Research Article

Hydraulic Performance of Pervious Concrete Based on Small Size Aggregates

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The paper aims to study the impact of clogging on pervious concrete mixes and explore a simple method to calculate permeability and clogging using the falling head method in a fabricated unit. The materials used are cementitious materials and aggregates, along with superplasticizers. The cementitious materials used are OPC Grade 53 cement and micro Ground Granulated Blast Furnace Slag (µGGBS). Two separate narrow aggregate gradations are used: 2.36–4.75 mm and 4.75–6.30 mm. The water-binder ratio is taken as 0.25, and the aggregate-binder ratio is taken as 3.33. The compressive strength, permeability, and clogging potential of pervious concrete are calculated. The average permeability for 2.36–4.75 mm and 4.75–6.3 mm is 4.78 mm/s and 8.16 m/s, respectively. The clogging materials used are clay and sand with a concentration of 5 g/l. The introduction of clay slurry reduces the permeability by 69.8% and 74.9%, respectively, and with sand, it decreases by 74.7% and 71.7%, respectively, in its first cycle. The permeability response for such small aggregates is different from the standard coarse aggregates. The paper compares the study’s compressive strength, porosity, and permeability with the existing literature. It concludes that the maximum clogging occurs when the clogging material is introduced to the specimen for the first time. The degradation of permeability depends on the clogging particle’s particulate size and the concrete matrix’s pore size. The smaller aggregates in pervious concrete are not recommended in areas of high siltation.

1. Introduction

Pervious concrete is a particular type of concrete in which narrow-sized aggregate gradations are used to increase the porosity. The coarse aggregates are narrowly graded to increase the porosity of the concrete [1]. It is one of the Best Management Practices (BMPs) recommended by the US Environmental Protection Agency (EPA). It is a mixture of cement, narrow-sized aggregates, water, and little or no sand, which creates an open cell structure that allows water and air to pass through it. It allows stormwater to infiltrate through the pavement and eliminates the need for additional control structures, such as retention ponds [2]. The increase in porosity and permeability causes a reduction in the strength of the concrete mix and vice versa [3]. Experimental studies are conducted to evaluate the strength and permeability of pervious concrete made using recycled wastes and aggregates [4]. In some cases, it is retrofitted into an existing system for better runoff management [5]. Incorporating pervious concrete pavement is comparable to the predevelopment stage of the concerned site for urban runoff calculation [6].

Table 1 summarizes the aggregates’ size, mix proportion, compressive strength, porosity, and permeability. The size of the aggregate used varies from 1.24 to 16 mm. The size of the aggregates is significant for creating the porous nature of pervious concrete [20]. The large size of aggregates in pervious concrete mixes causes raveling [21]. It is a process of removing the top surface of aggregates due to the weak bonding. Crounch et al. [22] stated that smaller aggregates produce a higher compressive strength than larger aggregates with similar porosities. A balance must be maintained...
| References          | CA size (mm) | A/B by weight | W/B by weight | Compressive strength specimen size (cm) | Compressive strength (MPa) | Porosity specimen (cm) | Porosity %/voids% | Permeability test method | Permeability specimen size (cm) | Permeability (mm/s) |
|---------------------|--------------|---------------|---------------|----------------------------------------|---------------------------|------------------------|---------------------|--------------------------|-------------------------------|------------------------|
| Marcaida et al. [7] | 3–5, 5–8, 8–10 | 5% binder content | Polyurethane binder | - | - | 15 - H, 10 - D | 30.7–34.3 | Constant head | 15 - H, 10 - D | 5.06–7.74 |
| Huang et al. [8]    | 5–10, 10–15 | 2.41–3.65 | 0.2, 0.25, 0.3 | As per CJJ/T135-2009 | 7.6–56.9 | As per CJJ/T135-2009 | 12.0–21.0 | Constant head | As per CJJ/T135-2009 | 0.42–2.98 |
| Tan et al. [9]      | 4.75–9.5 | 2.107–4.988 | 0.23 | 10 × 10 × 10 | 11.0–42.0 | 10 - H, 10 - D | 5.2–27.2 | Constant head | 10 - H, 10 - D | 0.67–8.2 |
| Hatanaka et al. [10] | 5.0–13.0 | 6.14 | 0.35 | - | - | 60 × 20 × 20 | 15–35 | Constant head, $h = 5, 10, 15, 20$ cm | 60 × 20 × 20 | Hydraulic gradient is calculated |
| Sandoval et al. [11] | 9.5 (max size) | 3.26 | 0.34 | 20 - H, 10 - D | 3.8–10.1 | 20 - H, 10 - D | 19.3–27.1 | Constant head, $h = 52$ cm | 20 - H, 10 - D | 5.0–15.1 |
| Lang et al. [12]    | 2.5–5, 5–10, 10–15 | 4.8 | 0.16 | 10 × 10 × 10 | 34.0–41.0 | 10 × 10 × 10 | 24.0–27.0 | Constant head, head diff - 15 cm | 20 - H, 10 - D | 6.0–7.0 |
| Azad et al. [13]    | 4.75–9.5 | 4–4.85 | 0.36 | 15 × 15 × 15 | 9.2–14.8 | 10 × 10 × 10 | 30.0–36.0 | Falling head | 10 × 10 × 10 | 6.17–5.36 |
| Lori et al. [14]    | 4.75, 12.5 | 3.35 | 0.3 | 10 × 10 × 10 | 17.9–23.5 | 10 - H, 10 - D | 20.4–21.6 | Falling head | 10 - H, 10 - D | 3.05–3.33 |
| Einspina et al. [15] | 10.0–14 | 3.5 | 0.35 | 30.48 - H, 15.24 - D | 10.1–29.1 | - | - | Falling head | 15.24 - H, 10.16 - D | 0.0192–0.0264, 5–9 agg. size - 0.02450 |
| Barisic et al. [16] | 4–8, 8–16 | 3.55 | 0.33 | 15 × 15 × 15 | 8.2–21.1 | 10 - H, 5 - D | 18.7–32.4 | Falling head | 10 - H, 5 - D | 14.88–48.10 |
| Kia et al. [17]     | 1.24–14 | Trial and error based on target porosity | 0.35 | 10 × 10 × 10, 15 - H, 10 - D | 6.0–59.0 | 10 × 10 × 10, 10 - D, 15 - H | 2.0–32.0 | Falling head - 100 cm - 25 cm | 15 - H, 9 - D | 3.0–16.0 |
| Jagadeesh et al. [18] | 9.5, 12.5 (max size) and combination 2.36–4.75, 4.75–9.5, 9.5–13.2 | 4.5 | 0.29 | - | - | 25 - H, 15 - D | 26 | Falling head from 22.5 cm to 2.5 cm | 25 - H, 15 - D | Intrinsic permeability was calculated |
| Wang et al. [19]    | 3.84–5.55 | 0.31 | 15 × 15 × 15 | 12.7–34.5 | 5 - H, 10 - D | 18.7–25.7 | Falling head, not Darcy | 5 - H, 10 - D | 6.1–7.1 |

CA: coarse aggregate, A/B: aggregate/binder ratio, and W/B: water/binder ratio. ∗ Fine aggregate used.
between voids, paste content, strength, and workability [23]. Yang and Jiang [24] stated that the binder area and quality have to be enhanced to improve the compressive strength. The essential requirement is to provide optimum cement paste to bind aggregates without paste drain at the bottom [25]. Most of the mixes are continuously graded with a wide range of aggregate sizes. The wide range increases the compressive strength but reduces the permeability. The tortuosity of the flow path increases due to the broad grading of aggregates [26]. In some of the mixes tabulated in Table 1, fine aggregate is used to increase the strength of the pervious concrete. Fine aggregates are added in small amounts to increase the strength of the concrete [27]. The aggregate-binder ratio varies between 2.1 and 6.14. The water-binder ratio varies from 0.16 to 0.36. Most of the water-binder ratios are around 0.3. The binder material generally used is Portland cement and pozzolanic cement. Fly ash, quarry dust, and Ground Granulated Blast Furnace Slag can be used as additional binder materials [28]. High-strength pervious concrete mixes are developed using silica fume, polymers, and superplasticizers [29]. Evaluating the critical water-cement ratio is essential to prevent cement fume, polymers, and superplasticizers [29]. Evaluating the critical water-cement ratio is essential to prevent cement fume, polymers, and superplasticizers [29].

The associated compressive strength, porosity, and permeability capture the variability of the strength and hydrological parameters based on the size and mix design of the pervious concrete mixes. Chai et al. [33] compared the saturated and unsaturated hydraulic conductivity for its analysis. The specimen size is also included to understand the variability of the specimen sizes used. Since there is a lack of standardization, there are different sizes used. The specimen’s shape is primarily cylindrical, while some are cuboidal or cubical. The method of permeability calculation is either a constant head or falling head. These permeability equations are originally used for soil medium based on the type of soil used. Qin et al. [34] compared the permeability measured using constant head and falling head permeameter and concluded that permeability estimated using the falling head method is lower than that calculated using the constant head method.

The clogging of pervious concrete is a significant disadvantage to this source sustainable urban drainage system. It also reduces the permeability of concrete. Hassan et al. [28] investigated the clogging potential due to dust. Fwa et al. [35] used an aqueous solution of fine-grained soil as a clogging material. Kia et al. [31] summarized the effect of clogging of pervious concrete due to clay and sand and their mixture. Deo et al. [36] used fine-grained (0.1–0.84 mm) and coarse-grained (0.84–1.8 mm) river sand as clogging material. Marcaida et al. [7] concluded that graded sand particles cause more clogging than single graded sand particles. Walsh et al. [37] developed a laboratory study to record how sediment accumulation affects the hydraulic conductivity of pervious concrete. Lin et al. [38] studied the effect of vehicle vibration on clogging of pervious concrete. Cui et al. [39] measured the electrical conductivity as an indicator of pervious concrete clogging. Ketcheson et al. [40] conducted laboratory experiments to understand the effect of sand application and temperature (frozen and thawed conditions) on concrete. Barisic et al. [16] concluded that pervious concrete made with smaller aggregate fractions is more prone to clogging.

This paper explores the clogging potential of pervious concrete based on small size aggregates and calculates the permeability and clogging in an unsaturated state. Since there is no standard method to calculate the permeability, a simple permeameter is fabricated to calculate permeability and clogging. Small aggregates in the size range of 2.36 mm to 6.3 mm have smaller pores, and their behavior of clogging is different from the clogging of large pores from large aggregates. The clogging material used in this study is clay and sand. The permeability and clogging potential are determined for the mix comprising the two narrow gradations of 2.36 mm − 4.75 mm and 4.75 mm − 6.30 mm to study the following phenomena: impact of pore size on the permeability and effect of clogging material gradation on the permeability.

2. Methodology

2.1. Composition and Mix Design. The materials used in the previous concrete mix are cement, aggregates, micro Ground Granulated Blast Furnace Slag (μGGBS), and superplasticizer. The aggregate-cement ratio is kept constant at 5.2, and the water-cement ratio is maintained at 0.3. The μGGBS is taken as 20% of cement. Therefore, the aggregate/binder ratio becomes 3.33, and the water/binder ratio becomes 0.25. The narrow aggregate size graduation used ranges between 2.36 mm − 4.75 mm and 4.75 mm − 6.3 mm in size. Table 2 tabulates the mix design used for the study. The above aggregates are selected to provide a smoother surface and avoid raveling aggregates, which is a common phenomenon in pervious concrete. The smaller aggregates ensure better bonding between the cement paste and the aggregates.

2.2. Experimental Setup. A transparent acrylic pipe series of diameter 15 cm, as shown in Figure 1, was fabricated to evaluate concrete permeability.

2.3. Compressive Strength Test. Compression test is the most common test conducted on hardened concrete to find out the strength of concrete. As per IS 516:2004 (Methods of Tests for Strength of Concrete), the IS standard compression test is carried out on cubes of size 150 × 150 × 150 mm. The specimens were cured for 48 hours, as after 24 hours, the concrete was not set properly. The test is carried out on the 28th day from the curing date.

2.4. Porosity Measurement. The porosity or a void ratio of the concrete is the number of voids present in the concrete. It is calculated by the following formula:
where \( P \) is the porosity, %, \( W_D \) is the oven dry weight, g, \( W_S \) is the submerged weight, g, \( \rho_w \) is the density of water, g/cm\(^3\), and \( V_T \) is the volume of the specimen:

\[
V_T = \frac{\pi D_{avg}^2 H_{avg}}{4}
\]

**2.5. Permeability Test.** Permeability refers to the ease with which water can flow through concrete. The principle of falling head permeameter is used. One liter of water is used consistently for both permeability and clogging tests. The test begins when water is poured on the top surface of pervious concrete. The time taken is calculated when the water level reaches 3 cm from the top of the surface. A falling head of 1.5 cm from 3 cm to 1.5 cm from the specimen’s top surface is maintained for the test. The time taken for a 1.5 cm fall is measured via video to calculate time accurately. Since the flow occurs quickly due to its porous nature, a video graphic aid for calculating time reduces the number of repetitions and increases the measurement’s accuracy. Since clogging is calculated, the unsaturated permeability is taken as the reference for calculating the reduction in permeability.

**2.6. Clogging Test.** In this study, the specimen is exposed to an aqueous solution of clay and sand. A concentration of 5 g/l is prepared by mixing 5 g of clay or sand with 1 liter of water. It is mixed at 40 rpm for 1 minute in a motorized mixer. The gradation of the clogging material—clay and sand—is tabulated in Figure 2. For sand, dry sieve analysis is performed using the sieves 4.75 mm, 2.36 mm, 1.18 mm, 600 \( \mu \)m, 300 \( \mu \)m, and 150 \( \mu \)m. For clay, hydrometric analysis is performed to plot the grain size distribution. This solution is passed through the matrix, and the same principle of calculating permeability is used. This was applicable for both gradations. The experiment is conducted for six cycles. Since the trials cannot be repeated, a video was beneficial for accurately calculating time. Figure 3 shows the top surface of the pervious concrete containing the narrow gradation of 2.36–4.75 mm before and after exposure to six clay and sand clogging cycles. Figure 4 shows the top surface of the pervious concrete containing the narrow gradation of 4.75–6.30 mm before and after exposure to six clay and sand clogging cycles. During the experiment’s conduction, clay clogging’s exfiltration had clay particles, whereas it was a clear solution for sand clogging. It was also observed that the top surface of the 2.36–4.75 mm gradation concrete retained a good amount of sand particles during the clogging cycles.

**3. Results and Discussion**

**3.1. Compressive Strength.** The compressive strength of pervious concrete is comparatively lower than that of conventional concrete due to pores’ presence. Compressive strength is the primary property to assess the ability of concrete to resist loads. In conventional concrete, the porosity is significantly less, and the concrete’s strength is not

**Table 2: Mix design of the pervious concrete mixes.**

| Mix proportions | Binder—cement (%) | Binder—GGBS % | Aggregate size | Aggregate/binder ratio | Water/binder ratio | Superplasticizer |
|-----------------|-------------------|---------------|----------------|------------------------|------------------|-----------------|
| M1              | 80                | 20            | 2.36–4.75 mm   | 3.33                   | 0.25             | 5% of water     |
| M2              | 80                | 20            | 4.75–6.30 mm   | 3.33                   | 0.25             | 5% of water     |
dependent on the porosity, whereas in pervious concrete, the compressive strength is dependent on the number and size of the pores. The compressive strength is calculated on the 28th day for the narrow gradation. Table 3 shows the average, maximum, and minimum compressive strength for 2.36 mm–4.75 mm and 4.75 mm–6.30 mm gradation, respectively. The 2.36–4.75 mm aggregate gradation has higher compressive strength than 4.75–6.30 mm. The results agree with [22], which concludes that small size aggregates result in higher compressive strength. Chindaprasirt [41] concluded that compressive strength in the range of 22–39 MPa is achieved with porosity in 15–25% by maintaining a low water-cement ratio of 0.25.

Table 4 tabulates the compressive strength, porosity, and permeability values from the American guidelines ACI 522R-10, guidelines by Finland Technical Research Center VTT-R-080225-13, and the Brazilian standards NBR 16416: 2015. The average compressive strength is within limits for all the cases except for VTT-R-080225-13, where the maximum compressive strength is 20 MPa. The 2.36–4.75 mm gradation has a higher compressive strength than the standard.

Table 5 shows the mix proportion, compressive strength, porosity, and permeability of the current study’s closest mix design ratios. Figure 5 shows the compressive strength’s pictorial representation tabulated in Table 5. The literature
shows variation in the compressive strength of the specimen. The compressive strength values in the present study are in a higher range than the paper with similar mix proportions. One of the prime reasons for the same is small aggregates.

3.2. Porosity and Density. The concrete is compacted in three layers instead of vibration. The uniform degree of compaction ensures uniformity in the engineering properties of the concrete. The calculated porosity and density are tabulated in Table 6. Since narrow gradation of aggregate is used, the porosity has increased with the increase in aggregate size. The porosity calculated above is the total porosity. It is essential to calculate the interconnected pores to correlate with permeability strongly [36]. The above results are on par with Fu et al. [45], where porosity increases with aggregate size. Ibrahim et al. [46] calculated the density for aggregate-cement ratio of 8, water-cement ratio of 0.35

| Reference       | Aggregate/binder ratio | Water/binder ratio | Compressive strength, N/mm² | Porosity, % | Permeability, mm/s |
|-----------------|------------------------|-------------------|----------------------------|-------------|--------------------|
| Azad et al. [13] | 4–4.85                 | 0.36              | 9.2–14.8                   | 30–36       | 5.36–6.17          |
| Cai et al. [42]  | 3–4.2                  | 0.3               | 4–12                       | 24.8–26.1   | 1.8–6.9            |
| Lori et al. [14]| 3.35                   | 0.3               | 17.93–23.5                 | 20.44–21.67 | 3.05–3.33          |
| Zhu et al. [43]  | 3.84–5.55              | 0.31              | 12.7–34.5                  | 18.7–25.7   | 6.1–7.1            |
| Sandoval et al. [11] | 3.26            | 0.34              | 3.83–10.1                  | 19.26–27.06 | 4.97–15.08         |
| Mohammed et al. [44] | 2.1, 2.61,3.36 | 0.3               | 2.5–19.9                   | 14.3–28.75  | 3.44–9.82          |
| The current paper | 3.33                  | 0.25              | 16.2–27                    | 15.2–23.3   | 4.34–6.61          |

| Reference | Aggregate/binder ratio | Water/binder ratio | Compressive strength, N/mm² | Porosity, % | Permeability, mm/s |
|-----------|------------------------|-------------------|----------------------------|-------------|--------------------|
| Azad et al. [13] | 4–4.85                 | 0.36              | 9.2–14.8                   | 30–36       | 5.36–6.17          |
| Cai et al. [42]  | 3–4.2                  | 0.3               | 4–12                       | 24.8–26.1   | 1.8–6.9            |
| Lori et al. [14]| 3.35                   | 0.3               | 17.93–23.5                 | 20.44–21.67 | 3.05–3.33          |
| Zhu et al. [43]  | 3.84–5.55              | 0.31              | 12.7–34.5                  | 18.7–25.7   | 6.1–7.1            |
| Sandoval et al. [11] | 3.26            | 0.34              | 3.83–10.1                  | 19.26–27.06 | 4.97–15.08         |
| Mohammed et al. [44] | 2.1, 2.61,3.36 | 0.3               | 2.5–19.9                   | 14.3–28.75  | 3.44–9.82          |
| The current paper | 3.33                  | 0.25              | 16.2–27                    | 15.2–23.3   | 4.34–6.61          |
with an aggregate size of 4.5 mm as 1780.31 kg/m³. The porosity values are within the range when compared to the standards in Table 4. The concrete mix has porosity values in tandem with the literature as shown in Figure 6. Since smaller aggregates are used, the maximum value of permeability is less in comparison with the literature. The creation of large pores is limited and since one of the gradations, namely, 2.36 mm–4.75 mm, falls under fine aggregate size, most of the pores are filled by the aggregates itself. From literature tabulated in Table 1, it is observed that lower binder aggregate ratio also causes lower porosity.

3.3. Permeability. The motorized vibration method is not done since it causes the settlement of cement slurry at the bottom and makes the concrete impermeable. A lower aggregate-cement ratio also causes the bottom layer of the concrete to become impermeable due to the cement paste drain at the bottom. The permeability was analyzed for both narrow gradations of aggregates. Though the compressive strength is higher for the narrow gradation of 2.36 mm–4.75 mm, there is a substantial reduction in the permeability due to lesser interconnected pores in the concrete matrix. The smaller pores due to the presence of smaller aggregates decrease the porosity and ultimately the permeability of the specimen.

Since the gradation is narrow, the size of the aggregates decides the size of the pores. Figure 7 represents the box plot representation of permeability. There is an average difference of 0.00337 m/s between the two gradations. Due to the pores' large size, the larger aggregate size gradation of 4.75 mm–6.3 mm shows higher permeability than the smaller size gradation of 2.36 mm–4.75 mm. The larger size gradation has more variation in permeability with a standard deviation of 0.00124 m/s. Since the compaction is manual, there is variability in the permeability of the specimens. The manual compaction has resulted in uneven distribution of pores within the concrete matrix. The lack of vibration of the concrete specimen has affected the uniformity in the internal structure of the concrete. The variation in the permeability of the larger gradation indicates the presence of numerous interconnected pores resulting in varying flow paths.

In contrast, the smaller aggregate gradation has a standard deviation of 0.00032 m/s, indicating a more uniform permeability. The permeability variation is less for the smaller aggregates, suggesting that manual compaction does not affect the pore structure. Since the aggregate size is small, the pore size is also small. It has resulted in the reduction of the interconnected pores in the specimen. Comparing the two gradations, as shown in Figure 7, the size of the aggregate and narrow gradation have a significant role in the permeability of the concrete specimen. Since high permeability is not desired for all use cases of pervious concrete, a curve between permeability and compressive strength effectively classifies the concrete based on the particular use. The permeability values are greater than the values prescribed in the standards, as tabulated in Table 4. The current study has comparable permeability with the literature, as shown in Figure 8. The maximum values are lower compared to the review papers.

3.4. Clay Clogging. Though the use of pervious concrete is gaining immense popularity, the clogging caused due to particles on the roadways and the nearby areas is a cause of concern to the life of the concrete and its maintenance requirements. The research on clogging is essential to understand the behavior of concrete in terms of its permeability. Clay is a very fine particle and can easily escape through most porous media. It is necessary to know the interaction between the clay particles and pore structure to assess the type of maintenance required for the concrete. Figure 9 shows the trend and the comparison of the clogging due to the two gradations of aggregates for clay clogging. The curve is exponential, and the inflection point is the first clogging cycle. The introduction of clay slurry of 5 g/l concentration causes a substantial decrease in permeability. There was a 69.8% and 74.9% reduction in permeability in the first cycle of clogging for a narrow gradation of 2.36–4.75 mm and 4.75–6.30 mm, respectively. The initial value of permeability is measured using plain water. The percentage reduction is calculated with respect to the initial permeability value. The clogging of pores in this magnitude limits the use of pervious concrete to places where the stormwater is almost free from solid particles.

The 2.36–4.75 mm gradation concrete shows a further decrease in permeability after the first cycle. The small pores and interconnections are getting clogged due to exposure to an aqueous clay solution, whereas for 4.75–6.30 mm gradation, the permeability is almost constant after the first clogging cycle. The comparatively larger pores allow excess clay particles to pass through. There were accumulation and flushing of clay particles in both cases on the specimen's top surface. The exfiltration also contained clay particles indicating the movement of clay through the permeable matrix.

3.5. Sand Clogging. Sand particles are larger in size and tend to cause more clogging than clay. The trend and the comparison of the clogging due to the two gradations of aggregates are shown in Figure 10. The curve is exponential, and the inflection point is the first clogging cycle. It also shows a substantial decrease in permeability due to the introduction of the sand slurry of a 5 g/l concentration. There were 74.7% and 71.7% reduction in permeability in the first cycle of clogging for a narrow gradation of 2.36 mm–4.75 mm and 4.75 mm–6.30 mm. It also shows that the change in permeability is very minimal after the initial decrease in permeability. Though clay and sand behave differently as clogging materials, the percentage reduction of permeability is almost the same as clay clogging. The sand particles are retained fully in the concrete matrix for all the cycles. The exfiltration did not contain sand particles, indicating the accumulation of sand particles in the concrete matrix for the six cycles.
3.6. Clogging Potential. The clogging material and size of the aggregates play an essential role in determining the pervious concrete mix’s clogging potential. The clogging potential is plotted when the clogging material is introduced to the concrete matrix. The clogging material is clay and sand. The change in permeability from the first cycle to the sixth cycle and its linearity are shown in Figure 11. The slope of the clogging cycles shows decreasing permeability except for the clay clogging of 4.75–6.30 mm. The governing equations and their $R^2$ values are tabulated in Table 7. The $x$ values are the
Figure 9: Comparison of permeability due to clay clogging.

Figure 10: Comparison of permeability due to sand clogging.

Figure 11: Clogging potential for all case scenarios.

Table 7: Clogging potential equation.

| S. No. | Aggregate gradation | Clogging material | Equation              | $R^2$ |
|--------|---------------------|-------------------|-----------------------|-------|
| 1      | 2.36–4.75 mm        | Clay              | $y = -0.031x + 0.001$ | 0.84  |
| 2      | 2.36–4.75 mm        | Sand              | $y = -0.017x + 0.001$ | 0.695 |
| 3      | 4.75–6.3 mm         | Clay              | $y = 0.009x + 0.001$  | 0.627 |
| 4      | 4.75–6.3 mm         | Sand              | $y = -0.014x + 0.002$ | 0.394 |
sediment input in kg, and $y$ is the permeability in m/s. The clogging pattern for clay in the gradation of 2.36–4.75 mm has the maximum negative slope indicating the maximum permeability decrease. All the equations’ slope is approximately zero, indicating that the permeability does not change significantly as the clogging cycle progresses. The least coefficient for determination $R^2$ is for sand clogging in the gradation of 4.75–6.3 mm, indicating the mean value’s deviation. The clogging material and size of the aggregates play an essential role in determining the pervious concrete mix’s clogging potential.

Comparing the permeability due to clogging with the standards tabulated in Table 4, the clogging of clay and sand on the pervious concrete with the narrow gradation of 2.36–4.75 mm causes the permeability value to go below the minimum value of 1 mm/s as per the American guidelines ACI 522R-10 and the Brazilian standards NBR 16146:2015. Also, after the first clogging cycle on the above mix, the value is below the minimum of 1.5 m/s as per the guidelines by Finland Technical Research Center VTT-R-080225-13. Such low permeability values will not serve the purpose of the pervious concrete. It is recommended not to use small aggregates when there is a chance of high siltation.

4. Conclusions

The research paper highlights the role of aggregate size gradation on the hydraulic properties of pervious concrete mixes. The following conclusions are drawn based on the project work.

The larger aggregate size gradation of 4.75 mm–6.3 mm shows higher permeability than the smaller size gradation of 2.36 mm–4.75 mm due to the larger pores. The variation of permeability is more in the larger aggregates due to the numerous interconnectivities of pores. It results in varying flow paths and flow directions within the concrete matrix.

The vibration of pervious concrete is not recommended as it has a higher chance of paste drain at the bottom. Compaction is a more suitable method. Uniformity in compaction pressure is essential for avoiding variation in porosity.

The compressive strength, porosity, and permeability are compared with the standards and literature using aggregate-binder and water-binder ratio. The results are in agreement with the literature.

The highest reduction in permeability is when the clogging materials are introduced to the specimen. Further degradation of permeability has a low impact compared to the initial decrease. The slope of the line drawn is approximately equal to zero, indicating a line drawn parallel to the x-axis.

The larger particle size of sand clogs the concrete matrix differently from clay particles. The fineness of clay particles causes a part of it to pass through the concrete matrix, whereas, in the case of sand, there is accumulation in the six cycles of the introduction of sand slurry.

It is not recommended to use aggregate size of 2.36–4.75 mm in the pervious concrete mix when the surrounding area has higher siltation.

The accumulation of sand particles on the top surface is more pronounced in the gradation of 2.36 mm–4.75 mm, where the sand particles can be easily swept from the surface due to the small pores present on the top surface.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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