the decrease in density with the increase in  $a/c$  ratio is related to a decrease in cement paste.

In Fig. 9(c), the impact of different aggregate gradations on BD is shown. Changes in aggregate gradation type did not affect the BD. The fresh and hardened BDs of pervious concretes produced with gradation B decreased by nearly 5–10  $\text{kg/m}^3$ . Although aggregates with gradation A had a grain size distribution of 4.75–12.50 mm and aggregates with gradation B had a grain size distribution of 9.50–12.50 mm, very significant differences in BD were not observed because the  $a/c$  ratios were very similar.

In previous studies, if the amount of coarse grains in the aggregate mass increased or if the  $D_{\max}$  value (maximum aggregate size) increased, then the density decreased. Kim and Lee (2010) produced pervious concretes from aggregates with 5 different gradations and  $D_{\max}$  values of 8, 12, 13, and 19 mm and found that, generally, as the  $D_{\max}$  value increased, the density decreased. Yu et al. (2019) studied the effect of the aggregate grain size distribution,  $D_{\max}$ , and proportion of fine grains on pervious concrete.

## Porosity

The porosity values of pervious concretes are given in Fig. 10. As shown in Fig. 10, the porosity values of the mixtures were higher than 59%. When the  $a/c$  ratio was equal to 4, the porosity exceeded 61%. If the  $w/c$  ratio was 0.36, the porosity was nearly 62%. Sample 4B36 had the highest porosity of 63%.

In Fig. 11(a), the impact of the change in the  $w/c$  ratio on the porosity is shown. If the  $w/c$  ratio was 0.34, the porosity

was nearly 61%. However, when the  $w/c$  ratio was 0.36, the porosity increased and exceeded 62%. High porosity is important for water passage through pervious concretes, but adequate strength must be maintained. With respect to the BD, it was observed that concretes with a  $w/c$  ratio equal to 0.32 yielded a maximum BD but a low porosity. However, it was also determined that the change in the  $w/c$  ratio did not cause a significant change in porosity.

In the studies available in the literature, similar results regarding the relationship between the  $w/c$  ratio and porosity have been observed. In the study conducted by Kant Sahdeo et al. (2020), in pervious concretes with  $w/c$  ratios of 0.30, 0.35, and 0.38, generally, with the increase in the  $w/c$  ratio, the porosity decreased. In other studies available in the literature, with an increase up to an optimum  $w/c$  ratio, the porosity decreased (Lian and Zhuge 2010; Lian et al. 2011; Debnath and Sarkar 2020).

As the  $w/c$  ratio increases, cement paste fills the gaps between aggregates better, and by surrounding the aggregates, the paste helps to absorb impacts (Ibrahim et al. 2014; Chandrappa and Biligiri 2016).

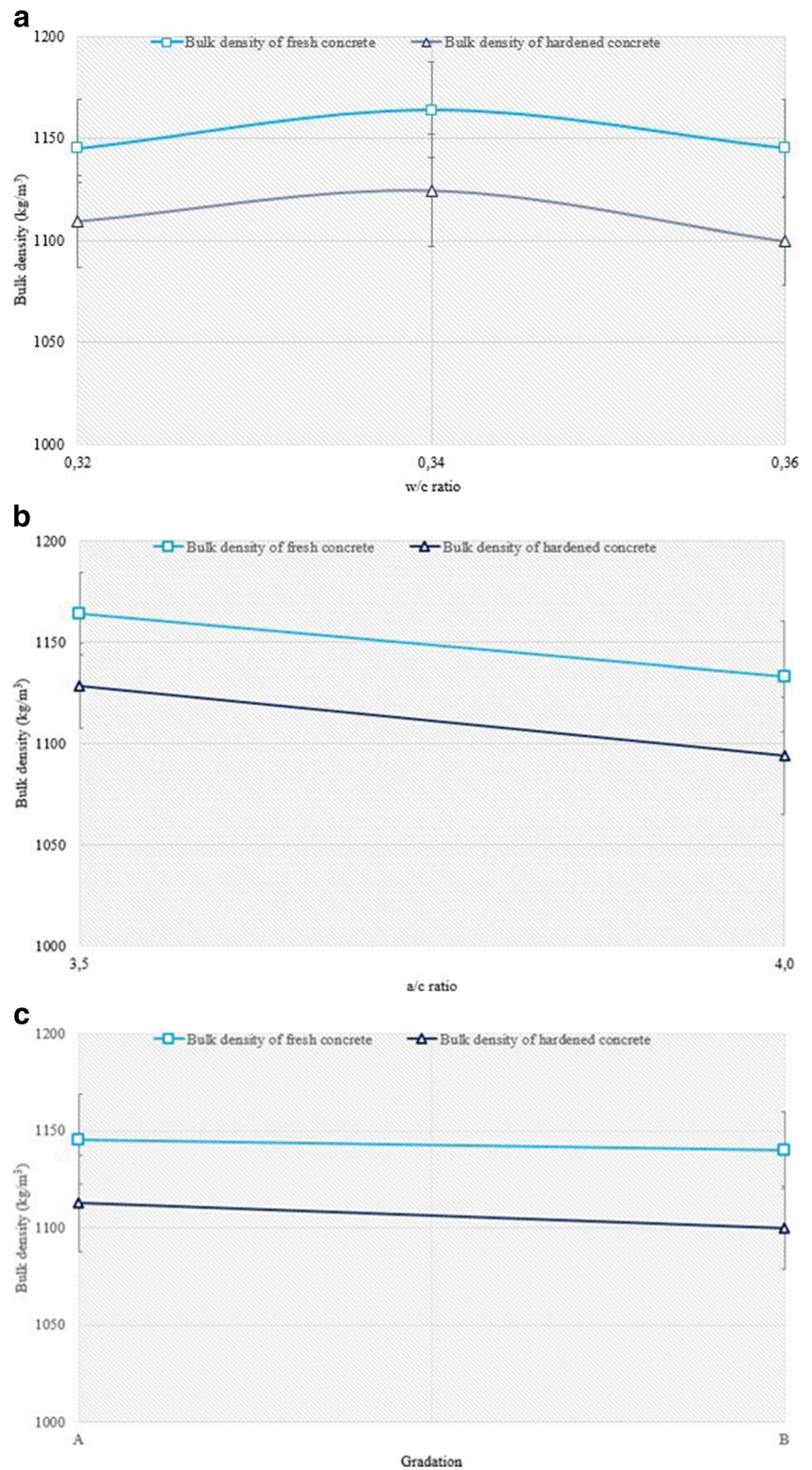
In Fig. 11(b), the impact of the  $a/c$  ratio on porosity is shown. With the increase in the  $a/c$  ratio, the porosity increased in the pervious concretes. If the  $a/c$  ratio was 4, the porosity was nearly 62%. If the  $a/c$  value was 3, the porosity was below 61%. Although the change in  $a/c$  ratio did not have a significant impact on the porosity, with the increase in  $a/c$  ratio, the porosity of the pervious concretes increased. With the increase in the  $a/c$  ratio, the porosity increased, as more aggregate was used in the mixture.

In the study conducted by Liu et al. (2019), an increase occurred in porosity with an increase in the  $a/c$  ratio. In the study conducted by Hariyadi (2015), as the  $a/c$  ratio increased from 4 to 8, the porosity increased and ultimately exceeded 35%.

The impact of the aggregate gradation type on porosity is shown in Fig. 11(c). The porosity values of pervious concretes



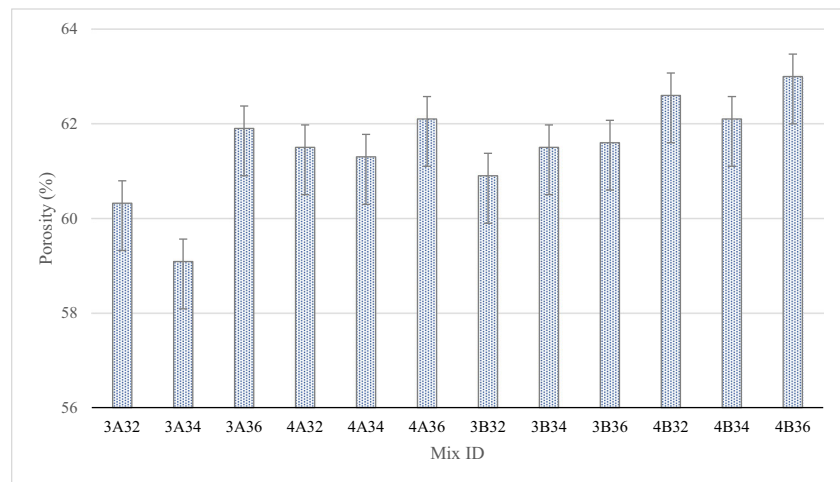
**Fig. 9** BD values of pervious concrete: impact of the (a) w/c ratio, (b) a/c ratio, and (c) gradation



produced with gradation B and a sieve opening of 9.00–12.50 mm were higher than those of the other concretes. As the grain size distribution of the aggregates with gradation A

varied from 4.75 to 12.50 mm, the porosity remained relatively low. A wider grain size distribution with gradation A caused a reduction in porosity.

**Fig. 10** Porosity values of the pervious concretes



In the study conducted by Bhutta et al. (2012), concrete was produced by using three different aggregate groups with grain size distributions of 2.5–5, 5–13, and 13–20 mm. As the particle size of the aggregate grains in the mixture increased, the porosity increased as well (Bhutta et al. 2012). However, other studies have obtained opposite results. In the study conducted by Kim and Lee (2010), a reduction in the size of grains within the aggregate mass increased porosity. Kim and Lee (2010) produced pervious concretes from light aggregates with sieve openings of 4–8, 8–12, and 12–19 mm. The porosity of pervious concretes with sieve openings of 12–19 mm was 36.3%, and the porosity of pervious concretes with sieve openings of 4–8 mm was 50%.

The relationship between porosity and hardened BD is shown in Fig. 12. As is the case with traditional concrete, as the BD of pervious concrete decreased, the porosity increased. An increase in the porosity within the structure of pervious concrete caused a reduction in BD ( $R^2 = 0.77$ ). In the study conducted by El-Hassan et al. (2019), a strong correlation was obtained between density and porosity ( $R^2 = 0.92$ ). As the porosity varied from 10 to 20%, the density varied from 1650 to 1950 kg/m<sup>3</sup> (El-Hassan et al. 2019).

## Compressive strength

The compressive strengths of the pervious concretes (Fig. 13) varied from 1.36 to 2.08 MPa. The highest compressive strength was obtained for sample 3A34, with a w/c ratio of 0.34 and an a/c ratio of 3.5. These compressive strengths are lower than those in the literature because the RCAs used had lower density and strength. Moreover, the concrete design, namely, the w/c and a/c ratios, was different from the design used for traditional concrete. Generally, the compressive strengths of mixtures with an a/c ratio equal to 4 are lower than the strengths of mixtures with other a/c ratios.

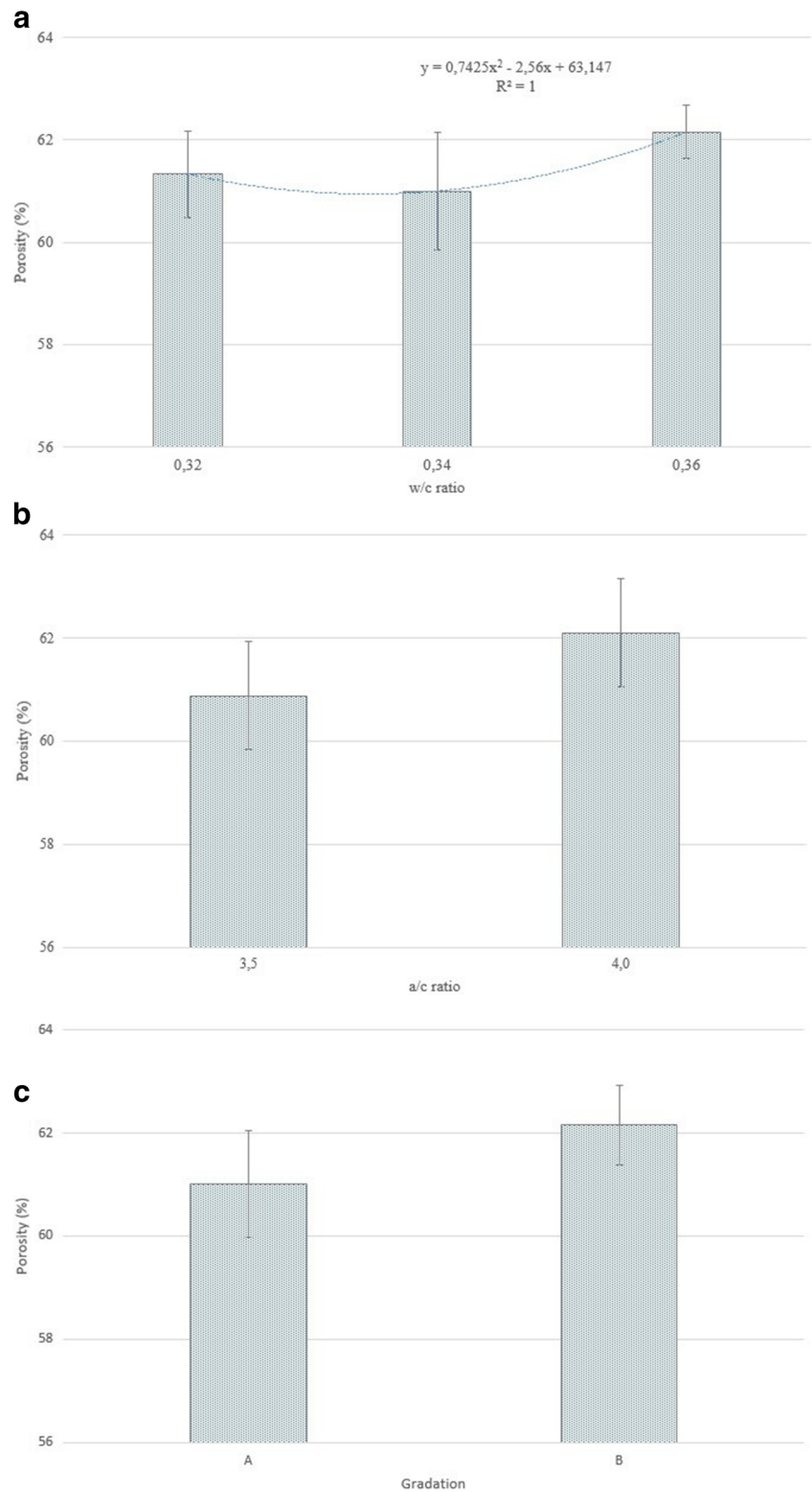
In Fig. 14(a), the impact of a change in the w/c ratio on the compressive strength is shown. When the w/c ratio was 0.32,

the compressive strength was higher than that at other a/c ratios. At a w/c ratio of 0.36, the compressive strength was lower than but similar to that at a w/c ratio of 0.32. In traditional concrete, with an increasing w/c ratio, it is generally observed that the compressive strength decreases. In pervious concretes, the impact of the w/c ratio on the compressive strength is different behavior in certain cases, primarily because of the workability, namely, the BD and porosity sections. An increase in the w/c ratio causes the paste volume to increase, which reduces the friction between coarse aggregates and reduces mold compressibility and porosity. As a result, with the increase in the w/c ratio, a corresponding increase in the compressive strength is observed. However, the w/c ratio at which the compressive strength is optimum must be determined. A w/c ratio that is too high can cause segregation and accumulation of cement paste at the bottom of the mold.

When the studies available in the literature are examined, it has been observed that increases in the w/c ratio (at the optimum level) resulted in corresponding increases in the compressive strength. In the study conducted by Kant Saheo et al. (2020), it was determined that as a result of increasing the w/c ratio from 0.30 to 0.38, the compressive strength was nearly equal to 24 MPa. Lian and Zhuge (2010) produced pervious concretes with w/c ratios of 0.28, 0.32, and 0.36. The highest 28-day compressive strength was obtained with pervious concretes with a w/c ratio of 0.36 (Lian and Zhuge 2010). In the study conducted by Ibrahim et al. (2020), pervious concretes with w/c ratios of 0.30, 0.35, and 0.40 were examined, and the optimum w/c ratio was determined to be 0.35. Debnath and Sarkar (2020) observed that as the w/c ratio (0.28, 0.30, 0.32, and 0.35) increased, the compressive strength increased, but the optimum w/c ratio was 0.30.

In Fig. 14(b), the impact of the change in the a/c ratio on the compressive strength is shown. An increase in the a/c ratio reduced the compressive strength. In pervious concretes with an a/c ratio equal to 4, the

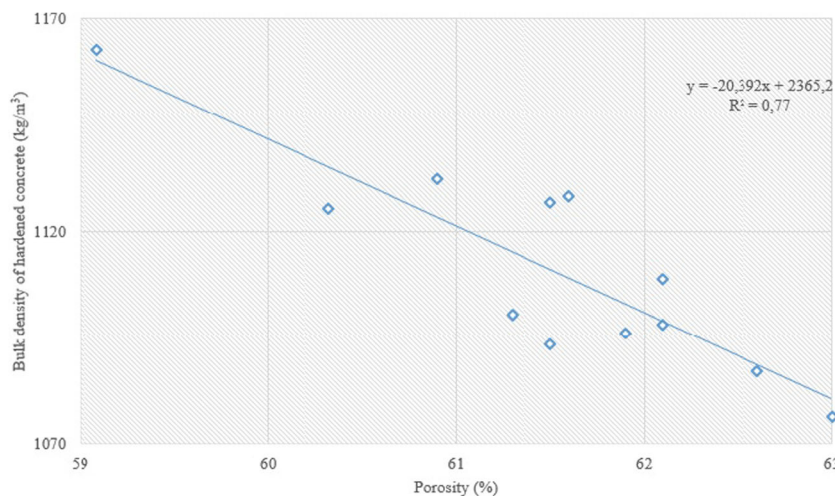
**Fig. 11** Impact on porosity of the (a) w/c, (b) a/c, and (c) gradation



compressive strength was determined to be nearly 1.5 MPa. An increase in the a/c ratio reduced the

compressive strength, but the reduction was small. This reduction in compressive strength can be explained

**Fig. 12** Relationship of porosity and hardened BD



by the reduction in paste volume that occurs as a result of an increase in aggregate amount.

In the study conducted by Liu et al. (2019), similar results were observed, and if the  $a/c$  ratio was 3.4 (instead of 2.2), the compressive strength fell below 10 MPa. In the study conducted by Hariyadi (2015), if the  $a/c$  ratio decreased from 8 to 4, the compressive strength decreased by nearly 50%. In the study conducted by Wang et al. (2019), it was emphasized that the  $a/c$  ratio decreases compressive strength because of an increase in porosity.

The compressive strengths of the pervious concretes produced with gradations A and B are shown in Fig. 14(c). A very significant aspect of aggregate gradation in relation to compressive strength could not be determined. The reduction in the compressive strength of gradation B with high porosity was negligible. The compressive strengths of pervious concretes produced with gradations A and B were determined to be nearly 1.5 MPa.

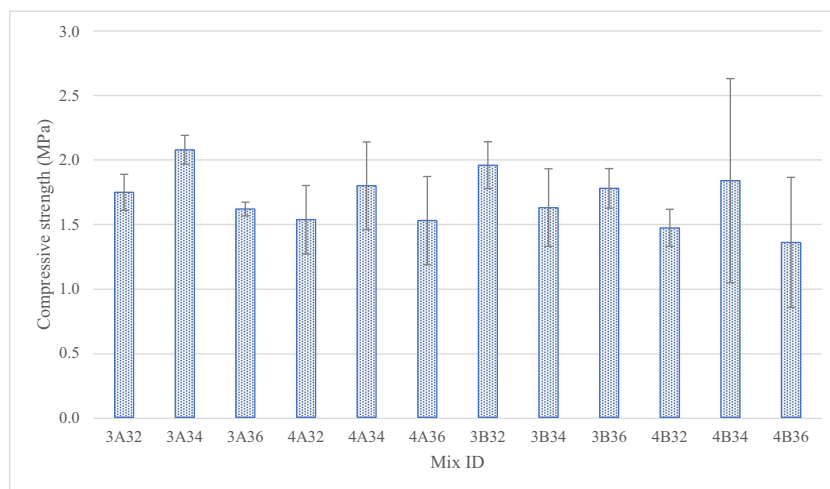
Liu et al. (2019) evaluated pervious concretes produced from 2.5–5, 5–13, and 13–20-mm aggregates and found that

the lowest compressive strength was obtained in concretes produced with 13–20-mm aggregates. In the study conducted by Kim and Lee (2010), an increase in grain size within the aggregate generally caused the compressive strength to decrease.

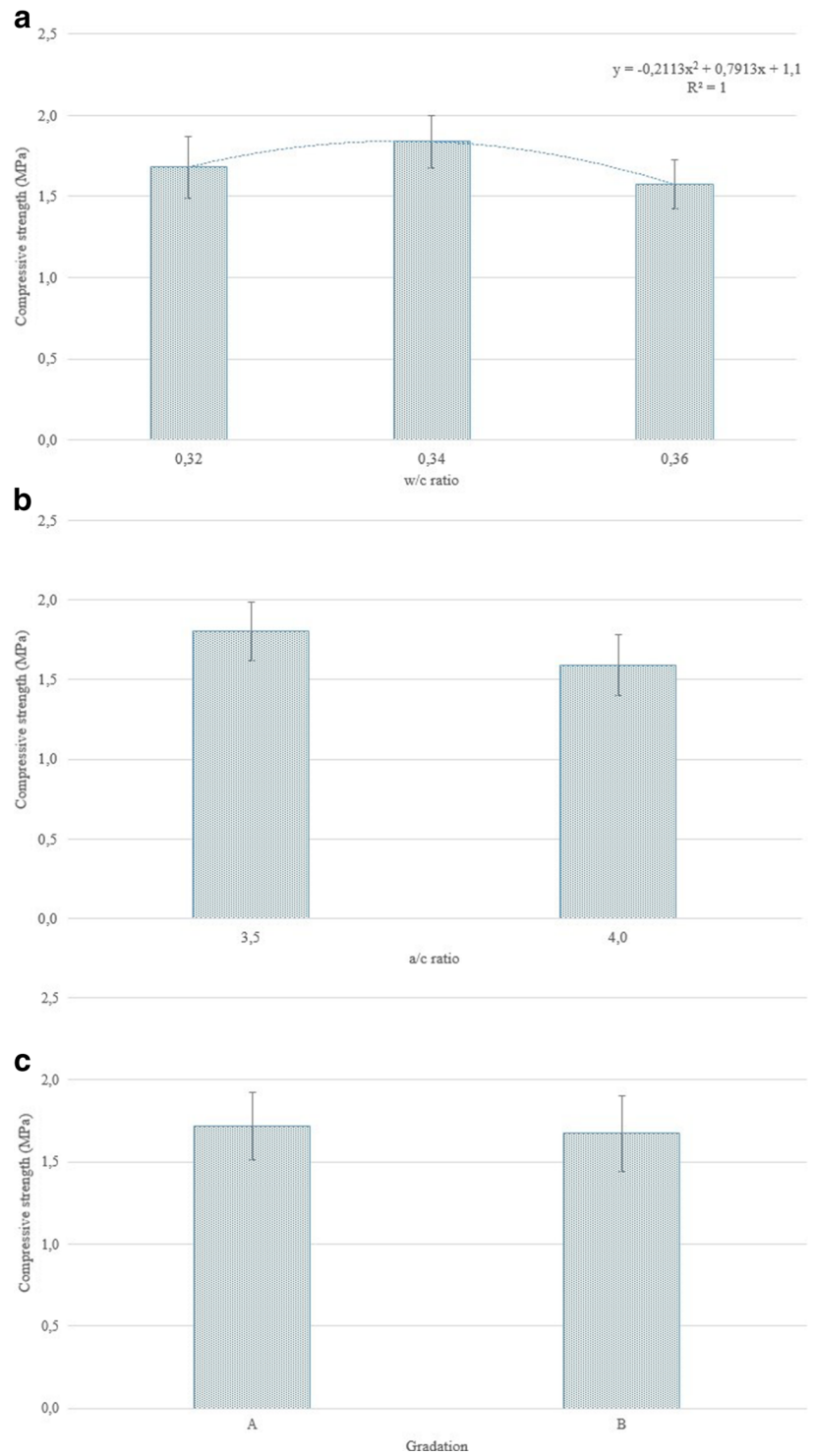
Figure 15(a) shows that with the increase in porosity, the compressive strength decreased. In the correlation between porosity and compressive strength, the  $R^2$  value was 0.67. As shown in Fig. 15(b), as the BD decreased, the compressive strength of the pervious concretes generally decreased.

In some studies, pervious concretes with low strength levels have been obtained. In the study conducted by Ibrahim et al. (2014), the 28-day compressive strengths of pervious concretes varied from 1 to 8 MPa. However, most of the pervious concretes had strengths of 1–3 MPa. The densities of the pervious concretes varied in the interval of 1650–1900 kg/m<sup>3</sup> (Ibrahim et al. 2014). In the study conducted by Yang et al. (2008), the 28-day compressive strengths of pervious concretes varied in the range of 5–6.5 MPa. The porosity values of pervious concretes varied in the range of 30.9–32.4%.

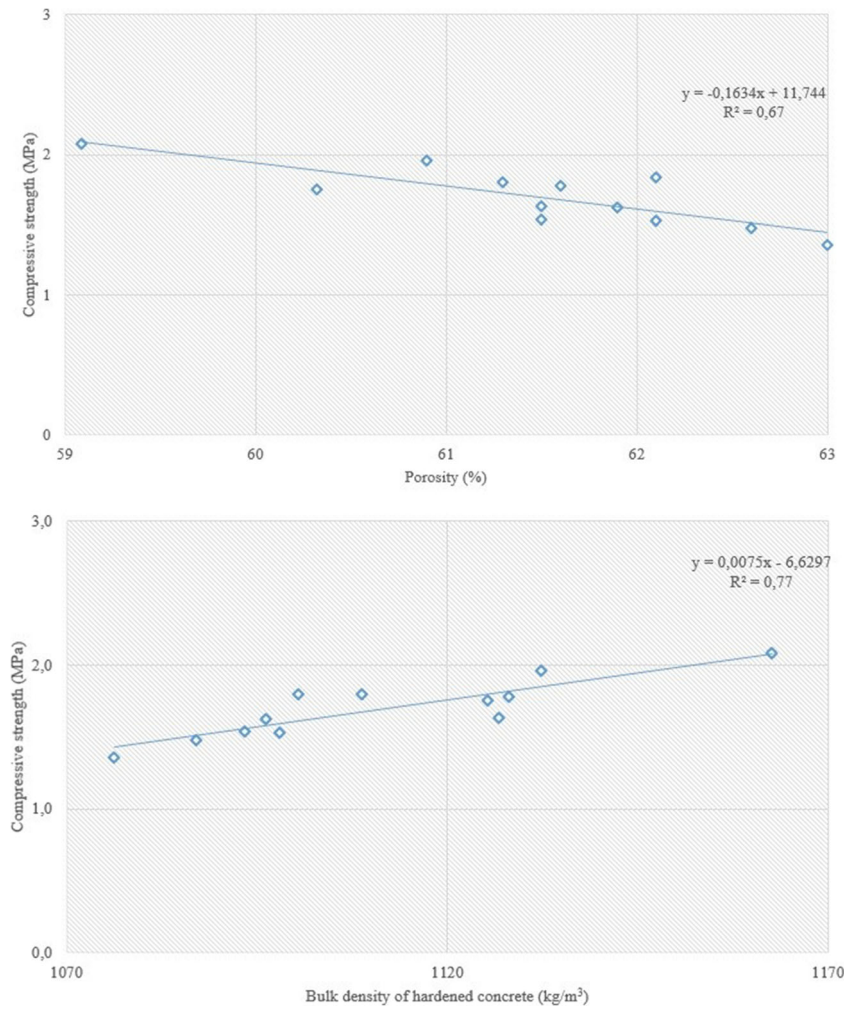
**Fig. 13** Compressive strengths of the pervious concretes



**Fig. 14** Factors affecting compressive strength: (a) w/c, (b) a/c, and (c) gradation



**Fig. 15** Relationship of the compressive strength with physical features: (a) porosity-compressive strength and (b) hardened BD-compressive strength

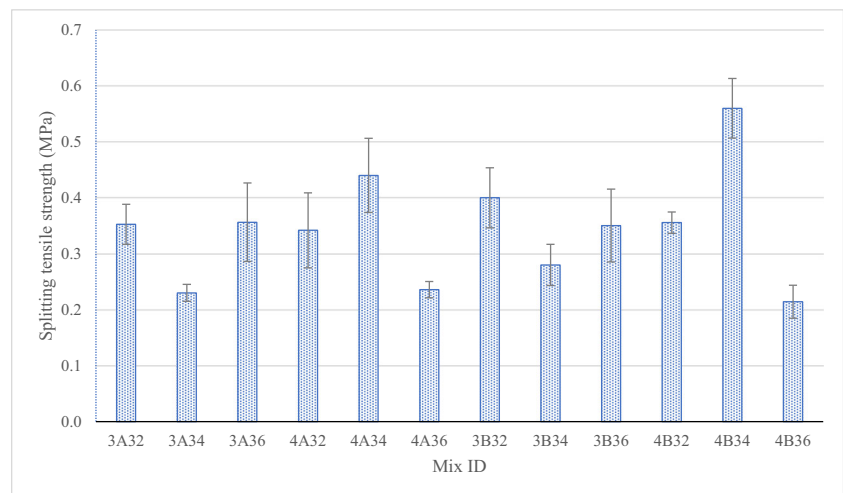


**Splitting tensile strength**

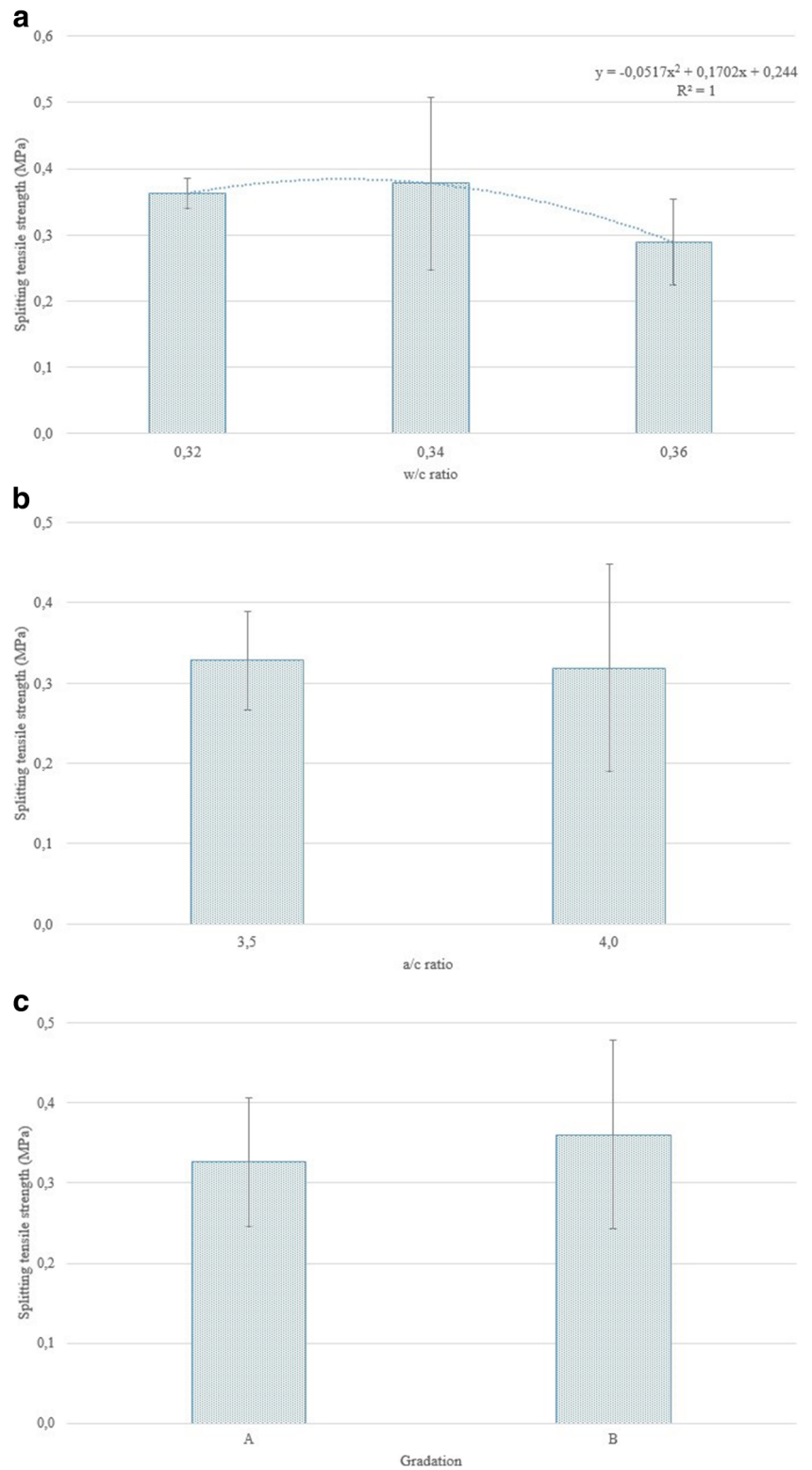
The splitting tensile strengths of pervious concretes are given in Fig. 16. The splitting tensile strengths of pervious concretes varied in the range of 0.21–0.56 MPa. The compressive

strength of sample 3A34 was high (> 2.0 MPa), but its splitting tensile strength was quite low. The highest splitting tensile strength was obtained with sample 4B34, with an a/c ratio of 4 and a w/c ratio of 0.34. In addition, the splitting tensile

**Fig. 16** Splitting tensile strengths of the pervious concretes



**Fig. 17** Splitting tensile strengths of pervious concretes: (a) w/c impact, (b) a/c impact, (c) gradation impact

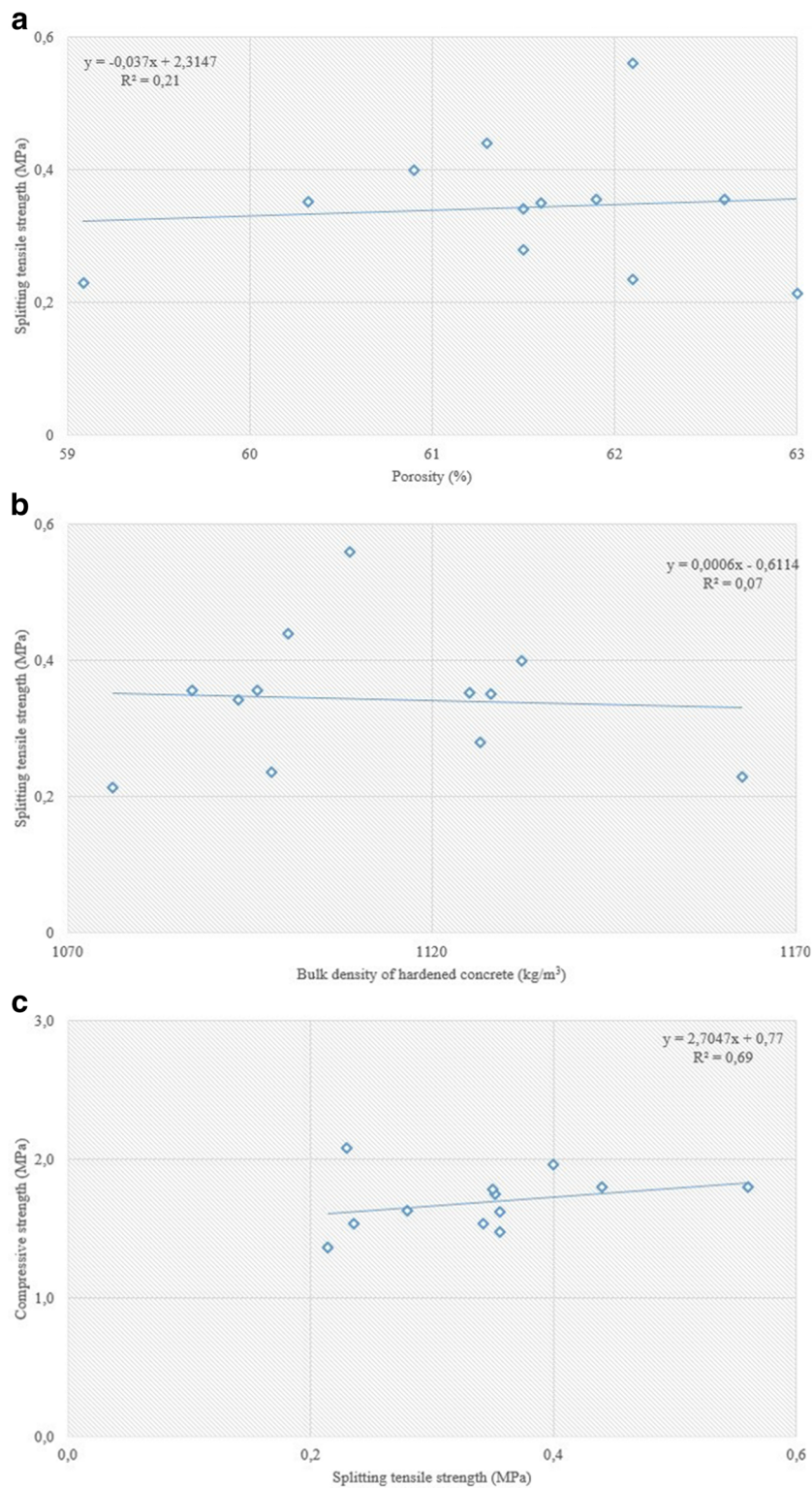


strength of sample 4A34 with gradation A was found to be 0.45 MPa.

In Fig. 17(a), the impact of the w/c ratio on the splitting tensile strength is shown. When the w/c ratio

was increased to 0.34, a relative increase occurred in splitting tensile strength. However, when the w/c ratio was increased to 0.36, the splitting tensile strength decreased by nearly 19%. The splitting tensile strengths of

**Fig. 18** Relationship of the splitting tensile strength with other concrete features. (a) Relationship of the splitting tensile strength with porosity. (b) Relationship of the splitting tensile strength with the hardened BD. (c) Relationship of the splitting tensile strength with compressive strength



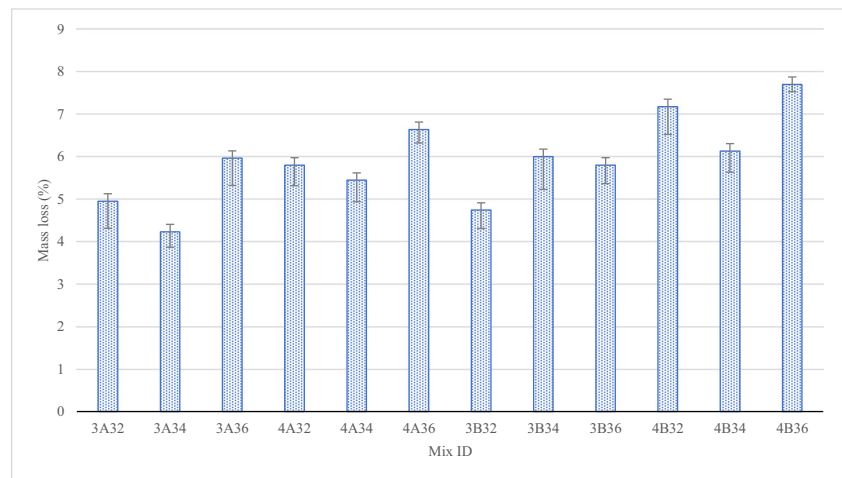
pervious concretes produced with w/c ratios of 0.32 and 0.34 were similar.

In the pervious concretes produced from brick waste by Debnath and Sarkar, similar results were observed. An increase in the w/c ratio initially increased but later decreased

the splitting tensile strength. In splitting tensile strength experiment, the load was applied as a line load over the length of the specimen, and the load was directly transferred from the cement paste to the aggregates, which caused the specimen to split. As the splitting tensile strength is mainly governed by



**Fig. 19** Weight losses of pervious concrete with abrasion impact



the cement matrix, the matrix strength and w/c ratio were the most influential factors in this experiment. Due to the improper hydration of cement at a low w/c ratio, the strength of the cement matrix is also very low, and the load cannot be distributed throughout the cement paste because the cement will split. On the other hand, a higher w/c ratio generates a thinner and weaker cement paste owing to the presence of excess water in the mixture. This thin cement paste cannot transfer a high amount of load because the load distribution from the cement matrix to the aggregate is insufficient and the specimen splits easily (Debnath and Sarkar 2020).

In Fig. 17(b), the impact of the a/c ratio on the splitting tensile strength is shown. It is seen that changes in the a/c ratio do not have a considerable effect on the splitting tensile strength. The splitting tensile strengths are higher than 0.3 MPa. In the study conducted by Liu et al. (2019), with the increase in the a/c ratio, the splitting tensile strength decreased.

The impact of the aggregate gradation on the splitting tensile strength is shown in Fig. 17(c). The splitting tensile strength of pervious concretes produced with gradation B was relatively high. However, for both gradations, the splitting tensile strengths of the pervious concretes were all higher than 0.30 MPa. Although the porosity ratio was higher for gradation B, the splitting tensile strength was higher. Studies investigating the impact of aggregate gradation on splitting tensile strength are available in the literature (Aliabdo et al. 2018; Wang et al. 2019; Debnath and Sarkar 2020).

As shown in Fig. 18, there was no correlation between the splitting tensile strength and the porosity or hardened BD. However, there was no correlation with compressive strength despite the low  $R^2$  value. Generally, as the compressive strength increased, the splitting tensile strength increased. For the splitting tensile strength, the strength of the cement paste is more important than the porosity. For this reason, the weak correlation with porosity does not provide much

information regarding this subject, which is an important issue for pervious concretes.

### Abrasion strength

The weight loss of pervious concretes as a result of experiments performed in accordance with the ASTM C944 procedure is presented in Fig. 19. The weight loss varied between 4.2% and 7.7%. It was determined that the weight loss was greater than that for traditional concrete. During the abrasion test, as aggregates separated from concrete as a whole, their weight loss was greater with respect to surface abrasion in pervious concretes. The reason why aggregate grains separate as a whole is due to low concrete strength. The lowest weight loss was obtained in sample 3A34, with the highest compressive strength. The weight losses of pervious concretes with an a/c ratio of 4 were relatively higher.

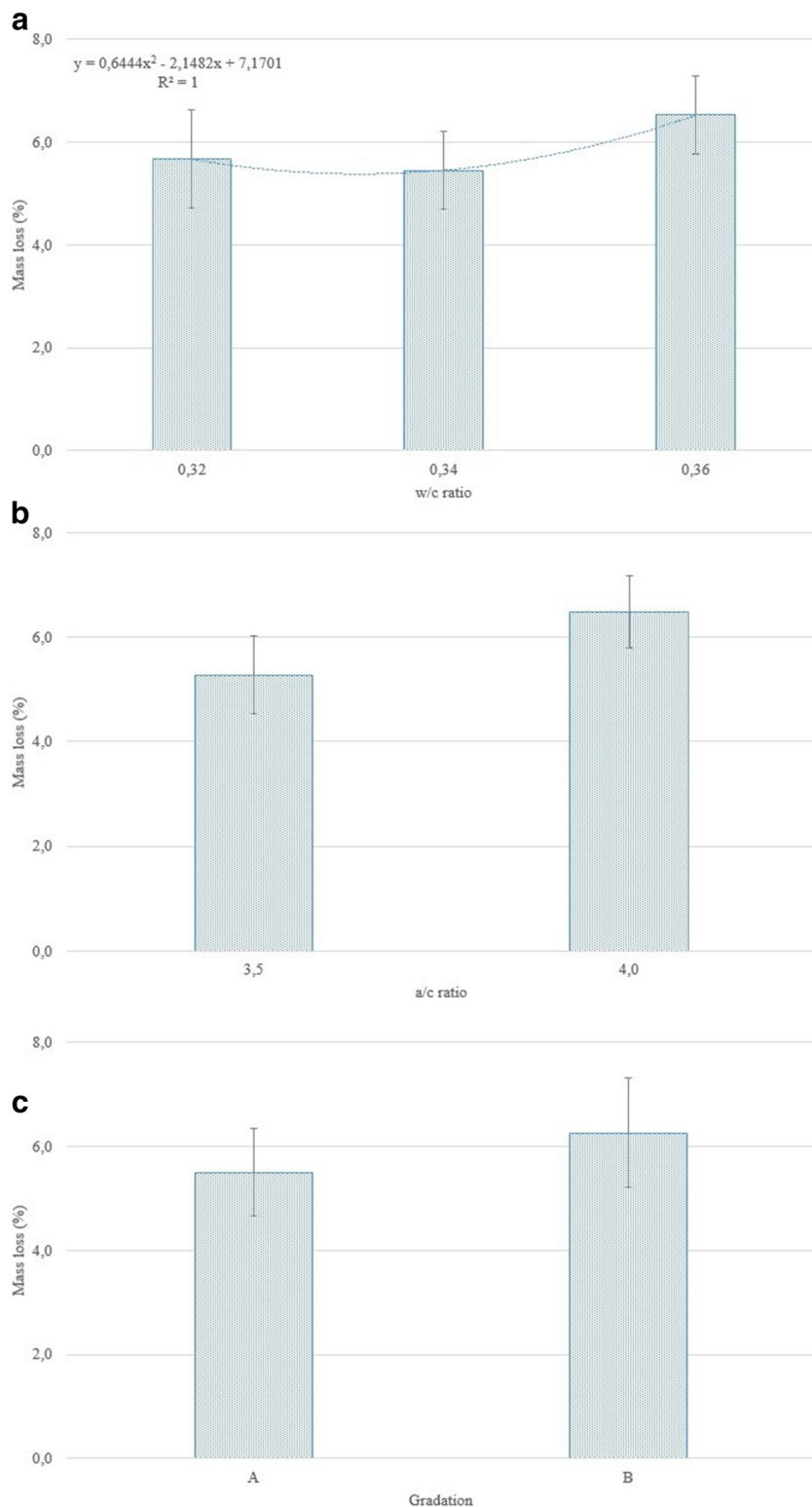
In Fig. 20(a), when the w/c ratio was 0.32 and 0.34, very significant differences were not observed. Although the weight loss was below 6% when the w/c ratio was 0.32 and 0.34, when the w/c ratio was 0.34, the weight loss exceeded 6%. It was observed that the relationship of weight loss with abrasion was similar to the relationship of weight loss with compressive strength.

In the study conducted by Kant Sahdeo et al. (2020), in the abrasion test conducted as per the ASTM C1747 (ASTM C1747/C1747M 2015) standard, increasing the w/c ratio from 0.30 to 0.35 reduced the weight loss.

In Fig. 20(b), the impact of the a/c ratio on the abrasion strength is shown. If the a/c ratio was 3.5, the weight loss was nearly 5%, and with the increase in the a/c ratio, the weight loss increased. The increase in the aggregate amount in the concrete mixture resulted an insufficient amount of cement paste, causing an increase in weight loss.

As shown in Fig. 20(c), pervious concretes produced from aggregates with gradation B underwent greater weight loss

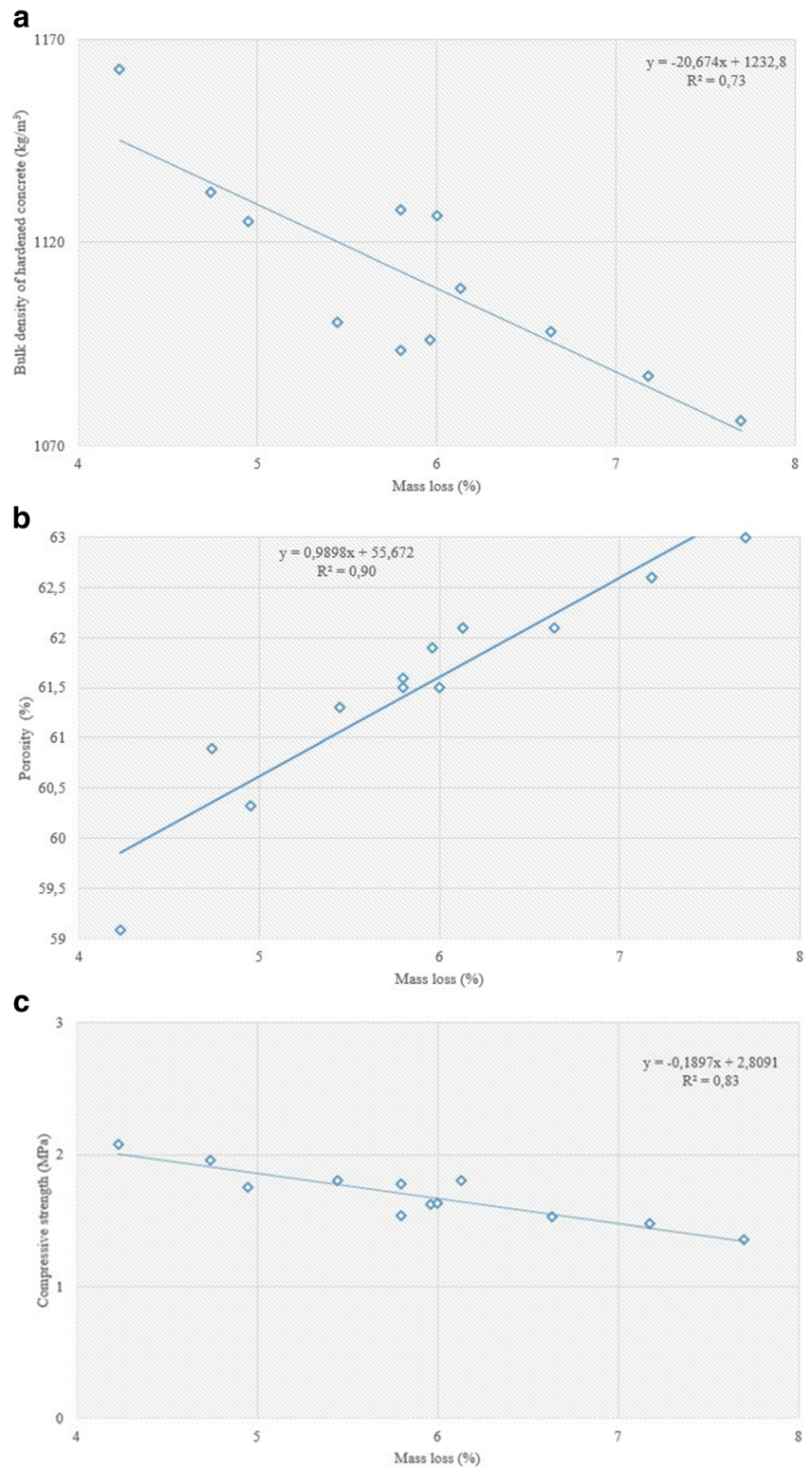
**Fig. 20** Factors affecting weight loss: (a) w/c, (b) a/c, and (c) gradation



than those with gradation A. Gradation A had a wider aggregate grain size distribution in its structure, which reduced its weight loss to below 6%. Compressive strength, which is dependent on the gradation type, is

an important factor affecting abrasion strength. In addition, with gradation A, the aggregates had more contact surfaces because of the lower porosity, also reducing the weight loss.

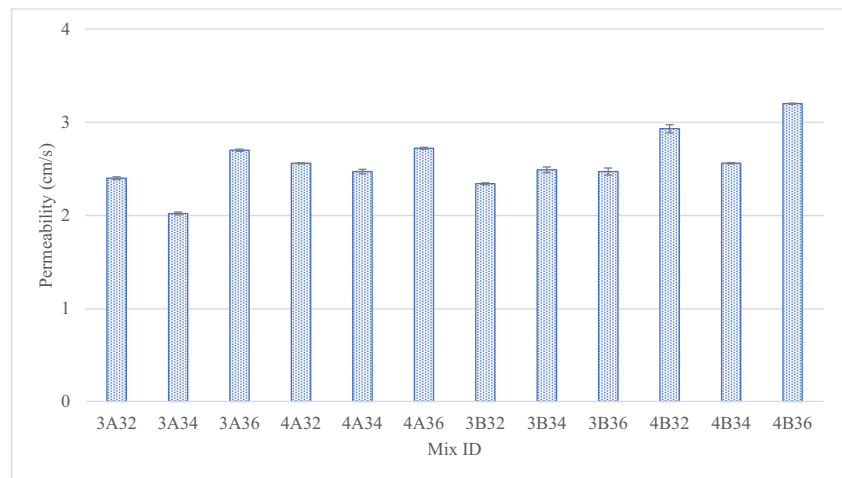
**Fig. 21** Relationship of weight loss with other concrete properties: (a) weight loss—hardened BD relationship; (b) weight loss—porosity relationship; and (c) weight loss—compressive strength relationship



In Fig. 21, the correlation of weight loss to other concrete properties is shown. As the hardened BD of the pervious concretes decreased, the weight loss increased (Fig. 21(a)). As the porosity increased, the weight loss increased (Fig. 21(b)). As a

result of the increase in compressive strength, the weight loss of the pervious concretes decreased (Fig. 21(c)). In Fig. 21, the correlation between weight loss and porosity is closer than that between weight loss and the hardened BD. For this

**Fig. 22** Permeability properties of the pervious concretes



reason, to increase abrasion strength, an optimum gap ratio is recommended. Furthermore, by considering the compressive strength, information can be obtained about the abrasion strength.

Gaedicke et al. (2014) reported that the abrasion strength of pervious concretes with the same a/c ratio and equal porosity was affected by aggregate roots and that the abrasion strength of fine aggregate samples was lower than that of coarse aggregates.

## Permeability

As shown in Fig. 22, the permeability of the concretes varied in the range of 2.02–3.23 cm/s. The permeability of sample 3A34, with an a/c ratio of 3.5 and a w/c ratio of 0.34, was equal to 2.02 cm/s. The permeability of sample 4B36 was above 3 cm/s. It is seen that the porosity affects permeability.

Figure 23(a) shows that at all w/c ratios, the permeability was generally below 3 cm/s. Additionally, the permeability at w/c ratios of 0.32 and 0.34 were similar. When the w/c ratio increased to 0.36, the permeability increased, primarily because of the porosity and the compressive strength. As the porosity of the pervious concretes with a w/c ratio of 0.36 was high, their water permeability was also high.

In the study conducted by Debnath and Sarkar (2020), similar results were obtained. When the w/c ratio reached the optimum point, the permeability improved. The permeability varied in the range of 0.53–2.11 cm/s (Debnath and Sarkar 2020). In the study conducted by Lu et al. (2019), it was stated that with increasing porosity, water permeability increases.

Figure 23(b) shows that the water permeability of the concrete increased when the a/c ratio increased to 4. At an a/c ratio of 3.5, the permeability was approximately 2.5 cm/s. At an a/c ratio of 4, the cement paste in the mixture was low, and the

porosity was high. As the porosity increased, the passage of water through the material was also easy, and therefore, the permeability coefficient was high. However, as a result, the compressive strength was low.

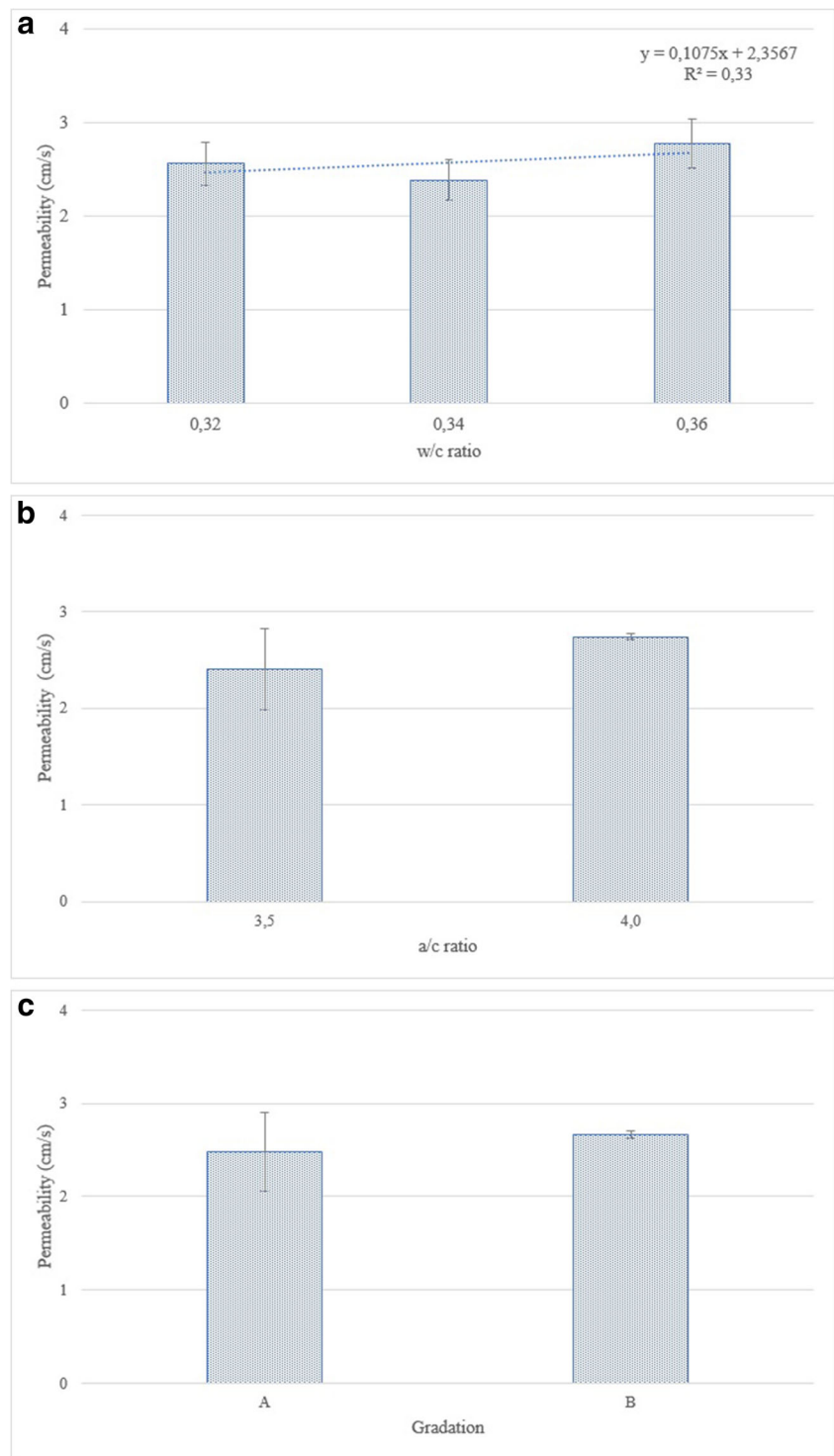
The permeability values of the concretes produced from aggregates with gradation B were higher than those for gradation A (Fig. 23(c)). The wider grain size distribution of the aggregate mass with gradation A decreased the permeability. In particular, the presence of aggregate grains close to 4.75 mm in gradation A caused this decrease in permeability. The high porosity of concretes with gradation B facilitated the passage of water.

The aggregate grain size distribution has an important effect on the mechanical properties and porosity. Smaller aggregates improve the compactness and mechanical properties while reducing the passage of water. When mixtures with unimodal and bimodal grain size distributions were compared, aggregates with a unimodal grain size distribution provided higher porosity, but the mechanical properties were negatively impacted (Debnath and Sarkar 2020).

In Fig. 24(a) and (b), it is seen that the permeability increased as the BD of the hardened concretes decreased, and the permeability decreased with decreasing porosity. As the compressive strength increased, the water permeability of the concrete decreased (Fig. 24(c)). When the correlations were examined, the porosity was found to have a considerable effect on the permeability. These findings are similar to those of other studies in the literature (Lu et al. 2019; Debnath and Sarkar 2020; Kant Sahdeo et al. 2020).

In Fig. 25, the correlations of compressive strength and permeability with porosity, being among the most important properties of pervious concrete, are given. An increase in porosity decreased the compressive strength and increased the water permeability. In Fig. 25, the point where the porosity-compressive strength and

**Fig. 23** Factors affecting permeability: (a) w/c, (b) a/c, and (c) gradation

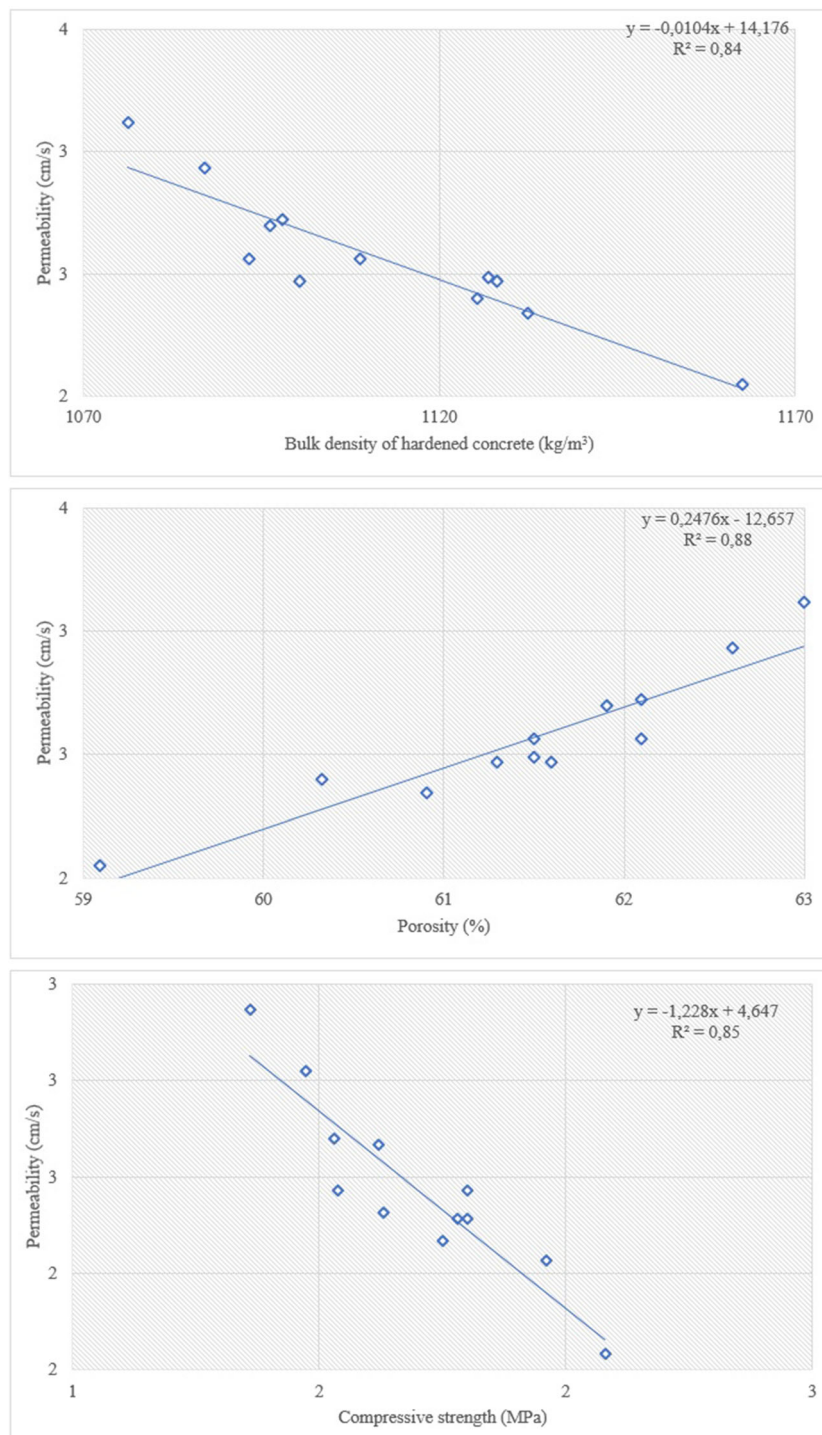


permeability curves coincide was determined as the optimum point, where the compressive strength of approximately 1.75 MPa, porosity of 60.3%, and permeability of 2.40 cm/s are considered optimum. The mixture closest to these values was sample 3A32, with a w/c ratio of 0.32 and an a/c ratio of 3.5.

**Conclusions**

1. The hardened BDs of pervious concretes varied from 1076 to 1162 kg/m<sup>3</sup>. At a w/c ratio of 0.34, the BD was high, but above this w/c ratio, the BD decreased. Similar results were obtained with regard to porosity, and 61%

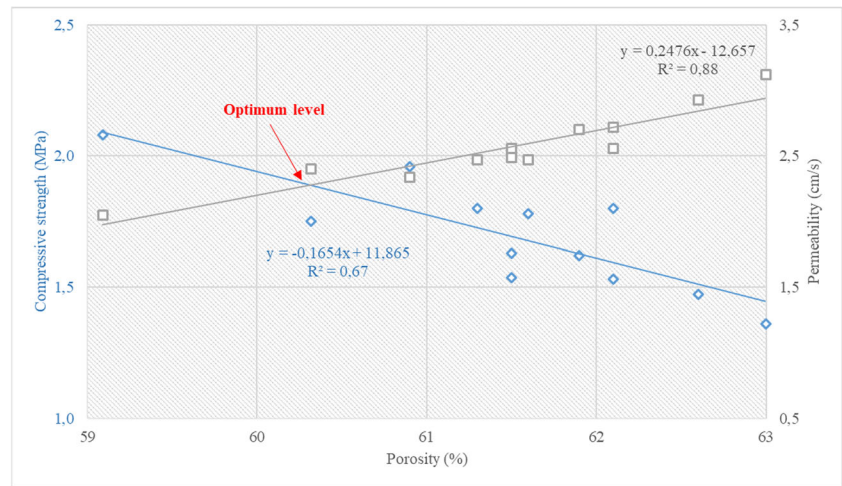
**Fig. 24** Relationship of permeability with other concrete properties: (a) permeability-hardened BD relationship, (b) permeability-porosity relationship, and (c) permeability-compressive strength relationship



porosity was obtained at a w/c ratio of 0.34. The decrease in porosity with the increase in the w/c ratio was explained by the increase in cement paste volume.

- In pervious concretes, possessing RCAs with low specific weights and mixture designs that were different than those of traditional concrete, the BD was below 1200 kg/m<sup>3</sup>. As a result, their compressive strength varied from 1.36 to
- 2.08 MPa. The compressive strengths of mixtures with low porosity values and w/c ratios of 0.34 were nearly 1.90 MPa.
- It was observed that the splitting tensile and abrasion strengths varied proportionally to the compressive strength. An increase in compressive strength improved other mechanical properties of concrete. Regarding the

**Fig. 25** Correlation coefficients of some pervious concretes



- splitting tensile strength, the importance of cement paste has been highlighted in the literature. In the present study, with the increase in the a/c ratio, the splitting tensile strength decreased. In relation to abrasion strength, an increase in the a/c ratio increased weight loss.
- With regard to permeability, an increase in the w/c ratio increased the water permeability. As stated in the literature, an increase in porosity increases the permeability coefficient. The permeability coefficients of the concrete varied between 2.05 and 2.12 cm/s.
  - The wide range of the aggregate grain size distributions adversely affected the water permeability of the pervious concretes. In particular, the mechanical properties of the pervious concretes produced from aggregates with grain sizes of 4.75–12.50 mm were good, but their permeability was low.
  - The compressive strengths of the pervious concrete were low. However, using 100% RCA is important for sustainability. It will be most suitable to use this type of concrete in pedestrian roads or parks without vehicle loads. In this way, environmental outcomes can be achieved by using recycled urban waste in pervious concretes that do not require high strength.
  - The mechanical properties of concrete can be improved by replacing a certain portion of RCA with good limestone or dolomite aggregates. In particular, the compressive strength and permeability of the mixtures obtained by adding some fine aggregate (recycled) should be examined.

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**Data availability** Not applicable

### Compliance with ethical standards

**Competing interest** The authors declare that they have no competing interests.

**Ethics approval and consent to participate** Not applicable

**Consent for publication** Not applicable

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