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PERMEABILITY COEFFICIENT OF PERVIOUS CEMENT MORTAR MEASURED BY THE CONSTANT HEAD AND FALLING HEAD METHODS

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The modified pervious concrete and cement mortar, known as pervious cement mortar (PCM), is designed with a specific composition to create pores. The coarse aggregate is removed to form smaller pore sizes. PCM acts as a water filter, needing higher permeability than cement mortar but less than pervious concrete. Its pores drain water while trapping impurities. This study compares the effects of sand-to-cement ratio (S/C), specimen thickness, and age on permeability and porosity. It also contrasts PCM's permeability coefficient determined by constant head and falling head methods. Numerous studies compare permeability coefficients in pervious concrete using these methods, but not for finer aggregate cement-based composite materials like pervious cement mortar. PCM uses fine aggregate (0.6 – 0.85 mm) at 3, 5, and 10 cm thickness with S/C ratios of 4 and 5. Findings show that S/C 5 specimens have significantly higher porosity than S/C 4. The S/C ratios notably impact permeability; the higher ratio means the higher permeability. Permeability coefficients for S/C 4 ranging from 0.006 – 0.075 cm/s, while S/C 5 ranging from 0.010 to 0.147 cm/s. The relationship between the permeability coefficient between the constant head and falling head methods at the age of 90 days specimen are Kc = 1.0516 Kf (S/C 4.2) and Kc = 0.9325 Kf (S/C 5.2). According to these findings, finer aggregates result in a significantly smaller permeability, to the extent that the constant head method is more reliable compared to the falling head method.

Keywords: Constant head, falling head, permeability, pervious cement mortar, porosity

1 INTRODUCTION

Pervious concrete (PC) is an eco-friendly material with minimal to no fine aggregate. Often used as pavement, this material helps the environment in many ways, including preventing flooding and surface runoff, purifying water, enhancing groundwater input, reducing urban heat islands, regulating road surface temperature and humidity, and more [1], [2]. PC is mechanically strong and has good hydraulic capabilities [3]–[5]. According to ACI 522R [6], pervious concrete has a porosity range of 15%–30% and a permeability range of 0.14 cm/s–1.22 cm/s. PC has been widely utilized in parking lots, walkways, shoulders, sidewalks, driveways, and paths because of its exceptional hydraulic qualities as a "water sponge" [1], [7], [8].

A modification of cement mortar and pervious concrete creates a composite material, which is then called pervious cement mortar (PCM). Pervious cement mortar is a mortar that is designed with a certain mixture of sand, cement, and water so that pores are formed in it. Pervious cement mortar is expected to be used as a water filter, which must have a smaller permeability and pores size than pervious concrete so that the use of coarse aggregate is removed from this pervious mortar. The pores contained in this mortar can drain water while the impurities are trapped in it. In contrast with PC, the pervious mortar only contains a fine aggregate of almost uniform size, cement, and water. Pervious concrete has been employed in a variety of water filtration processes, including those that remove coliform bacteria, turbidity [9]–[12], heavy metals lead (Pb) [13], total nitrogen and total phosphate from water bodies [14]. The modification of cement mortar and pervious concrete, so-called pervious mortar, aims to reduce the pore size of pervious concrete so that it can be applied as a water filter in decentralized water treatment on a household to communal scale. Because pervious mortar has narrow pores, it could trap tiny, delicate particles in dirty water.

As a water filter, the hydraulic characteristics of this material have a very important role. The pervious concrete, as well as pervious cement mortar, produced by mixing various constituent materials, determines its porosity and permeability. The effective voids are present because pervious concrete is composed of certain aggregate, cement, and water ratio [9], [10], [15]–[17]. Porosity and permeability are crucial characteristics for the drainage capacity of pervious concrete, with porosity greatly influencing the performance of a concrete filter. Porosity is affected by various factors, including aggregate size, type, gradation, cement type, sand-to-cement (S/C) ratio, water-to-cement (W/C) ratio, admixture type, dose, and mixing and forming procedure [1], [15]. Permeability is directly related to porosity, with the permeability coefficient of pervious concrete increasing as porosity increases [1]. However, factors such as pore size, connectivity, dispersion, and tortuosity also influence permeability [1], [16], [17]. For a given porosity, the permeability coefficient increases with larger aggregate size, while finer aggregate and proper grading enhance the mechanical strength of pervious concrete but reduce water permeability. Increasing the aggregate-to-cement ratio for the same aggregate size improves water permeability [1], [3], [18],

[19]. These considerations regarding permeability and porosity in pervious concrete also apply to pervious cement mortar.

Two laboratory methods are commonly used to determine the permeability coefficient in pervious concrete: the constant head and falling head methods. The falling head method is employed to measure permeability for fine particle sizes (silt and clay), while the constant head method is designed for coarse grain sizes (gravel and sand) [20]. Each of these techniques requires specific steps, and the choice of method can influence the resulting permeability coefficient values significantly. Therefore, it is crucial to precisely specify the initial and final heights in both the constant head and falling head tests [1]. Several studies have compared these two methods for calculating the permeability coefficient in pervious concrete. Sandoval's research [21] reported a higher permeability coefficient using the constant head approach, while other researchers, such as Zhang [1] and Qin [22], found that the falling head method yielded higher permeability coefficient values than the constant head method.

Many studies have compared the permeability coefficients in pervious concrete using the falling head and constant head methods. However, comparing the permeability coefficient of composite materials with finer aggregate (pervious cement mortar) has yet to be widely carried out, especially for water filter purposes.

In this study, the permeability test of the pervious cement mortar will be compared using the constant head and falling head approaches in the following terms:

a) Porosity on different sand-to-cement ratios (S/C) and thickness
b) Permeability coefficient on different sand-to-cement ratios, thickness, and age of filter
c) Comparison between permeability coefficient measured by the constant head and falling head methods
d) Relationship between porosity and permeability coefficient

2 MATERIALS AND METHODS

2.1 Materials

Sand, cement, and water were the materials employed in this study. The sand is derived from the Progo River, Bantul Regency, Indonesia. The utilized sand has a particle size range of 0.6 to 0.85 mm, a fineness modulus of 2.7, and a uniformity coefficient 1.6. The sand in this mixture must be saturated surface dry (SSD) after being rinsed and soaked for 24 hours. Semen Gresik, a composite Portland cement, is used to produce PCM. The water used is drinking water with a total dissolved solids (TDS) content of 10 ppm. Table 1 provides information on cement and sand's physical and chemical properties.

Table 1. Physical and chemical properties of sand and cement

Sand (Progo Sand)		Cement (PCC)	
Element	Value	Element	Value
SiO_2 (mg/kg)	$391x10^3$	SiO_2 (mg/kg)	$185.2x10^3$
P_2O_5 (mg/kg)	$37.7x10^3$	P_2O_5 (mg/kg)	$66.5x10^3$
SO_3 (mg/kg)	$5.1x10^3$	SO_3 (mg/kg)	$20.5x10^3$
CaO (mg/kg)	$99.6x10^3$	CaO (mg/kg)	$675.3x10^3$
TiO_2 (mg/kg)	$43.5x10^3$	TiO_2 (mg/kg)	$6.33x10^3$
MnO (mg/kg)	$5.32x10^3$	MnO (mg/kg)	$1.21x10^3$
Fe_2O_3 (mg/kg)	$317x10^3$	Fe_2O_3 (mg/kg)	$42.3x10^3$
CuO (mg/kg)	$0.66x10^3$	CuO (mg/kg)	$0.51x10^3$
ZnO (mg/kg)	$0.66x10^3$	ZnO (mg/kg)	$0.36x10^3$
Rb_2O (mg/kg)	$0.19x10^3$	Rb_2O (mg/kg)	$0.07x10^3$
SrO (mg/kg)	$1.99x10^3$	SrO (mg/kg)	$0.52x10^3$
BaO (mg/kg)	$1.02x10^3$	BaO (mg/kg)	$0.38x10^3$
Al_2O_3 (mg/kg)	$76.50x10^3$	As_2O_3 (mg/kg)	$0.08x10^3$
K_2O (mg/kg)	$19.81x10^3$	NiO (mg/kg)	$0.68x10^3$
Density (kg/m3)	2,480	Density (kg/m3)	2,960

2.2 Mix design

The amount of sand, cement, and water required for PCM production is determined using the absolute volume method. The sand is utilized in a saturated surface dry (SSD) state, and the sand-to-cement ratio (S/C) is denoted as 'M.' The sand-to-cement ratio (M), water-to-cement ratio (W/C), and specimen thickness (H) are taken into account in the calculation of material quantities necessary for PCM production. In this study, two different values of M, namely 4.2 and 5.2, were utilized, each associated with specimen thicknesses of 3, 5, and 10 cm. Table 2 provides the mixture proportions for M 4.2 and M 5.2, with a fixed W/C ratio of 0.4. Table 2 represents the calculation of the mortar mixture proportion following the commonly used standard of mortar mix as also applied in another study [23] and following the basic equation as mentioned in the National Precast Concrete Association (NPCA) (precast.org).

2.3 Production of PCM

The PCM is molded in a PVC pipe with a diameter of 3 inches (or 8.2 cm), a thickness of 3, 5, and 10, and a fine sand (<0.6 mm of sand size) coating applied in the PVC wall with PVC glue as an adhesive. Sand is used in PVC walls to tighten the binding between PCM and PVC. There will be no extraction of the PCM from the mold. They will be packaged to be used as a filter as a whole.

The design of PCM in this recent study modifies earlier studies (Maadji, 2018b). The authors adjusted the standard to ensure the specimens' homogeneity for this study. Using a "Hobart" mortar mixer set to a speed level of 2, sand, cement, and water that have been weighed following the results of calculations in Table 2 are mixed. Half of the sand and half of the cement were added to the mixer, and the mixture was stirred for two minutes to ensure thorough mixing. Then, the mixture was stirred for two minutes after adding the remaining sand and cement materials. When the mixture had been confirmed to be homogenous, water was added using a sprayer equally distributed throughout while stirring for two minutes. The PCM mixture was ready for molding.

Table 2. The mixture proportion of PCM

S/C ratio	Materials	Density (kg/m^3)	Ratio Abs Volume	Absolute Volume of dry mortar* for 1 m^3 of wet mortar (m^3)	Weight of materials (kg)
S/C 4.2	Cement	2960	1	0.26	757
	Sand	2840	4.2	1.07	3051
	Water	1000	0.4	0.30	303
	Total		5.2**	1.63	4111
	Unit weight (kg/m^3)				2518
S/C 5.2	Cement	2960	1	0.21	635
	Sand	2840	5.2	1.12	3168
	Water	1000	0.4	0.25	254
	Total		6.2**	1.58	4057
	Unit weight (kg/m^3)				2561

*Dry mortar = wet mortar (1 m^3) x 1.33, **excluding water

On the PVC mold, each piece is individually molded. Every PVC mold base has a plate on a shaker covering it. The PCM mixture was weighed up to 200 grams and placed in the PVC mold, and a load plate (8 cm in diameter and 226 grams in weight) at the mixture's surface. This process ensured that the mixture was subjected to the same pressure simultaneously. The mold was shaken on the vibrating table at a maximum speed of 10 for one minute. The entire sequence was completed until the PCM mixture reached the top of the mold. To ensure no pressure during the flattening process, the mixture that exceeds the height of the mold was carefully leveled using a ruler. After that, a load plate was placed on top of the mold, which was then turned around and vibrated for a minute. The mold was set back in place and vibrated vigorously for 30 seconds to align the mixture. By carrying out this procedure, different numbers of loads and vibrations were carried out for each thickness of the specimens as a compaction process. For 3, 5, and 10 cm of specimen thickness, there were 2, 3, and 5 loads and vibrations, respectively. After that, following 24 hours of air drying, the fresh specimen followed a 90-day curing process in a humid blanket.

Eight specimens were used in this experiment for each M and thickness. The number of specimens was determined based on earlier research by Sandoval et al. [21]. According to that study, 7 and 8 specimens for the falling head and constant head tests were sufficient to ensure that the results were within a 10% error of the mean. According to Sandoval (2017), eight specimens were evaluated in this study for the falling head and constant head tests for each sand-to-cement ratio and thickness. For sample coding, the S/C ratios of 4.2 and 5.2 are written as 4 and 5, respectively. The samples are divided into six variations, namely (sand type, S/C ratio, thickness in cm): b43, b45, b410, b53, b55, and b510. A, B, C, D, E, F, G, and H are the eight specimens comprising each variety. In the following graphs, the S/C ratio will be written as M.

2.4 Description of porosity test

In this study, the effective porosity (%) of pervious cement mortar was calculated using the America Society for Testing and Materials (ASTM) C1754-12 method (density and void content of hardened pervious concrete) with Equation 1. This method is also applied in other studies [24], [25].

$$P = \left[1 - \left(\frac{Wd - Ws}{\rho w.V}\right)\right] x100 \qquad (1)$$

Where P is the effective porosity of the specimen (%), Wd is the weight of the specimen air-dried for 24 hours (kg), Ws is the weight of the specimen submerged in water (kg), V is the volume of the specimen (mm3), and ρw is the density of the water (kg/mm3). The age of specimens tested in this study was 90 days.

2.5 Description of permeability test

The permeability of PCM is calculated using the constant head and falling head methods. The scheme of permeability coefficient calculation and apparatus used in this permeability test can be seen in Fig. 1.

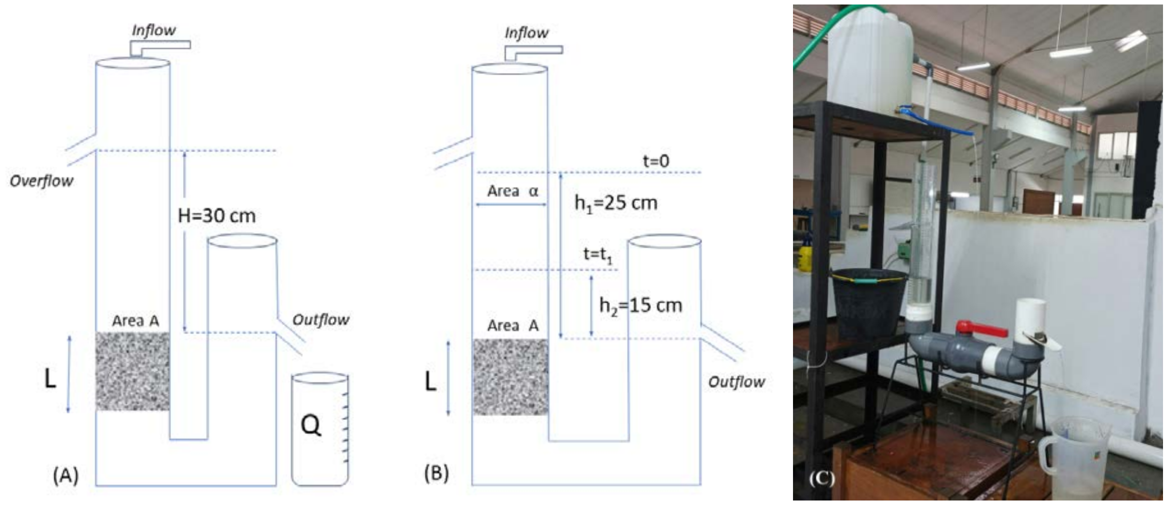

Fig. 1. The scheme of permeability coefficient calculation (A) constant head method, (B) falling head method, and (C) Permeability test apparatus for both constant head and falling head method

2.5.1 Constant head (CH) permeability test

Permeability is calculated using two methods, i.e., constant head and falling head. The constant head method has been widely used to determine the permeability value of the PCM. ASTM has established a standard for permeability testing of granular soils, which can also be applied to pervious concrete. The permeability coefficient with the constant head method is calculated based on ASTM D2434 with Equation 2.

$$K_C = \frac{Q.L}{\Delta h.A.t} \quad (2)$$

where K_C is the constant head permeability coefficient (cm/s), Q is the volume of collected water volume (cm^3), L is the length of the specimen (cm), A is the area of PCM specimen (cm^2), Δh is the hydraulic head between constant head inflow and outflow (cm), and t is the time of the test (s). The constant head level is 30 cm from the outflow, and the testing time is 20 seconds.

2.5.2 Falling head (FH) permeability test

In addition to the constant head method, the falling head method is widely used in permeability tests. This method has advantages such as simple equipment, ease of operation, and low apparatus manufacturing costs (Y. Zhang et al., 2020). This method is also commonly applied to test concrete samples in the form of cylindrical tubes. The permeability coefficient is calculated using ASTM D5084 with Equation 3.

$$K_F = \frac{\alpha.L}{A.t} \ln\frac{h_1}{h_2} \quad (3)$$

Where K_F is the falling head permeability coefficient (cm/s), α is the area of the reservoir (cm^2), L is the length of specimen (cm), A is the area of PCM specimen (cm^2), h_1 is the initial water level (cm), h_2 is final water level (cm), and t is the time taken from initial to final water level (s). The calculation of time (t) starts when the water is precisely at the initial water level (h_1) and ends when the water is at the final water level (h_2). The initial height of the water in this study was 25 cm, and the final height was 15 cm.

3 RESULTS AND DISCUSSIONS

3.1 Porosity on different sand-to-cement ratios and thickness

Table 3 presents the laboratory test results for different sand-to-cement ratios (S/C) and thicknesses, indicating porosity values (%), average porosity, and standard deviation of the PCM. The influence of thickness and S/C ratio on porosity is visually represented in Fig. 2. The majority of PCM samples tested in the lab exhibited porosity values ranging from 15% to 28.2%, which aligns with the recommended porosity range for pervious concrete (15% to 35%) [5], [18] and National Ready Mixed Concrete Association (NRMCA) guidelines. Only a few samples displayed porosity values below 15%. Average porosity values for each specimen demonstrate how the S/C ratio impacts cement utilization within the specimen's pores, consequently affecting pore numbers. Despite a uniform production procedure, a notable standard deviation is observed, likely attributable to variations in pore distribution within the specimens.

Table 3. Laboratory-tested porosity of PCM

Sand to cement (S/C) ratio	S/C 4.2 or M 4.2			S/C 5.2 or M 5.2		
Size of sand aggregate	0.6 – 0.85 mm					
Shape	Cylinder Ø8.2 cm					
Thickness	3 cm	5 cm	10 cm	3 cm	5 cm	10 cm
Porosity (%)	16.7	12.1	7.8	17.3	28.2	15.5
	19.7	13.9	9.8	20.6	17.8	17.2
	23.3	15.0	10.2	22.0	20.8	16.2
	20.8	16.3	10.8	21.1	24.0	20.8
	25.1	16.1	14.1	23.2	25.4	18.4
	21.3	14.8	15.5	23.6	21.4	11.4
	21.9	23.6	15.3	22.9	21.8	15.1
	23.5	22.7	17.5	23.1	25.4	14.1
Average porosity (%)	21.5	16.8	12.6	21.7	23.1	16.1
Standard deviation (Sd) (%)	2.6	4.1	3.4	2.1	3.3	2.8

Fig. 2 illustrates the relationship between the S/C ratio and PCM porosity (%), where M 4.2 represents an S/C ratio of 4.2, and M 5.2 corresponds to an S/C ratio of 5.2. It is observed that as the M number increases, the porosity value also increases. This aligns with the prevailing theory that higher cement content in the specimen reduces pore volume, leading to lower porosity [24]. Conversely, reducing the cement content increases pore volume and higher porosity.

These findings are consistent with prior research, such as [1], [26], which employed different cement-to-aggregate (C/A) ratios while maintaining the same aggregate gradation. This earlier research demonstrated that specimens with higher C/A ratios had lower porosity values. Porosity is further influenced by aggregate size, uniformity coefficient, and A/C ratio. Larger aggregates tend to yield higher porosity, whereas smaller aggregates or uniform gradation increase porosity even further. In cases of poor or inconsistent aggregate gradation, fine and coarse grains intermix, reducing void size, void count, and overall porosity. In this study, the aggregate used exhibited a uniformity coefficient of 1.6, indicating near uniform, accounting for the samples' predominantly high porosity.

Furthermore, it is worth noting that thicker filters at the same A/C or S/C ratio result in lower porosity within the specimen. A higher number of compaction may have reduced the porosity of the thicker specimens, as also found by [27]–[29] in pervious concrete. This implies that the compaction process in a 10 cm thick specimen resulted in a lower porosity compared to the others.

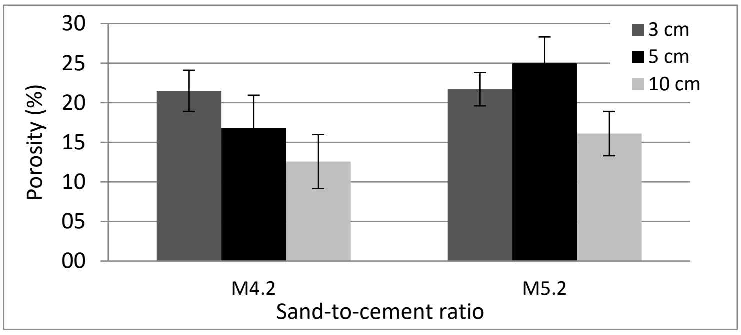

Fig. 2. Effect of sand-to-cement ratio and thickness on its porosity

3.2 *Permeability coefficient on different sand-to-cement ratios, thickness, and age of filter*

Fig. 3 and Fig. 4 present the permeability coefficients of PCM using the constant head (Kc) and falling head (Kf) methods. Fig. 3 specifically presents permeability coefficients for S/C ratios of 4.2 and 5.2 and specimen thicknesses of 3, 4, and 5 centimeters at 28, 60, and 90 days of age. The research findings indicate that higher S/C ratios result in elevated permeability coefficients, particularly at the 90-day specimen age. This relationship is primarily influenced by this study's fine and uniform aggregate size. As depicted in Fig. 3, specimens with an S/C ratio of 4.2 (M 4.2) exhibit lower permeability coefficients than those with an S/C ratio of 5.2 (M 5.2). This trend arises because lower S/C ratios increase the proportion of cement in the mixture, filling pores with cement and restricting water flow, thus lowering permeability. These findings are consistent with prior studies that also identified the S/C ratio as a determinant of the permeability coefficient [15], [30], [31]. The other study found that the increase of permeability was consistent with the increase in the A/C ratio [2].

Furthermore, specimen thickness impacts the permeability coefficient in this research. Thicker specimens (28, 60, or 90 days) exhibit reduced permeability coefficients due to increased water flow barriers. Thicker specimens require water to pass through more pathways, slowing down permeability. Thinner specimens, as shown in Fig. 3, demonstrate higher permeability coefficients due to lower PCM resistance. In comparison, 10 cm thick specimens show slower permeability than their 3 or 5 cm thick specimens.

Fig. 4 illustrates the differences in permeability coefficients for specimens aged 28, 60, and 90 days, determined using the constant head and falling head methods. Both methods yield similar results, albeit with differing values. Notably, at a thickness of 3 cm, the permeability coefficient of specimens with an S/C ratio of 5.2 is lower than that of specimens with an S/C ratio of 4.2, contrary to theoretical expectations. This discrepancy may be attributed to the casting process, which leads to denser materials in M 5.2 specimens despite adhering to established casting standards. The potential for errors persists due to the manual manufacturing process.

At 5 and 10 cm thicknesses, the permeability coefficient for specimens with an S/C ratio of 4.2 is lower than that of specimens with an S/C ratio of 5.2. This aligns with the prevailing theory that higher cement content in a specimen results in more pore coverage by cement, reducing pore count and pore size and, consequently, reducing the permeability coefficient. This finding corroborates Zhang's (2020) research, which observed a similar trend: increased cement content led to lower permeability coefficients in specimens with an A/C ratio of 4.1 and aggregate size of 2.36 - 4.75 mm. Zhang (2020) [1] reported permeability coefficients of approximately 0.12 cm/s and 0.28 cm/s in cylindrical specimens with a diameter of 10 mm and a thickness of 5 cm, values significantly higher than those in this study. The disparity is attributed to differences in aggregate size, with this study employing smaller aggregates (0.6 - 0.85 mm) compared to Zhang's (2020) larger aggregates.

In this study, permeability coefficients for specimens with an S/C ratio of 4.2 ranged from 0.041 to 0.066 cm/s (3 cm), 0.032 to 0.075 cm/s (5 cm), and 0.006 to 0.022 cm/s (10 cm). In Zhang's (2020) study, which used an A/C ratio of 4.1 and a 5 cm thickness, the permeability coefficients were approximately 0.12 cm/s and 0.28 cm/s. These variations can be attributed to the differences in aggregate size, with smaller aggregates wrapped in the same cement layer thickness resulting in lower porosity and permeability than larger aggregates.

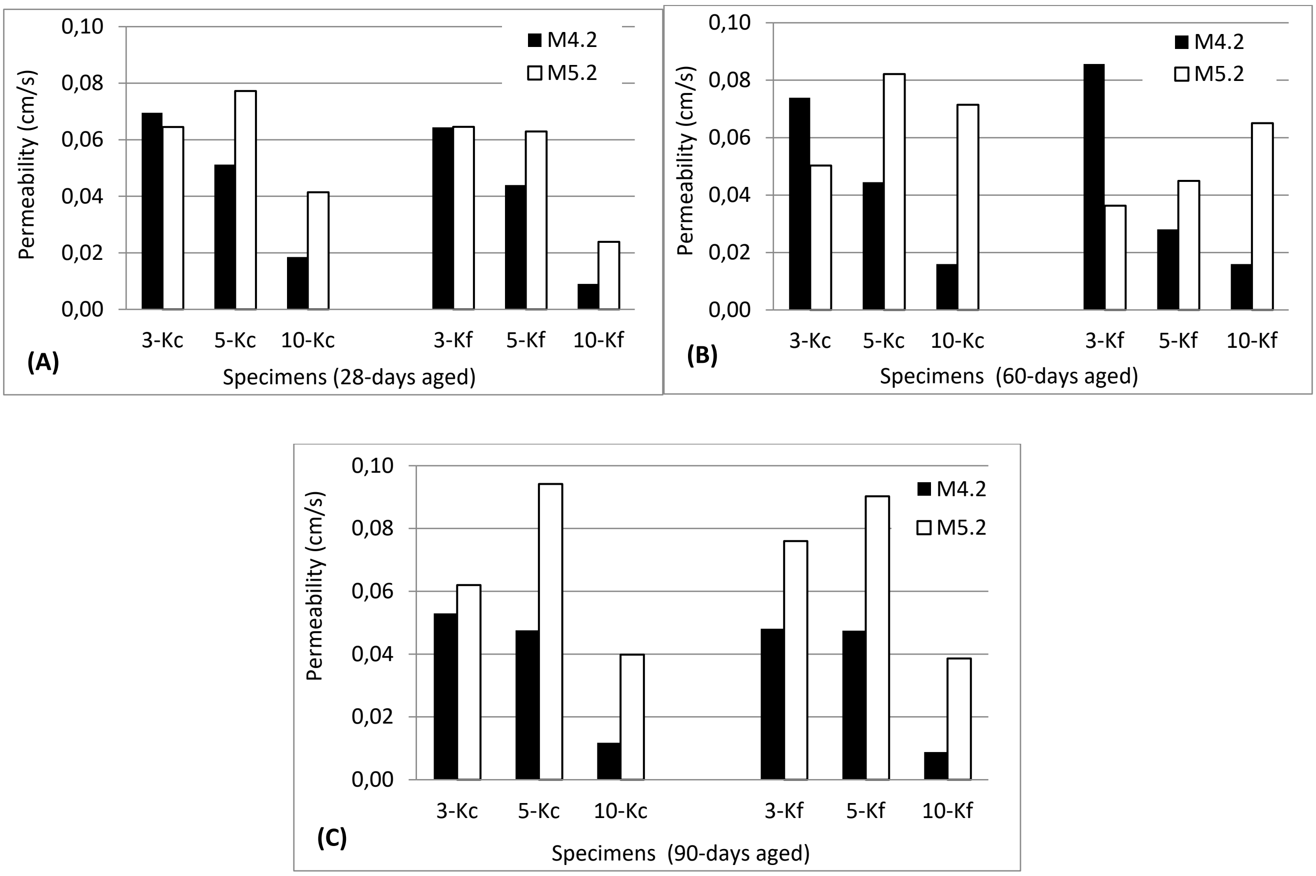

Fig. 3. Permeability coefficient at different S/C ratios and thicknesses at the age of (A) 28 days, (B) 60 days, and (C) 90 days

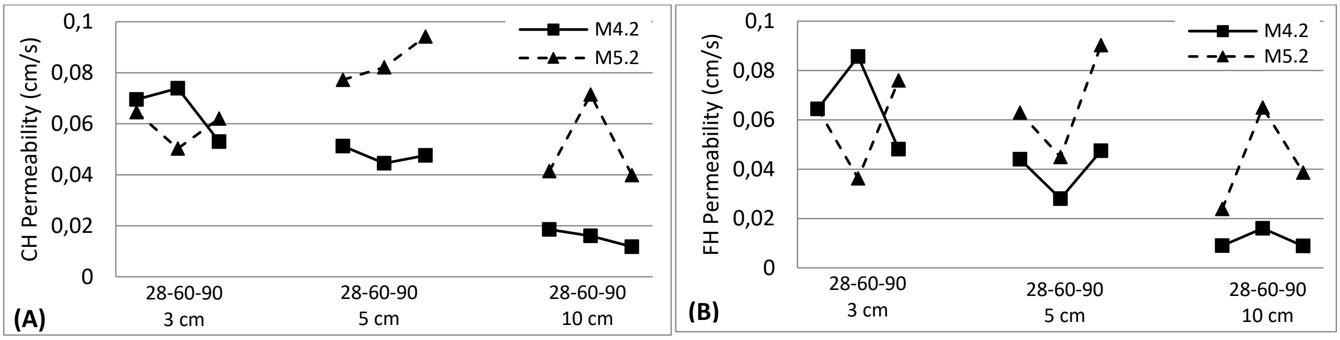

Fig. 4. Permeability coefficient at different ages of specimens and thickness by (A) constant head and (B) falling head method

3.3 Relationship between permeability coefficient measured by the constant head and falling head methods.

Fig. 5 and Fig. 6 represent the correlation between permeability measurements obtained by the falling head and constant head methods for specimens with S/C ratios of 4.2 and 5.2. Fig. 5 illustrates a strong linear correlation between the two methods at an S/C ratio of 4.2, with high correlation coefficients (R^2) of 0.9148, 0.7518, and 0.9693 for specimen ages of 28 days, 60 days, and 90 days, respectively. Similarly, Fig. 6 demonstrates a robust linear correlation between the methods for specimens aged 28 days, 60 days, and 90 days, yielding high correlation coefficients (R^2) of 0.7813, 0.7276, and 0.9189, respectively. Notably, specimens with S/C 5.2 exhibited lower correlation coefficients than S/C 4.2, and the highest correlations were observed in specimens older than 90 days. This pattern likely results from stable hydration, influencing consistent pore size and a proportional response between the permeability coefficients measured by the falling head and constant head methods.

The results of the study regarding the permeability coefficient reveal a consistent pattern in which the permeability coefficient obtained by the constant head method exceeds that of the falling head method. These findings align with Sandoval et al. (2017) research. Comparisons of permeability coefficients in pervious concrete from various studies [1], [21], [22], [32] have shown divergent results. Sandoval et al. (2017) reported higher permeability values with the constant head method [21], whereas Zhang (2020) found higher values with the falling head method [1]. This discrepancy underscores the lack of standardized and universally accepted methods in the field. Measuring using different methods yields a different permeability coefficient value on the same sample. As a result, methods currently need to be available that are standardized and widely accepted by researchers [33], [34]. The primary distinction between the two methods lies in the water level within the column, which can either remain constant or fall. The falling head method calculates permeability based on the duration of water travel time between h1 and h2 (water height difference), while the constant head method computes it using the volume of water accumulated at a specific time.

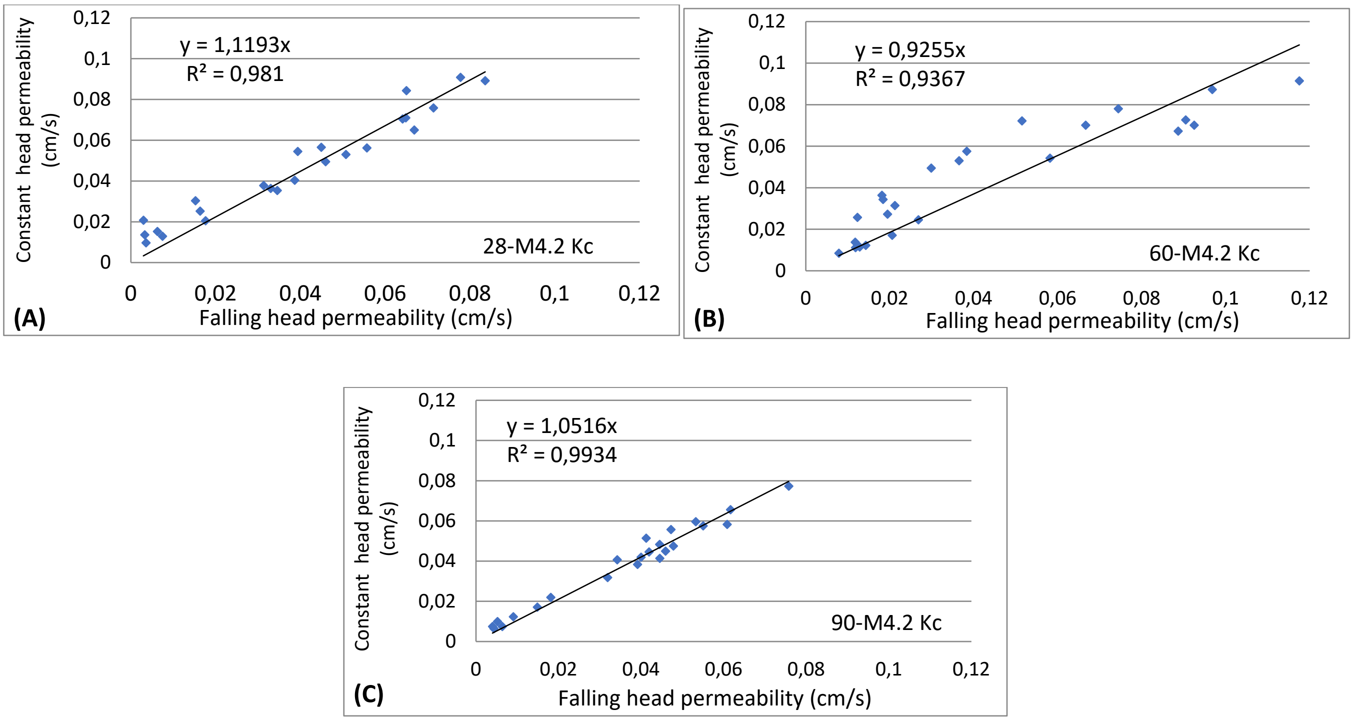

Fig. 5. Correlation of PCM permeability measured by the constant head and falling head method (S/C 4.2) in different ages (A) 28 days, (B) 60 days, and (C) 90 days

Zhang et al., Qin et al., and Sandoval et al. conducted comparative studies on permeability tests using both the falling head and constant head methods [1], [21], [22]. These comparisons consistently revealed differences in permeability coefficients obtained from the two methods, with the falling head method consistently producing higher values [1], [22]. These differences can be attributed to several factors, including the influence of gravity on the rapid decrease in water level in the falling head method and the pressure difference between the inside and outside of the test column in the constant head method [1].

In the falling head method, the column sizes from inflow to outflow are uniform, allowing for free and unobstructed water flow. Permeability coefficient measurements in this method involve observing the time it takes for the water level to drop from h1 to h2, without considering the volume of water. Conversely, the constant head method factors in the volume of water accumulated over a specified period. Zhang [1] noted that the pipe size at the outflow in the constant head method is smaller than the inflow pipe size. This can impede water flow, especially in cases of high porosity and permeability, significantly impacting the volume of accumulated water and, subsequently the permeability coefficient [1]. It is important to note that the constituent materials of pervious concrete can also influence permeability coefficient analysis using these methods.

The study used fine aggregate with a fairly uniform size to produce PCM, resulting in significantly lower permeability potential compared to typical pervious concrete. Consequently, constant head measurements yielded more stable results and a faster calculation than the falling head method. Due to the time it takes for water to drop from 25 cm to 15 cm and potential pressure loss, the falling head method can be slower. In contrast, the constant head method offers faster and more precise results with a fixed water level, using a set time (20 seconds) to collect water under constant head pressure. Hence, the constant head method is recommended for permeability tests on pervious composites with fine aggregates like PCM. This finding was supported by the study conducted by [2] that the falling head method showed higher uncertainty than the constant head method.

However, it is worth noting that the constant head method may entail higher equipment, labor, stages, and overall costs than the falling head method [1], [21]. To facilitate future research, Equation 4 and 5 establish a relationship between the permeability coefficient obtained through the constant head and falling head methods for the same type and size of sand or aggregate and the S/C ratio used in this study, particularly for specimens at 90 days.

$$(A/C\ 4) \qquad Kc = 1.0516Kf \qquad (R^2 = 0.9693) \tag{4}$$

$$(A/C\ 5) \qquad Kc = 0.9325Kf \qquad (R^2 = 0.9237) \tag{5}$$

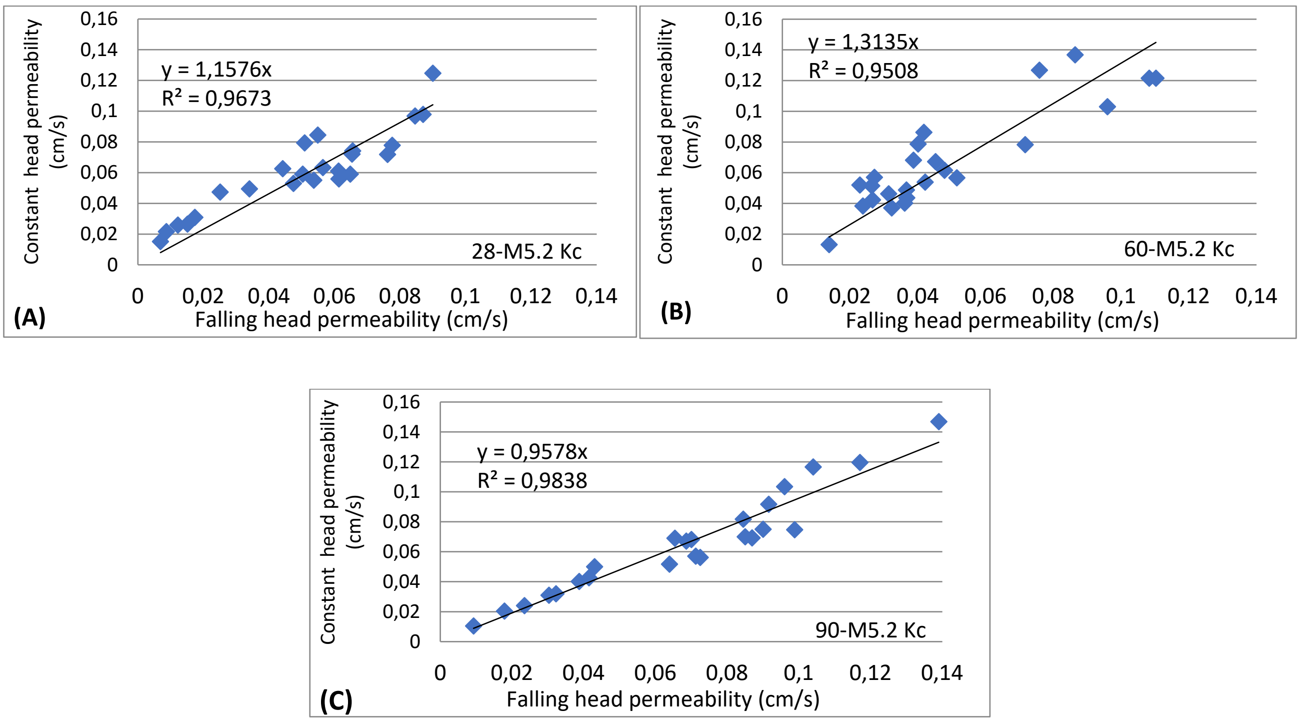

Fig. 6. Correlation of PCM permeability measured by the constant head and falling head method (S/C 5.2) in different ages (A) 28 days, (B) 60 days, and (C) 90 days

The permeability coefficients obtained through both methods exhibit a strong correlation. Researchers faced with constraints regarding tools and funds for calculating the constant head permeability coefficient can convert the falling head method results into the constant head permeability coefficient. It is worth noting that the falling head method is often considered more efficient than the constant head method in terms of procedure, equipment, labor, and overall costs [1]. As indicated by this study and others [18], [21], [22], the reported permeability coefficient value for pervious concrete should always specify the water level and the applied test method.

3.4 Relationship between porosity and permeability coefficient

Fig. 7 illustrates the relationship between porosity and constant head and falling head permeability coefficients for S/C ratios of 4.2 and 5.2. Fig. 7A shows that the constant head permeability coefficient for M 4.2 is slightly higher than the falling head method, particularly for specimens with 3 cm and 10 cm thicknesses. However, in specimens with a 5 cm thickness, both methods yield nearly similar permeability coefficients. On the other hand, for M 5.2 specimens in Fig. 7B, the constant head method produces higher permeability coefficients at 5 cm thickness, while the falling head method is superior for 3 cm thickness. Both methods show nearly identical permeability coefficient values for specimens with a thickness of 10 cm and M 5.2.

The permeability coefficient values obtained from both the constant head and falling head methods align with changes in porosity for M 4.2 specimens, as indicated in Fig. 7A. This indicates that as porosity decreases, permeability decreases, and vice versa. The correlation between porosity and permeability for constant head and falling head measurements in M 4.2 specimens is fairly strong, with correlation coefficients (R^2) of 0.6277 (Kf) and 0.6998 (Kc) as can be seen in Fig. 8A. These findings are consistent with previous research where permeability values correspond to porosity values [15], [16], [18], [24], [25], [35], [36].

Conversely, in M 5.2 specimens, the permeability coefficient values obtained from both methods do not consistently align with changes in porosity, as evident in Fig. 7B. This inconsistency is highlighted by a significant increase in the permeability coefficient despite relatively constant-moderate porosity in b53F, b53G, and b53H specimen.

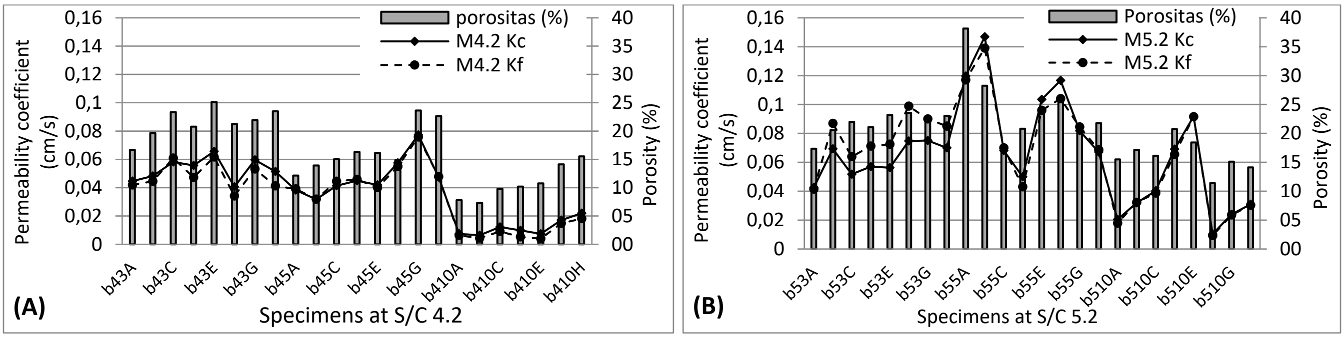

Fig. 7. Relationship of permeability and porosity of PCM specimens at (A) S/C 4.2 and (B) S/C 5.2

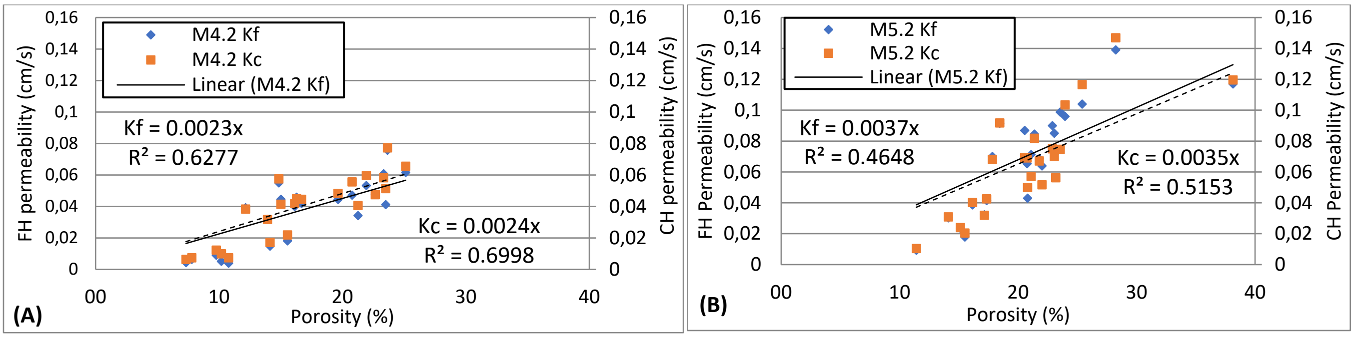

Fig. 8. The correlation between the porosity and permeability coefficient of PCM is measured by the constant head and falling head method at (A) S/C 4.2 and (B) S/C 5.2

Conversely, the b55A specimen exhibits a decrease in permeability coefficient even with a significant increase in porosity, potentially due to the presence of large cavities within the specimen. Such discrepancies in porosity may result from variations in the manual manufacturing process despite adherence to casting procedure standards. This analysis is crucial for quality control in PCM, helping identify suitable specimens for use as filters. The lack of a strong correlation coefficient (R^2) further emphasizes the inconsistency between permeability coefficient and porosity in most S/C 5.2 specimens, with values of 0.4648 (Kf) and 0.5153 (Kc) shown in Fig. 8B.

4 CONCLUSION

a) The constant head method is more reliable for the PCM permeability measurement.

b) A higher number of compactions may have reduced the porosity of the thicker specimens in PCM, as also found by Mulu, A. et al. (2022), Feric, K. et al. (2023), and Wijekoon, S.H. et al. (2023) in pervious concrete. This implies that the compaction process in a 10 cm thick specimen resulted in a lower porosity compared to the others.

c) Low porosity resulted in low permeability of PCM. The fairly strong correlation coefficient (R2) between porosity and permeability of both constant head and falling head, achieved by the S/C 4.2 specimens, i.e. 0.6277 (Kf) and 0.6998 (Kc)

d) Permeability coefficients of PCM for S/C 4 ranging from 0.006 – 0.075 cm/s, while S/C 5 ranging from 0.010 to 0.147 cm/s.

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