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MIXTURE PROPORTIONING DESIGN OF PERVIOUS CONCRETE USING THE PASTE CONTENT RATIO METHOD (A SINGLE PARTICLE SIZE 19MM AND 9.5MM)

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Abstract

In this work, we used the concept of paste content ratios in the mixture proportioning design of pervious concrete so that the concrete paste content could be adjusted to satisfy the requirements of different engineering applications. We experimentally demonstrated that compressive strength is negatively correlated with the coefficient of permeability and positively correlated with the paste content ratio. The highest compressive strength achieved in this study was 286 kgf/cm^2, whereas the highest permeability coefficient was 0.123 cm/s. Design graphs for flowability, compressive strength, and permeability coefficient of the concrete mixtures were also constructed to be used by engineering companies as reference data.

Keywords: pervious concrete; paste content ratio method; compressive strength.

Introduction

Conventional pervious concrete typically contains voids that lead to high permeability; however, it could also lead to insufficient cement paste in the concrete, which reduces its strength and workability. Therefore, to produce high-performance permeable concrete, the paste content of a concrete mixture must be adjusted to improve its workability, permeability, and compressive strength.

The proportioning of pervious concretes is usually performed using the volumetric ACI 211.3 method (ACI 211.3R, 2009). However, this approach only accounts for the volume of voids between the aggregates when designing filler volumes, whereas the volume of the lubricating paste that coats the surface of the aggregates is simply neglected. The specific surface area-based approach of Kennedy (Kennedy, C. T., 1940) accounts for the quantity of lubricating paste on aggregate surfaces, but this approach does not account for the volume of the voids between the aggregates. Hence, both proportioning theories have their own weaknesses and pervious concretes designed using these methods tend to have poor workability and strength. Therefore, we have combined the volumetric ACI 211.3 method and Kennedy (1940)'s specific surface area-based method to refine concrete proportioning theories, increasing the paste content of the concrete. This increases the workability and strength of the pervious concrete without sacrificing permeability (Su, J.-H., Hsieh, H.-Z., Tang, Z.-B., 2012). However, the optimal paste filler quantity is unique to each engineering application. Therefore, we have introduced the concept of the paste content ratio, r_p, so that the proportioning of concrete mixtures may be adapted to the strength or permeability requirements of any given engineering application.

The Paste Content Ratio Method For Proportioning Pervious Concretes

In this work, the volumetric ACI 211.3 standard was used as the basis for the design of mix proportions. By incorporating the concept of paste content ratios, we systematically enhanced the paste quantity of the filler in pervious concrete, which acts as a lubricant and enhances the bonding strength of the cement layer. This is expected to lead to a proportioning method that further improves the performance of pervious concretes. Figure 1 illustrates the comparison of the proportioning methods discussed in this work.

As pervious concrete requires a degree of permeability (1×10^{-2} cm/s), a certain void volume must be retained in the mix design. This is achieved by setting a certain target percent of voids (R_{void}), while the remaining void volume is denoted as the 'to-be-filled volume' (V_{pr}). In this work, the paste content ratio for the pervious concrete is expressed by Equation (1).

$$r_p = V_p / (V_v - R_{void}) = V_p/V_{pr} \quad (1)$$

where r_p is the paste content ratio, V_p is the volume of cement paste, V_v is the volume of all voids, and Rvoid is the target percent of voids. In the paste content ratio method, the filler paste quantity has an additional $(r_p\text{-}1)V_{pr}$ term that represents the quantity of lubricating paste compared to the volumetric ACI 211.3 method; when $r_p = 1$, the paste content ratio method is equivalent to the ACI 211.3 method. In this work, the effects of the paste content ratio on the mechanical properties of pervious concrete were investigated by adjusting the value of this term.

The mixture design algorithm of the paste content ratio method for pervious concrete is as follows:

1. Calculate the true volume fraction of coarse aggregates,

$$X_G = W_G/(G_G\times10^3) \quad (2)$$

where W_G(kg/m^3) is the unit weight of the coarse aggregate and G_G is the specific gravity of the coarse aggregate.

2. Calculate the remaining void volume,

$$V_{pr} = (1\text{-}X_G)(1\text{-}R_{void}) \quad (3)$$

3. Calculate the cement paste volume,

$$V_p = r_p \times V_{pr} \quad (4)$$

4. Calculate the per unit cement quantity,

$$W_C\ (\text{kg/m}^3) = (10^3\times V_p)/[(W/C) + (1/G_C)] \quad (5)$$

where W/C is the water-cement ratio and G_C is the specific gravity of the cement.

5. Calculate the per unit water quantity,

$$W_C\ (kg/m^3) = (10^3 \times V_p)/[(W/C) + (1/G_C)] \qquad (6)$$

Proportioning Factors And Level Selection

The primary determinant for the strength of a concrete is the C_3S content of the cement; in the hydration reaction, the weight of the C_3S phase was 456 g while the weight of water was 108 g. Hence, the theoretical water-cement ratio of the full hydration reaction is 0.24. If one considers the effects of water - induced volume expansion in the C-S-H gel, which reduces its density to 75%, the appropriate water-cement ratio becomes 0.42. However, a higher water-cement ratio produces soft concrete that tends to sag, reducing the permeability (Han, N.-B., 2006; China Building Materials Academy., 2008; Song, Z.-N., & Shi, Y.-X., 2011). When the water-cement ratio ranges between 0.35 and 0.42, autogenous shrinkage occurs during hydration; however, if the water-cement ratio is lower than 0.35, shrinkage is less pronounced due to spatial constraints (Hwang, C.-L., 2007). Therefore, the appropriate water-cement ratio for pervious concrete ranges between 0.24 and 0.35. This range was equally divided into three levels, i.e., 0.25, 0.30, and 0.35. In most cases, the target percent of voids of pervious concrete should not exceed 40% because this leads to excessive void-induced losses in strength. Target percent of voids below 25% would also lead to the obstruction of permeable voids. Hence, the target percent of voids of the concrete should range between 25% and 40%. This range was equally divided into two levels, at 30% and 35%. Regarding the required quantity of lubricating paste, the paste content should be increased over the levels specified in the volumetric ACI 211.3 method. Therefore, the paste content ratio must be greater than 1. However, excessive paste content may lead to sagging. Three levels were thus defined for the paste content ratio, at 1.15, 1.25, and 1.35. Two levels were defined for the particle size of coarse aggregates (aggregate gradation), at 19 mm and 9.5 mm, because these particle sizes are commonly used in engineering applications. Due to permeability concerns, only a single particle size was used in each mix.

Analysis And Discussion Of Experimental Results

Design providing 36 combinations for concrete casting. Four 15×30 cm cylindrical specimens were prepared using each of these combinations for flowability, permeability, and compression tests. Newly mixed concretes were prepared according to ASTM C31/31M-17 Standard Practice for Making and Curing Concrete Test Specimens in the Field, while workability tests were performed according to ASTM C124-71 Method of Test for Flow of Portland-Cement Concrete by Use of the Flow Table. Compressive strength tests were conducted according to ASTM C39/C39M-17 Compressive Strength of Cylindrical Concrete Specimens. Permeability tests were carried out according to the CNS 14995 A2288 Permeable Concrete Paving Block standard and the coefficients of permeability were measured using the constant-head test (Darcy's Law).

Figures 2–5 demonstrate how the flowability, compressive strength, and permeability coefficient are related to each other at the same aggregate size and target percent of voids. The optimal mix designs based on the considerations for compressive strength and permeability coefficient are as follows:

1. Figure 2 shows that an aggregate size of 19 mm and target percent of voids of 30% result in the flowability values of 23.23–69.29%, compressive strength values of 101–286 kgf/cm^2, and permeability coefficients of 0.019–0.114 cm/s. The optimal conditions for satisfying the strength and permeability requirements were the paste content ratio of 1.25 and water-cement ratio of 0.3; these conditions resulted in a flowability of 38.58%, permeability coefficient of 0.092 cm/s, and compressive strength of 212 kgf/cm^2.

2. Figure 3 shows that an aggregate size of 19 mm and target percent of voids of 35% result in a flowability of 18.11–59.06%, compressive strength of 87–215 kgf/cm^2, and permeability coefficients of 0.042–0.117 cm/s. A paste content ratio of 1.35 and water-cement ratio of 0.35 were found to be optimal conditions as they resulted in a flowability of 59.06%, permeability coefficient of 0.042 cm/s, and compressive strength of 215 kgf/cm^2.

3. Figure 4 shows that an aggregate size of 9.5 mm and target percent of voids of 30% yield a flowability of 4.33–55.91%, compressive strength of 74–275 kgf/cm^2, and permeability coefficient of 0.052–0.118 cm/s. The optimal conditions for satisfying the strength and permeability requirements were the paste content ratio of 1.25 and water-cement ratio of 0.35; These conditions resulted in a flowability of 50.79%, permeability of 0.074 cm/s, and compressive strength of 239 kgf/cm^2.

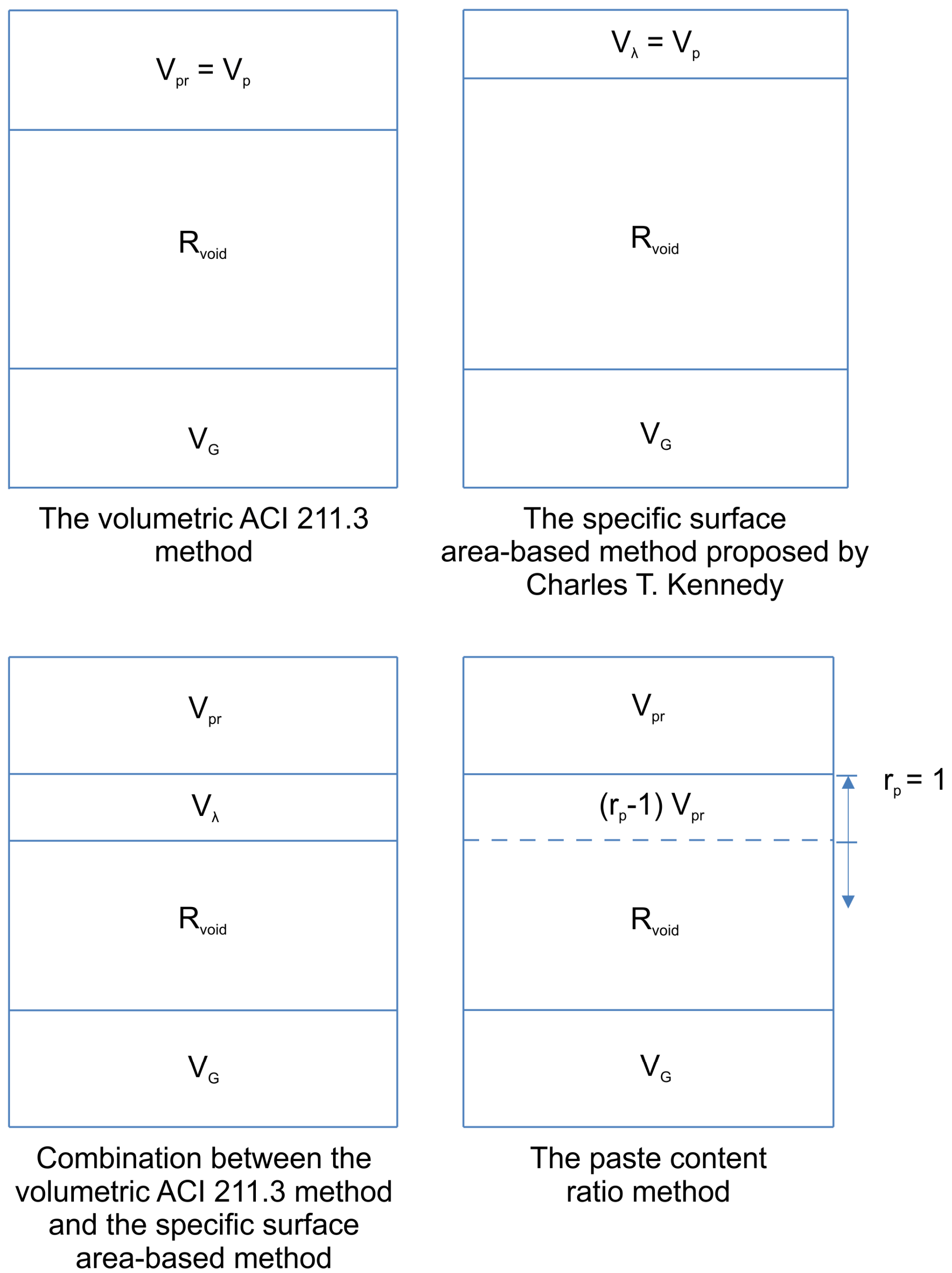

Figure 1. Comparison of methods for proportioning pervious concretes

4. Figure 5 shows that an aggregate size of 9.5 mm and target percent voids of 35% yield flowability values between 3.15% and 46.46%, compressive strengths between 73 kgf/cm^2 and 210 kgf/cm^2, and permeability coefficients between 0.080 cm/s and 0.123 cm/s. A paste content ratio of 1.35 and water-cement ratio of 0.35 were found to be optimal conditions, as they produced a flowability of 46.46%, permeability

coefficient of 0.080 cm/s, and compressive strength of 210 kgf/cm^2.

5. Figures 2–5 shows that the flowability values ranged between 3.15 and 69.29%. Flowability is positively correlated with the paste content ratio. The optimal proportioning conditions for maximizing flowability were the aggregate size of 19 mm, target percent of voids of 30%, water-cement ratio of 0.35, and paste content ratio of 1.35, producing a flowability of 69.29%.

6. Figures 2–5 shows that the compressive strength values obtained over the course of this experiment ranged between 73 and 286 kgf/cm^2. The compressive strength is positively correlated with the paste content ratio. The optimal proportioning conditions for compressive strength were the aggregate size of 19 mm, target percent of voids of 30%, water-cement ratio of 0.35, and paste content ratio of 1.35, producing a compressive strength of 286 kgf/cm^2.
7. Figures 2–5 shows that the experimental permeability coefficients ranged between 0.019 and 0.123 cm/s. Permeability coefficient is negatively correlated with the paste content ratio. The optimal proportioning conditions for the permeability coefficient were the aggregate size of 9.5 mm, target percent of voids of 35%, water-cement ratio of 0.25, and paste content ratio of 1.15, producing a permeability coefficient of 0.123 cm/s.

Therefore, the best overall design involves the aggregate size of 19 mm, target percent of voids of 30%, water-cement ratio of 0.3, and paste content ratio of 1.25, yielding flowability of 38.58%, permeability coefficient of 0.092 cm/s, and compressive strength of 212 kgf/cm^2.

Conclusions

In this work, the paste content ratio concept was used to design concrete mix proportions that meet the requirements of different engineering applications by making appropriate adjustments to the paste content. The following conclusions were drawn from the results.

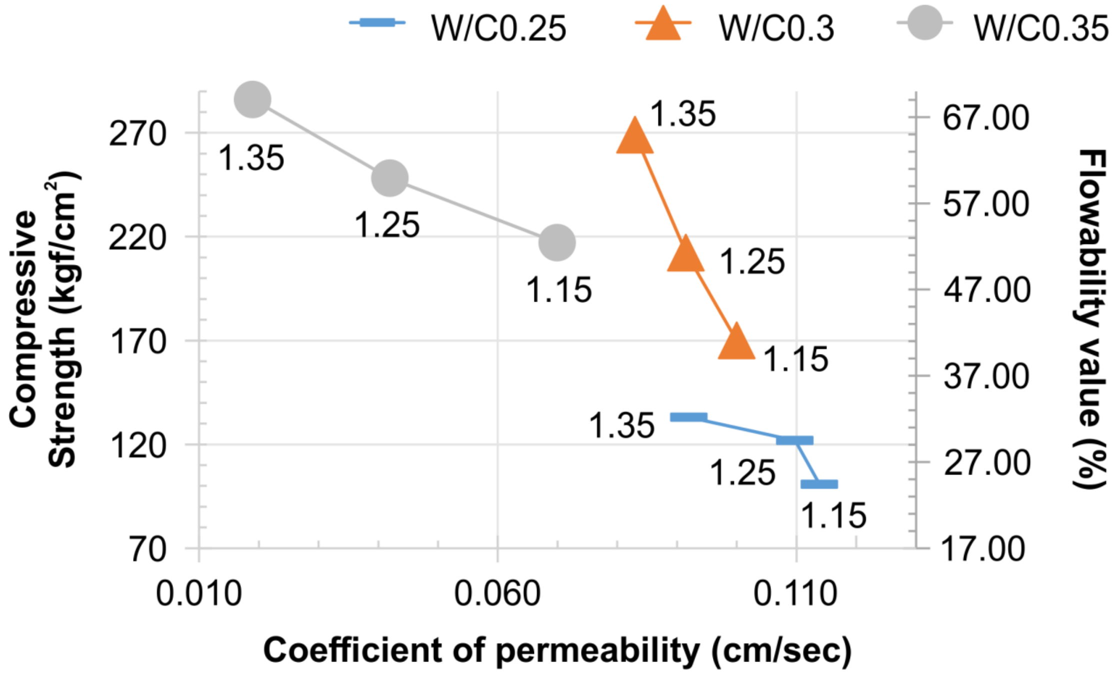

Figure 2. Relationship between compressive strength, flowability value, and the coefficient of permeability with an aggregate size of 19 mm and target percent of voids of 30%

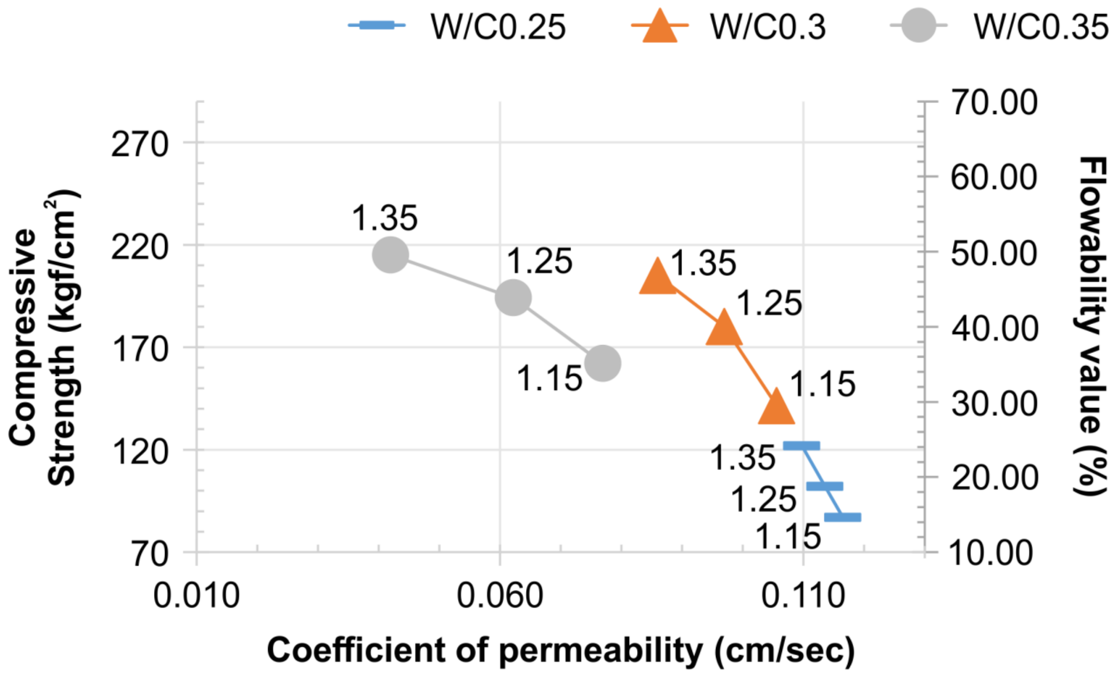

Figure 3. Relationship between compressive strength, flowability value, and the coefficient of permeability with an aggregate size of 19 mm and target percent of voids of 35%

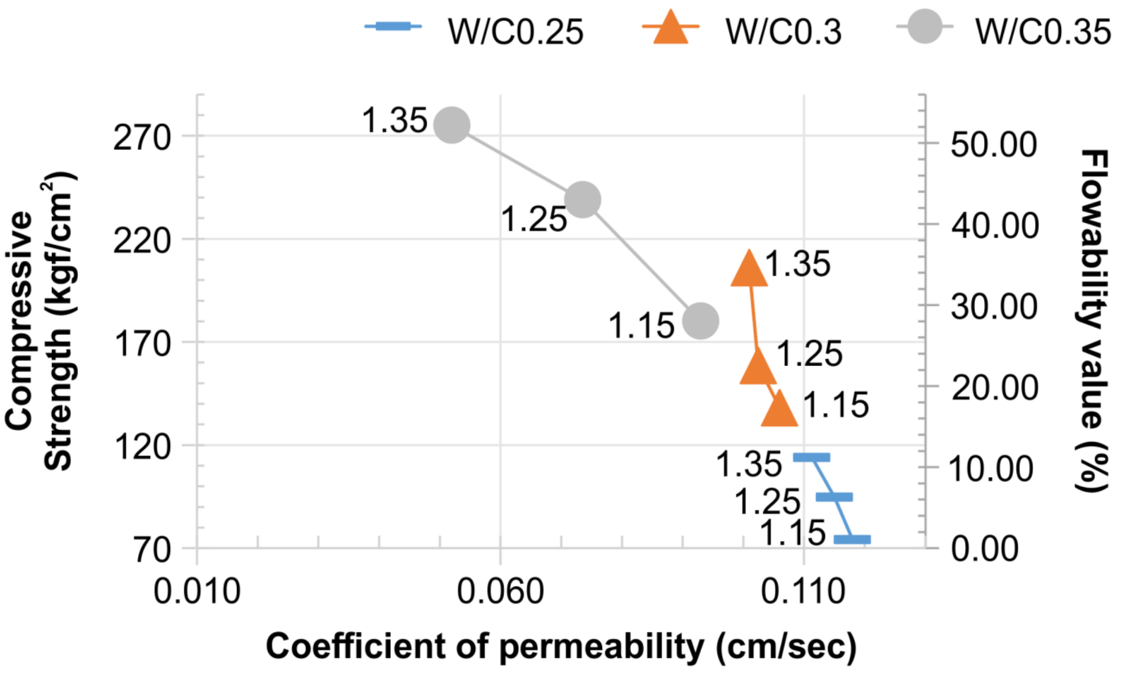

Figure 4. Relationship between compressive strength, flowability, and the coefficient of permeability with an aggregate size of 9.5 mm and target percent of voids of 30%

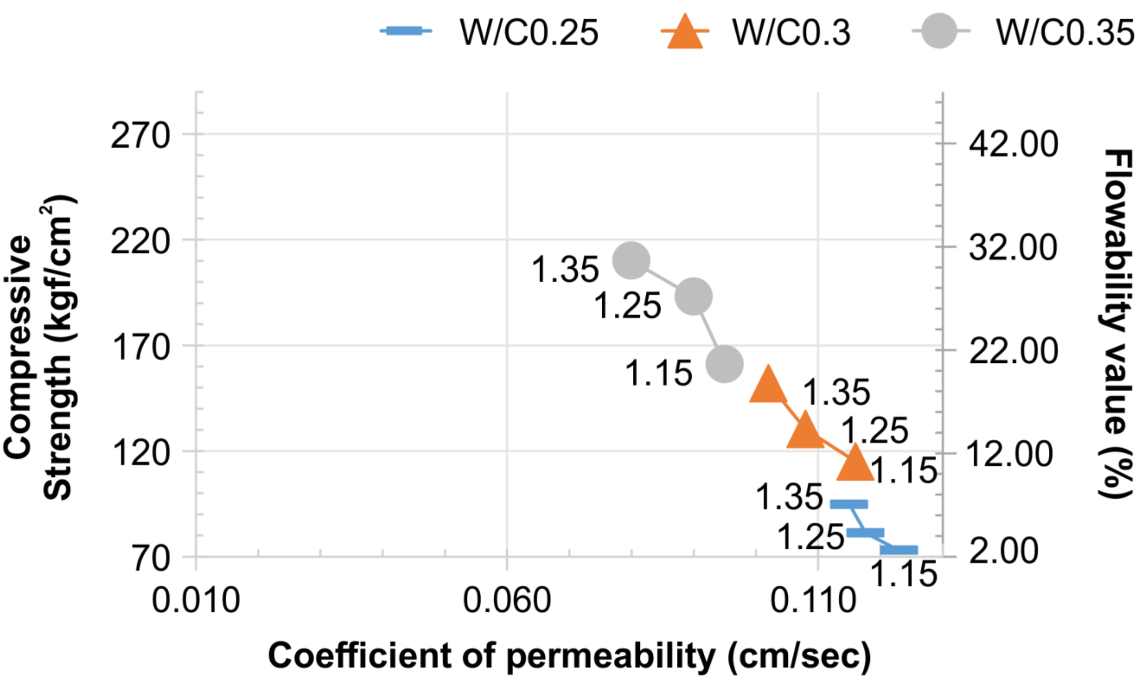

Figure 5. Relationship between compressive strength, flowability, and the coefficient of permeability with an aggregate size of 9.5 mm and target percent of voids of 35%

(1) In the design of pervious concrete mixtures, it is possible to meet the requirements of different engineering applications by incorporating the concept of paste content ratios in the volumetric ACI 211.3 standard. This approach also represents a theoretical refinement of the volumetric ACI 211.3 method.

(2) Flowability is positively correlated with the paste content ratio and water-cement ratio and negatively correlated with the target percent of voids. The experimental flowability values ranged between 3.15 and 69.29%. The optimal conditions for maximizing flowability were an aggregate size of 19 mm, target percent of voids of 30%, water-cement ratio of 0.35, and paste content ratio of 1.35, producing a flowability of 69.29%.

(3) Compressive strength is positively correlated with the paste content ratio and water-cement ratio and negatively correlated with the target percent of voids. The experimental compressive strength values ranged between 73 and 286 kgf/cm^2. The optimal conditions for maximizing compressive strength were the aggregate size of 19 mm, target percent of voids of 30%, water-cement ratio of 0.35, and paste content ratio of 1.35, producing a compressive strength of 286 kgf/cm^2.

(4) The coefficient of permeability is negatively correlated with the paste content ratio and water-cement ratio and positively correlated with the target percent of voids. The experimental permeability coefficients ranged between 0.019 and 0.123 cm/s; the entirety of this range exceeds the 1×10^{-2} cm/s specification for pervious concrete. The optimal conditions for maximizing permeability were the aggregate size of 9.5 mm, target percent of voids of 35%, water-cement ratio of 0.25, and paste content ratio of 1.15, producing a permeability coefficient of 0.123 cm/s.

(5) Figures 2–5 can be used as reference diagrams by engineers for designing pervious concrete mix proportions based on the compressive strength or permeability coefficient requirements. The best overall conditions were as follows: an aggregate size of 19 mm, target percent of voids of 30%, water-cement ratio of 0.3, and paste content ratio of 1.25, producing a flowability of 38.58%, permeability coefficient of 0.092 cm/s, and

compressive strength of 212 kgf/cm^2.

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