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Investigating the physical properties of modified pervious concrete containing different lightweight aggregates

Huda H. Gghail*, *Mosah S. Abdulsada*, and *Tumadhir M. Borhan

Department of Civil Engineering, College of Engineering, University of Al-Qadisiyah Al-Diwaniyah, Iraq.

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ABSTRACT

Pervious concrete is an environmentally friendly paving concrete that has attracted significant attention due to its environmental advantages, particularly in mitigating the influences of urban heat and improving stormwater runoff. This study aims to investigate the influence of three types of lightweight coarse aggregates on the physical properties of pervious concrete mixtures. These types are pumice and two types of lightweight expanded clay aggregates (LECA): low density (LD) and high density (HD). Previous concrete mixtures were modified by styrene butadiene rubber (SBR) at 5% by cement mass and prepared. The physical properties of this type of concrete, including porosity, permeability, and hardened density, were investigated. The results indicated that replacing the normal coarse aggregate with a volumetric ratio of 10% lightweight coarse aggregates resulted in a significant increase in permeability and porosity while at the same time reducing density. The highest value of permeability was achieved by the mix containing 10% of LD without SBR, with an increment of 35.9%, compared to the control mix. The porosity was increased by 28.6% in the mix containing 10% of PA without SBR, compared to the control mix. On the other hand, Regardless of the type of lightweight coarse aggregate used, the addition of SBR to the lightweight aggregate mixtures significantly decreases the porosity and permeability while increasing density. Based on the findings of this study, it can be concluded that the type of aggregate chosen has a significant effect on the physical properties of pervious concrete.

1. Introduction

The impermeable surfaces used in the urban and suburban regions have resulted in several environmental problems, especially surface flooding problems during rain events that may cause problems to both vehicles and pedestrians [1]. Due to this, the use of porous pavement technology has drawn a lot of interest throughout the world. The technology is feasible to manage the surface runoff in urban areas and assist in the preservation and recharge of groundwater. Moreover, it helps in the sustainability of the environment by partially filtering pollutants in the runoff during the percolation process [2,3]. Pervious concrete (PC), or porous concrete, is a developed design for a unique product. Based on the Portland cement mixture, the porosity of pervious concrete is designed by deleting all or most of the fine aggregates, allowing its porous structure to pass through water freely into the soil without compromising its integrity or durability. The pore diameters range from 2 to 8 mm and the void contents are between 15% and 35%. Moreover, its permeability ranges from 0.14 to 1.22 cm/s [4]. PC can successfully address many environmental issues and support sustainable development due to its ability to reduce urban heat island effects, mitigate stormwater runoff rate, and remove water pollution by reducing the concentrations of heavy metals, such as chromium, copper and zinc, commonly found in stormwater from road surfaces and urban areas [5]. PC is associated with low mechanical performance due to its high porosity; nevertheless, it suits very well to a wide range of applications such as porous pavements, thermal insulation, water purification, and acoustic noise reduction [6]. Using lightweight coarse aggregates (LWCAs) as coarse aggregate in pervious concrete provides some benefits, such as making the concrete being environmentally friendly, decreasing stormwater runoff rate and wastewater contamination, reducing the depletion of natural resources, and enhancing PC's physical properties. The research by Huang et al. [7] compared the effectiveness of permeable interlocking pavers, porous asphalt, and pervious concrete in terms of reducing stormwater, enhancing the surface infiltration capacity, and eliminating pollutants under cold climate conditions. The findings showed that the three pavement types are effective in mitigating stormwater runoff. Hariyadi and Tamai [6] tested the influence of substituting natural coarse aggregates with pumice in pervious concrete. Their results showed that the addition of pumice caused a rise in porosity and a reduction in the modulus of elasticity, whereas the tensile strength was higher than the values given in the ACI standards. Teymouri et al [8]. carried out an experimental study to explore the potential of using porous concrete for improving the quality of wastewater and stormwater by adding mineral adsorbents, specifically LECA, pumice, zeolite, and perlite. The research investigated how partially replacing natural coarse aggregates with these materials at levels of 5%, 10%, and 15% by weight affected key characteristics such as water permeability, porosity, and compressive strength. The findings stated that zeolite was the most effective material for enhancing water quality parameters, achieving a reduction of 40% in suspended solids, 48% in biochemical oxygen demand, and 30.5% in chemical oxygen demand. Additionally, mixes that included zeolite and pumice showed superior performance in permeability, compressive strength, and porosity compared to those containing the other types of aggregates. Although PC have been widely used in road applications, several challenges are related to its implementation and use. These challenges are mostly associated with the fact that this type of concrete is not very durable [9].

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*Corresponding Author.

E-mail address: tumadhir.borhan@qu.edu.iq ; Tel: (+964) 782-972 0588 (Tumadhir Borhan)

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Nomenclature			
A	Oven-dry mass of the specimen (g)	K	Factor= 1273240 $(mm^3.kg/m^3.g)$
B	The underwater mass of specimen (g)	L	The average specimen length (mm)
D	The average specimen diameter (mm)	ρ_w	The water density (kg/m^3)

To enhance the durability of PC, many researchers have carried out experimental studies by incorporating cementitious materials (fly ash, silica fume), chemical admixtures (polymers), sand and fibers, or by using different size aggregates and varying water-cement ratios [10–14]. The utilization of polymer type styrene butadiene rubber (SBR) to enhance the properties and durability of PC has been investigated by Kevern [15] the author found that the addition of SBR in latex form at relatively low cement content significantly improved strength and freeze-thaw resistance. Zhao et al. [16] also conducted an experimental study demonstrating that combining SBR with acrylate latexes significantly enhances the freeze-thaw resistance of pervious concrete. This combination also leads to reduced dry shrinkage and minimizes strength loss when the concrete is soaked in a sulfate solution. Wu et al. [17] examined whether adding fiber or latex to pervious concrete improved its resistance to abrasion. They found that while the addition of fiber had no effect, latex enhanced the abrasion resistance. This study explores the effect of use three types of lightweight coarse aggregates, pumice and two types of LECAs, with a replacement rate of 10% of natural coarse aggregates by volume, on the physical properties of pervious concrete. In addition, the effect of adding styrene butadiene rubber (SBR) on these properties was also examined.

2. Experimental details

2.1 Materials properties

2.1.1 Cement

Sulphate-resistant Portland cement produced by the cement company Lafarge, with properties that are in agreement with Iraqi specification No.5 [18] CEM I 42.5R-SR3.5, as depicted in Table 1, was used as a primary binder.

2.1.2 Aggregate

In pervious concrete, monogranular aggregate (single-sized aggregate) selection is critical in the creation of a network of interconnected voids that ensure the infiltration capacity [2, 4]). Therefore, a 5-10 mm grain size uncrushed gravel with a spherical shape and properties that meet Iraqi specification No.45 [19] was utilized in this investigation as a natural coarse aggregate (NCA). In addition, three types of lightweight coarse aggregate (LWCAs), Pumice (PA), and two different lightweight expanded clay aggregates (LECA) with particle sizes ranging between 5-10 mm were employed as a partial replacement for the natural coarse aggregate throughout this research study. The LECA types utilized were referred to as LD, low-density LECA, and HD, high-density LECA. The physical characteristics of the used aggregate are given in Table 2, while Fig. 1 shows the particle shape of the used LWCAs.

(a) PA (c) LD (b) HD

Figure 1. LWCAs particle shape.

Table 1. Employed cement's physical and chemical properties.

Physical properties						
Property	Specific surface area	Setting time in min..		Compressive strength (MPa)	
		Initial set.	Final set.	2d	28d
Test value	318	60	299	21.88	57.44
I.S.Q. No.45 limits	$\geq 300\ m^2/kg$	≥ 45	≤ 600	$\geq 20MPa$	$\geq 42.5MPa$

Chemical composition												
Oxide comp.%	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	$L.O.I.$	$I.R$	C_3S	C_2S	C_3A	C_4AF
Test value %	62.942	22.788	3.321	2.819	3.372	1.814	2.864	0.936	49.073	28.313	3.095	10.261
I.S.Q. No.45 limits	——	——	——	$\leq 5\%$	——	$\leq 2.5\%$	$\leq 4\%$	$\leq 1.5\%$	——	——	$\leq 3.5\%$	——

Table 2. Physical characteristics of the utilized coarse aggregate.

Type of aggregate	**Maximum size** (mm)	**Specific gravity**	**Dry rod bulk density** (kg/m^3)	**Loose bulk density** (kg/m^3)	**Absorption** $(24h)$
NCA	10	2.6	1681	—-	0.9%
PA	10	1.8	—-	728	14%
LD	10	0.75	—-	384	24%
HD	8	1.1	—-	643	14%

2.1.3 Polymer latex

A polymeric additive commercially known as Cempatch SBR 100 (milky fluid), supplied by DCP Co. in Iraq and formulated from Styrene-Butadiene Rubber latex (SBR), was used in this study. It had solid content of 57%, pH value of 10.7, and a specific gravity of 1.02.

2.2 Pervious concrete mix proportions

In the present study, the reference mix was proportioned using a volumetric ratio of 1:5 cement: aggregate $(C:A)$, following the approach of previous studies [20–23] to meet the requirements of ACI 522R-10 [4]. To investigate the influence of LWCAs on the physical properties, natural coarse aggregate was considered for partial replacement by LWCAs, specifically at a substitution level of 10% by volume. In addition, SBR was added in a dosage of 5% as a percentage of cement mass to investigate its impact. To determine the appropriate w/c ratio, a trial test was conducted following the guidelines outlined by Tennis et al. [2] and NRMCA [24]. The results indicated that a w/c ratio of 0.32 was suitable for creating moldable pervious concrete. Therefore, this w/c ratio was used for all tested mixes in this study. Table 3 summarizes the proportions used in the pervious concrete mixes. The pervious concrete mixes are identified by the type of aggregate utilized. For instance, the MH mix consists of NCA, with 10% replaced by HD. In the case of the MHP mix, the letter P signifies the addition of polymer.

2.3 Mixing and specimen preparations

A tilting-type drum mixer was employed to mix the pervious concrete ingredients in this experimental research study. To prevent the LWCAs from absorbing the cement paste water due to their high-water absorption, they were prewetted for 24 hrs [25–27] prior to mixing. After prewetting, the LWCAs were allowed to air dry Fig. 2 until they reached a saturated surface dry condition (SSD) to prevent increasing the water content of the paste. Initially, the coarse aggregate in SSD condition and a small amount of water were mixed for 15 seconds to enhance the bond between the cement paste and the coarse aggregate by wetting its surface. After that, the cement was added and the mixture was blended for about 30 seconds. Finally, the remaining water was added while the mixing was ongoing, and the mixing continued until a cohesive mix was obtained. For mixes containing SBR, the same process was performed after dissolving the SBR in water. Nine identical cylindrical specimens with ($\phi 100 \times 200 mm$) dimensions were cast in standard steel moulds for each mix. The fresh concrete was poured into the designated moulds in two layers, with a minimum hand compaction following the ASTM C192 specification [28]. After moulding, the specimens were covered with a polyethene sheet after 20 min of casting to hold the moisture in the concrete, following the guidelines outlined in ACI 522R-10 [4]. After 24 h, all the specimens were removed from the mould and stored in a water tank at 23 ± 2°C until testing. Figure 3 shows the pervious concrete mixing and casting process.

Figure 2. Air drying of the LWCAs.

Figure 3. Pervious concrete mixing and casting process.

2.4 Testing Procedures

2.4.1 Density and porosity

The ASTM C1754 specification [29] was used to evaluate the density and porosity of pervious concrete cylinders (ϕ 100 × 200 mm). Three replicate specimens were tested, and the mean value was reported for each pervious concrete mix. The density was evaluated after 7 and 28 days of water curing using Eq. 1, while Eq. 2 was employed to assess the porosity after a curing period of 28 days in water.

$$Density\ (kg/m^3) = \frac{K \times A}{D^2 \times L} \tag{1}$$

Where A is the oven-dry mass of the specimen (g), L is the average specimen length (mm), D is the average specimen diameter (mm), and K is a factor (1273240) in SI units ($mm^3.kg/m^3.g$).

$$Porosity(\%) = \left[1 - \frac{K \times (A - B))}{\rho_w \times D^2 \times L}\right] \times 100 \tag{2}$$

Where A is the oven-dry mass of specimen (g), B is the underwater mass of specimen (g), L is the average specimen length (mm), D is the average specimen diameter (mm), K is a factor (1273240) in SI units ($mm^3.kg/m^3.g$), and ρw is the water density (kg/m^3)

2.4.2 Coefficient of permeability

The coefficient of permeability test was conducted using the falling head method, following the guidelines outlined in ACI 522R-10 [4]. For this test, a permeability device similar to the one described in ACI 522R was fabricated, as shown in Fig. 4. Three cylindrical specimens, each measuring 100 mm in diameter and 200 mm in height, were tested for each pervious concrete mix, and the mean value was reported as the test value. Before testing, a rubber sleeve was wrapped around each specimen, and circular clamps were used to tighten it, ensuring there was no water leakage between the device and the specimen, allowing water to flow only through the specimen's area. The permeability coefficient was then calculated using Darcy's law, as demonstrated in Eq. 3.

$$k = \frac{a \times l}{A \times t}\left(ln\frac{h_1}{h_2}\right) \tag{3}$$

Where k, a, L, A, t, h_1, and h_2 are the coefficient of permeability (cm/s), the cross-sectional area of the tube (cm^2), the average specimen length (cm), the cross-sectional area of the specimen (cm^2), the required time for the water to drop from h1 to h2 (s), the initial heads of water (39 cm), and the final heads of water (17 cm) respectively.

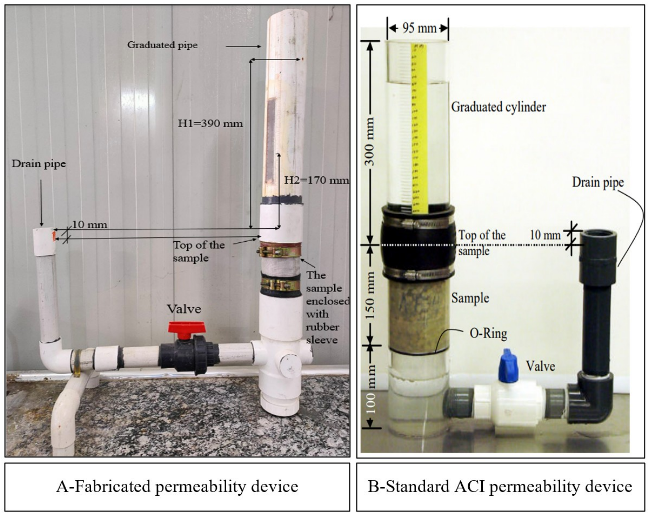

Figure 4. Apparatus of permeability test.

3. Results and discussion

Table 4 shows the test results of the hardened density, porosity, and permeability coefficient of pervious concrete mixes obtained during this experimental study.

3.1 Hardened density

The density of porous concrete is primarily affected by the properties and content of its constituents as well as the compaction method used during placement [2]. The impact of using LWCAs as a partial replacement for the normal coarse aggregate on the density of porous concrete and the effect of adding SBR are depicted in Fig. 5. The results revealed that the inclusion of LWCAs led to a decrease in the density of porous concrete. The results indicated that at a replacement level of 10% by volume, the density reduced by 1.5%, 3.9%, and 4.8% in the MH, ML, and MP mixes, respectively, as compared to the reference mix. This behaviour could be explained by the fact that compared to normal coarse aggregates, LWCAs possess lower densities and greater void contents. In addition, it can be shown that the use of PA showed the highest decrease in density. This could be due to the angular nature of PA, which may not allow compacting of aggregate particles during the rodding process. As a result, a lower density was achieved [30]. It can be observed from Fig. 5 that the addition of SBR had a noticeable effect on the hardened density of porous concrete mixes. The density increased from 1991, 1942, and 1923 kg/m3 to 1997, 1965, and 1977 kg/m3 for the MHP, MLP, and MPP mixes, respectively, representing only a reduction of 1.2%, 2.8%, and 2.2% in compression to the reference mix. This increase in density may be attributed to the polymerization

Table 3. Details of the pervious concrete mix proportions (kg/m^3).

Mix. No.	Mix. ID	C:A	w/c	Cement	Water	SBR	Coarse aggregate			
							NCA	HD	LD	PA
1	MR	1:5	0.32	378	121	—-	1560	—-	—-	—-
2	MH	1:5	0.32	378	121	—-	1404	66	—-	—-
3	ML	1:5	0.32	378	121	—-	1404	—-	45	—-
4	MP	1:5	0.32	378	121	—-	1404	—-	—-	108
5	MHP	1:5	0.32	378	121	19	1404	66	—-	—-
6	MLP	1:5	0.32	378	121	19	1404	—-	45	—-
7	MPP	1:5	0.32	378	121	19	1404	—-	—-	108

Table 4. Hardened density, porosity, and permeability coefficient test findings.

Mix.ID	7-Day Hardened density (kg/m^3)	28-Day Hardened density (kg/m^3)	28-Day Porosity (%)	28-Day Permeability (cm/s)
MR	2008	2021	15	0.64
MH	1931	1991	17.4	0.69
ML	1863	1942	17.7	0.87
MP	1891	1923	19.3	0.84
MHP	1976	1997	12.6	0.41
MLP	1907	1965	13	0.34
MPP	1947	1977	17.5	0.66

process of SBR, which effectively fills the pores, cracks, and microcracks in the interfacial transition zone (ITZ) between the cement and the aggregate during the hardening process of cement [31–33]. Moreover, it can be observed from Fig. 5 that the increase in density after 7 days is limited when the mixes are tested after 28 days. This suggests that most hydration processes crucial for improving strength and refining the pore structure happen early in the curing process, affected by the kind of cement used and the low water-to-cement (w/c) ratio applied [34]. The 28-day hardened density of the tested pervious concrete mixes in this study ranges between 1923 and 2021 kg/m^3. This density range is akin to traditional pervious concrete mixes, as outlined by Tennis et al [2].

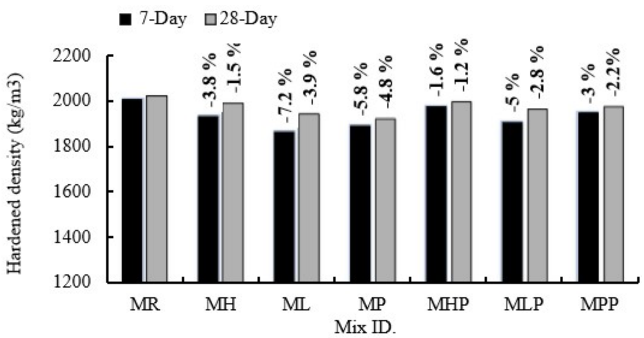

Figure 5. Previous concretes hardened density results with LWCAs and SBR.

3.2 Porosity

The proportions, shape, and size of the aggregates utilized in the mix design of porous concrete greatly influence the porosity of concrete [35, 36]. Figure 6 shows the impact of LWCAs as a partial replacement for the normal coarse aggregate and the impact of SBR on the porosity findings of porous concrete mixes. It is clear from the Figure that the utilization of LWCA, regardless of the type, increases the porosity of the porous concrete. The increasing in porosity was 16%,18%, and 28.6% for the MH, ML, and MP mixes, respectively, relative to the reference mix. The enhancement in porosity for the MH and ML mixes can be mainly attributed to the more rounded shape of LECA, relative to normal coarse aggregate, which findings in more interconnected pores [26]. Furthermore, LECA's higher porous cellular structure in comparison to the normal coarse aggregate contributes further to this impact [37]. Similar results have been studied by [27, 38, 39]. Moreover, from Fig. 6, it can be showed that the use of LD led to higher porosity in porous concretes than the use of HD. This can be attributed to the greater porosity and larger particle size of LD aggregates, which promote the formation of larger interconnected macrospores in the ML mix when compared to the MH mix [4, 40–44].In the case of the MP mix, the notable increase in porosity is likely because of the angular shape and rough surface texture of PA, which impedes compaction and results in a higher volume of voids within the concrete matrix [30, 38, 42]. Additionally, PA has a higher porous structure than normal coarse aggregate. The impact of SBR on the porosity of pervious concretes is illustrated in Fig. 6. It is well perceived from the figure that the incorporation of SBR led to a decrease in the porosity of pervious concretes, regardless of the type of LWCA used. This finding is in agreement with the results stated by [45]. The reduction in pervious concrete porosity was 16% and 13.3% for MH and ML mixes, respectively, compared to the reference mix, while for the MPP mix, the porosity decreased from 19.3% to 17.5%, indicating a 16.6% improvement compared to the reference mix. This reduction in porosity by using SBR can be attributed to its ability to enhance workability. As a result, the fluidity of the cement paste increases, allowing it to flow into the voids and effectively seal them [38, 42, 46]. Nevertheless, according to ACI 522R-10 [4], and Tennis et al. [2], the porosity of pervious concrete typically ranges from 15% to 35%. Consequently, all tested PC mixes, except for MHP10 and MLP10, met the specified porosity limits for previous concrete pavements.

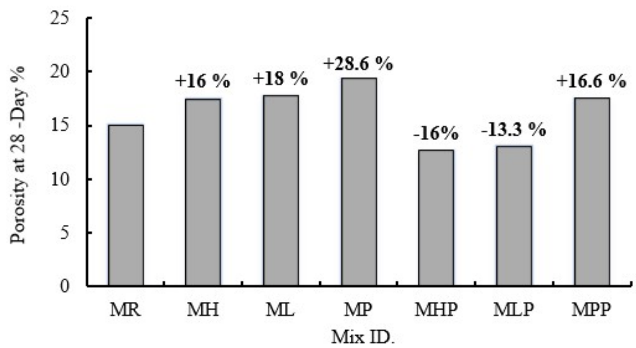

Figure 6. Previous concretes porosity results with LWCAs and SBR.

3.3 Permeability

The primary aim of pervious concrete is to establish a continuous network with adequate porosity, allowing water to flow freely through it. The size of the pores in concrete and the structure of its porous network determine its permeability [47]. The water permeability coefficients of different pervious concretes containing LWCAs as a partial substitution for the natural coarse aggregate and SBR at 5% by cement mass are shown in Fig. 7. The results indicate that the porous concretes, including LWCAs, showed greater permeability coefficients compared to the reference mix. The porous concretes, including LD and HD, exhibited permeability enhancements of 35.9% and 7.8%, respectively, compared to the reference mix. This may be since the LECA exhibited a rounded shape, which is consistent with findings in higher pore connectivity [26]. Moreover, it was noted that there is a notable difference in the increase in permeability between the ML and MH mix. This condition could be because of the larger particle size of LD compared to HD, resulting in larger interconnected pores within the ML mix. Similar, comparable results were emphasized by [42–44]. On the other hand, in the case of MP mix, the permeability coefficient increased by 31.2% compared to the reference mix.

This may be attributed to the angular shape of PA, which results in decreased workability, leading to larger interconnected pore sizes [30, 42]. Concerning the impact of SBR on the permeability coefficient, as seen in Fig. 7, the influence of SBR on the permeability coefficient is similar to its impact on porosity, indicating that the incorporation of SBR reduces the permeability coefficient. The decrease in permeability coefficient was 46.8% and 35.9% for MLP and MHP mixes, respectively, relative to the reference mix, however, for the MPP mix, the permeability coefficient reduced from 0.84 cm/s to 0.66 cm/s, representing an increase of 3.1% compared to the reference mix. These actions may be attributed to the ability of SBR to improve workability. This increases the contact area between neighboring aggregate particles, leading to a decrease in the connected pores. Consequently, the porosity and permeability of pervious concrete reduces. These results align with the previously study's findings by [33, 38, 42, 44]. The permeability coefficient values obtained in this study ranged from 0.41 cm/s to 0.84 cm/s, which meets the criteria for pervious concrete, which generally ranging from 0.14 cm/s to 1.22 cm/s [4].

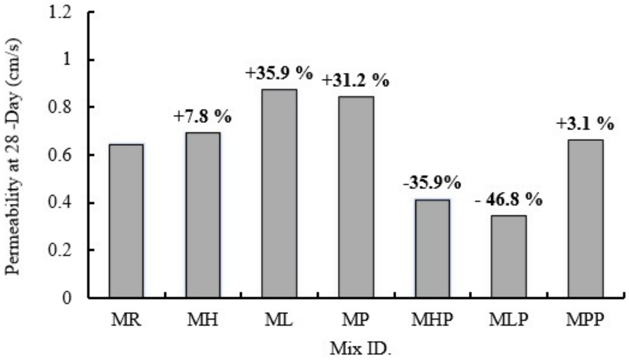

Figure 7. Pervious concretes permeability results with LWCAs and SBR.

4. Conclusions

This study aimed to examine the physical properties of modified pervious concrete, whereby natural gravel was partially replaced with pumice aggregate and two types of LECAs. The influence of using LWCAs and SBR on the porosity, permeability, and hardened density was evaluated. Based on the findings obtained, the following conclusions can be reached.

- The incorporation of LWCAs as a partial replacement for the normal coarse aggregate at a volumetric ratio of 10% led to a reduction in the hardened density of porous concrete regardless of the kind of LWCAs used or curing age. The MP mix containing PA showed the most significant density decrease (4.8%) compared to the reference mix among all the tested mixes, attributed to its angular particle shape and decreased specific gravity.
- Test on Permeability and porosity demonstrated that partial substitution of natural coarse aggregates with LWCAs enhanced both characteristics, irrespective of the kind of LWCAs used. Specifically, the ML mix exhibited the most significant enhancement in permeability (35.9%), while the MP mix showed the greatest improvement in porosity (28.6%) relative to the reference mix.
- Adding SBR latex increased the cement matrix's workability and aggregate dispersion. The polymerization procedure enhances the hardened density of porous concrete while decreasing porosity and permeability.
- Despite the incorporation of SBR resulting in a reduction in both permeability and porosity, all modified mixes remained within the permissible parameters for porous concrete, confirming their efficacy for sustainable pavement applications and stormwater management.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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