Mechanical performance of permeable concrete using chemical and mineral admixtures: An experimental study

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- An experimental study was performed to evaluate the performance and optimal mixture proportions of permeable concrete.
- Fifteen concrete mixtures were developed with a total of three specimens cast and tested for each mixture. Mixture variations included different aggregate-to-cement ratios, different aggregate sizes, and addition of silica fume and high-range water-reducing admixture.
- Types of testing performed included compressive strength, flexural strength, split tensile strength, permeability, and porosity.

Permeable concrete is a zero-slump concrete made of portland cement, coarse aggregate admixture, and water. When the constituents of permeable concrete are mixed, a porous and complex material is produced, the suitable range of compressive strength for permeable concrete used in pavements is 7 to 15 MPa for pedestrian walkways and 15 to 25 MPa for parking lots. For proper water drainage, the permeability of the concrete should be between 15% and 25% with pore widths of 0.080 to 0.32 in.[1,2] The study described in this article evaluated aggregate-to-cement ratios, variations in the proportions of different sizes of aggregate, and the impact of high-range water-reducing admixture (HRWRA) and silica fume in permeable concrete mixtures. The findings contribute to the understanding of optimum permeable concrete mixture proportions.

Background

In urban areas, impermeable pavements have increasingly replaced green spaces, leading to substantial challenges related to stormwater management, particularly during heavy rainfall and flooding events. Recently, permeable paving solutions have emerged as effective strategies to address these issues. Among these materials, permeable concrete has gained attention because of its various environmental benefits. In addition to enhanced water permeability, permeable concrete is associated with noise reduction, surface cooling, and improved driving safety.[3–7] Permeable concrete is used to pave pedestrian, recreational, and light-traffic surfaces, which is beneficial for the environment.[8] Compared with traditional concrete pavements, permeable concrete surfaces decrease the urban heat island effect (the phenomenon in which temperatures in cities are higher than those in surrounding areas due to the higher concentration of buildings and infrastructure and diminished green).[9]

Li et al. have investigated the strength and permeability characteristics of permeable concrete mixtures.[10] Some investigations have aimed to determine how aggregate size affects concrete's permeability and compressive strength. In many cases, uniformly sized aggregates are used in permeable concrete mixtures. Aggregate size affects properties such as porosity and the thickness of the cementitious paste.[11] The quantity of pores in the cementitious paste influences the compression strength and permeability of permeable concrete.[12]

Test results indicate that replacing 5% to 10% of portland cement (by weight) with silica fume substantially improves both short-term and long-term strength.[13] Duval and Kadri found that a mixture with 4% to 8% silica fume increased compressive strength by 25% and improved the workability of concrete.[14] In their study, when the proportion of silica fume was increased to 15%, compressive and tensile strengths were reduced.

The type of aggregate appears to influence the porosity and compressive strength of permeable concrete more significantly than the aggregate size.[15] In permeable concrete, compressive strength is inversely proportional to porosity, whereas permeability increases as porosity increases.[16] Increasing the proportion of silica fume decreases the permeability and increases the strength of the concrete. As a result, the pore size is reduced.[17]

Material and methods

Materials

This investigation evaluated the various components of permeable concrete, including normalweight aggregates of different sizes (4.75, 9.5, and 12.5 mm), portland cement, and admixtures (**Fig. 1**). The types of admixture used were silica fume and G-type HRWRA. Silica fume is a tiny (less than 1 µm diameter) particulate matter consisting of spherical particles with an average size of roughly 0.15 µm.[18] A silica fume particle is approximately 100 times smaller than a typical cement particle.[19]

Methodology

In total, the experimental study evaluated 15 concrete mixtures, which were cast in three series of specimens. In the first series, three mixtures (S1, S2, and S3) were tested with different cement-to-aggregate ratios. The second series evaluated three other concrete mixtures (S4, S5, and S6) and focused on variations in the proportions of different sizes of aggregate. In the third series, nine mixtures (S7 to S15) were tested, which incorporated different proportions of silica fume and

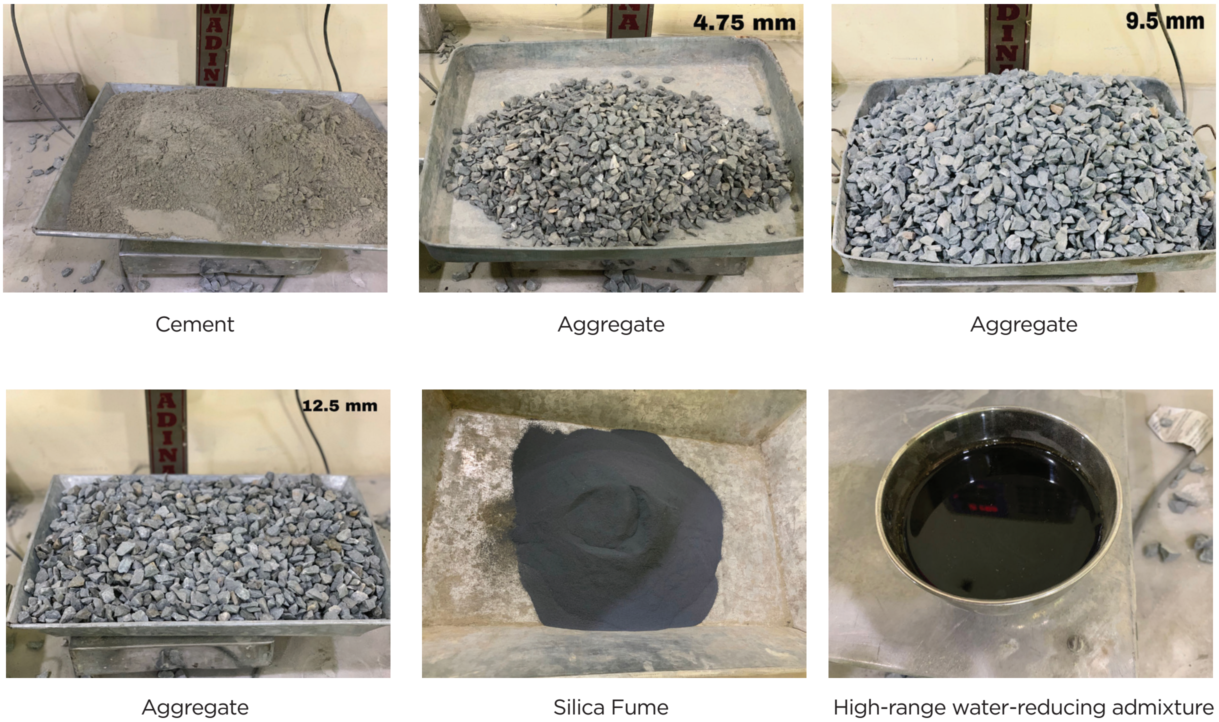

Figure 1. Materials used to produce permeable concrete. Note: 1 mm = 0.0384 in.

HRWRA. **Table 1** presents information about the composition and proportions of the 15 mixtures.

Three specimens were cast and tested from each of the 15 concrete mixtures to ensure the accuracy and reliability of the results, following the guidelines outlined in the American Concrete Institute's (ACI's) *Selecting Proportions for Normal-Density and High Density-Concrete—Guide* (ACI 211.1).[20] The cement-coated method was used to prepare the test samples.[21,22] For the first set of mixtures (S1, S2, and S3), water and aggregates were combined in a two-stage process. Initially, 40% of the total water was added to prewet the aggregates. Once the aggregates were sufficiently moistened, the remaining 60% of the water was introduced to achieve a uniform blend of water, cement, and aggregates. The same mixing procedure was followed for the second set of mixtures (S4, S5, and S6). The mixing approach was slightly modified for the third set of mixtures, which included the admixtures (S7 through S15). Initially, 20% of the total water was used to partially wet the aggregates. Subsequently, cement and silica fume were incorporated, and the remaining 80% of the water and the HRWRA were added to provide a homogeneous mixture of all components.

All test specimens were cylindrical. ASTM C31[21] standard test methods were followed during the casting and curing procedures. All samples were tested to determine their compressive, flexural, and split tensile strengths.[23,24] Permeability tests were conducted separately using a dedicated permeability apparatus. (**Fig. 2**) The compressive strength evaluations were carried out at 7 and 28 days to evaluate the structural and longevity characteristics of the concrete over time.

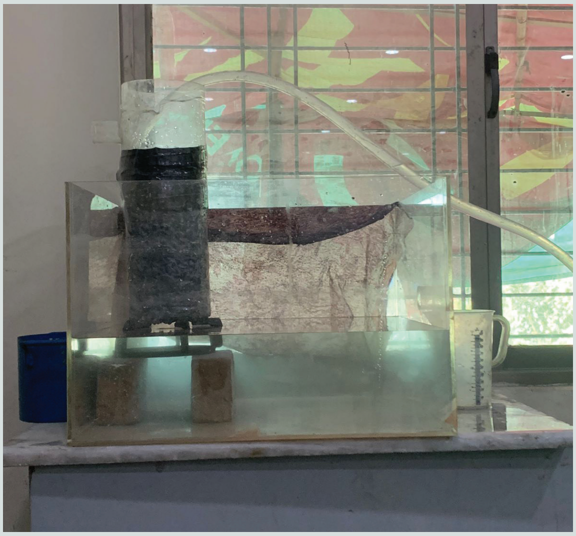

Figure 2. Permeability apparatus.

Table. 1. Mixture proportions of permeable concrete

Mixture designation	Aggregate content, %			Water-cement ratio	Aggregate-to-cement ratio	Silica fume, %	High-range water-reducing admixture, %
	4.75 mm	9.5 mm	12.5 mm				
S1	0	50	33	0.3	5:1	0	0
S2	0	50	30	0.3	4:1	0	0
S3	0	50	25	0.3	3:1	0	0
S4	5	35	35	0.3	3:1	0	0
S5	5	40	30	0.3	3:1	0	0
S6	5	45	25	0.3	3:1	0	0
S7	5	40	30	0.3	3:1	2.5	0.75
S8	5	40	30	0.3	3:1	2.5	1
S9	5	40	30	0.3	3:1	2.5	1.5
S10	5	40	30	0.3	3:1	5	0.75
S11	5	40	30	0.3	3:1	5	1
S12	5	40	30	0.3	3:1	5	1.5
S13	5	40	30	0.3	3:1	10	0.75
S14	5	40	30	0.3	3:1	10	1
S15	5	40	30	0.3	3:1	10	1.5

Note: 1 mm = 0.0384 in.

Porosity

Porosity of permeable concrete is measured using the Archimedes method:[25]

Porosity = (volume displayed/volume of samples) × 100

The initial step was to wash the sample using a brush, choose the dried sample weight with a weighing balance, and carefully assess the sample's dimensions. The next step was to fill a graduated beaker with water, marking the water level, and then totally submerge the sample in the water. The new water level was carefully observed, and the volume displaced by the sample was computed. The calculation of porosity was performed by using the concept of displaced volume.

Permeability

The permeability coefficient was determined using a custom-fabricated apparatus (Fig. 2) and a constant head permeability test method.[26] The difference in water pressure was 300 mm (11.8 in.). The specimen's height was also measured at 300 mm, and its diameter was recorded as 150 mm (5.9 in.). During the experimental procedure, the variation in water head height *H* was measured at regular intervals of 5 seconds. The following equation was used to determine the permeability coefficients of the concrete cylinders from these data.

$$K = QL/AHT$$

where

K = water permeability coefficient

Q = volume of flow

L = specimen length

A = specimen surface area

T = time the measurement

Results and discussion

Effect of aggregate-to-cement ratio on compressive strength and permeability

The findings presented in **Table 2** and **Fig. 3** show that the specimens made from S3, with an aggregate-to-cement ratio of 3:1, had greater compressive strengths at 7 and 28 days than the specimens made from S2 or S1, with aggregate-to-cement ratios of 4:1 and 5:1, respectively. The better packing of aggregates in S3 explains why its specimens had greater compressive strength.[27]

Mixture S1 had the highest average permeability coefficient

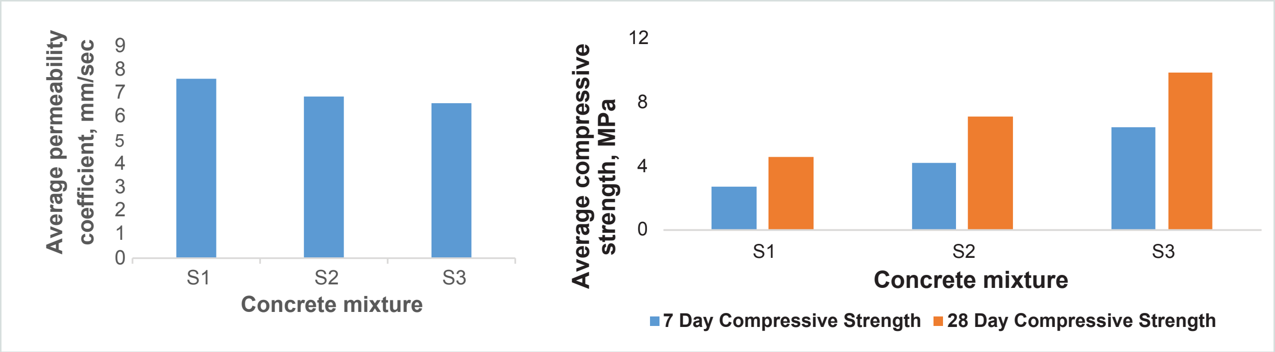

Figure 3. Comparison of compressive strength and permeability coefficient for concrete mixtures S1, S2, and S3.
Note: 1 mm/sec = 0.0384 in./sec; 1 MPa = 0.145 ksi.

Table 2. Test results for mixtures S1, S2, and S3

Mixture designation	Average density, kg/m³	Average 7-day compressive strength, MPa	Average 28-day compressive strength, MPa	Average permeability coefficient, mm/sec	Average porosity, %	Average flexural strength, MPa	Average split tensile strength, MPa
S1	2185	2.76	4.63	7.66	27.218	0.6	0.5
S2	2183	4.23	7.1	6.88	26.281	0.823	0.737
S3	2179	6.44	9.87	6.62	25.58	0.962	1.212

Note: 1 mm = 0.0384 in.; 1 mm/sec = 0.0384 in./sec; 1 kg/m³ = 1.6875 lb/yd³; 1 MPa = 0.145 ksi.

of 7.66 mm/sec (0.3 in./sec) (Table 2). An increased volume of coarse aggregate within the concrete matrix generates larger interstitial voids, which in turn facilitate greater water flow and increase permeability. Mixture S1 exhibited the most extensive unfilled pore space, and consequently, it had the highest permeability of the three mixtures evaluated in the first phase. Conversely, S3 had the lowest average permeability coefficient of 6.62 mm/sec (0.26 in./sec), as the greater density of the matrix impeded water infiltration.[28]

Effect of aggregate-to-cement ratio on flexural strength, split tensile strength, and porosity

The findings in Table 2 and **Fig. 4** show that flexural and split tensile strengths were greater in the specimens made from concrete mixtures with higher cement content. Specimens made with mixture S3 had the highest flexural strength (0.962 MPa [0.14 ksi]) and the highest split tensile strength (0.121 MPa [0.018 ksi]) due to the concrete's dense, well-bonded matrix. The average flexural and tensile strengths for the specimens made with mixture S2 were 0.832 and 0.737 MPa (0.12 and 0.107 ksi), respectively; these moderate values reflect the balanced composition of this mixture. The specimens made with mixture S1 had the lowest strengths of 0.6 MPa (0.087 ksi) for flexural and 0.5 MPa (0.073 ksi) for tensile, which was due to the mixture's more-porous, less-cohesive matrix.

Mixture S1 had the highest average porosity of 27.218%, while mixture S2 had 26.281% and S3 had 25.58%. Because mixture S1 had a greater proportion of aggregates than S2 and S3, it had more voids and a lower overall material density.

For all three mixtures (S1, S2, and S3), compressive strength values were significantly higher than flexural strength values, which is typical of concrete behavior. While compressive strength reflects load-bearing capacity under compression, flexural strength is more sensitive to matrix integrity and crack resistance.

Effect of aggregate sizes on compressive strength and permeability

Aggregates play an important role in influencing concrete's mechanical properties, and research shows that aggregate size significantly affects the strength of permeable concrete. Generally, as the aggregate size increases, the strength also increases.[29]

The second series of specimens investigated mixtures S4, S5, and S6, in which the proportions of small (4.75 mm [0.187 in.]), medium (9.5 mm [0.374 in.]), and large (12.5 mm [0.492 in.]) aggregates were varied while a 3:1 aggregate-to-cement ratio was maintained (Table 1). Specimens made from mixture S5 achieved the highest average 28-day compressive strength (13.71 MPa [1.99 ksi]) (**Table 3** and **Fig. 5**). This finding can be attributed to mixture S5's well-graded and optimally proportioned aggregate blend. In contrast, the average 28-day compressive strengths of specimens made from mixtures S4 and S6 were 11.83 and 12.65 MPa (1.72 and 1.83 ksi), respectively; it seems that the more heterogeneous distributions of aggregates reduced particle bonding and matrix integrity.

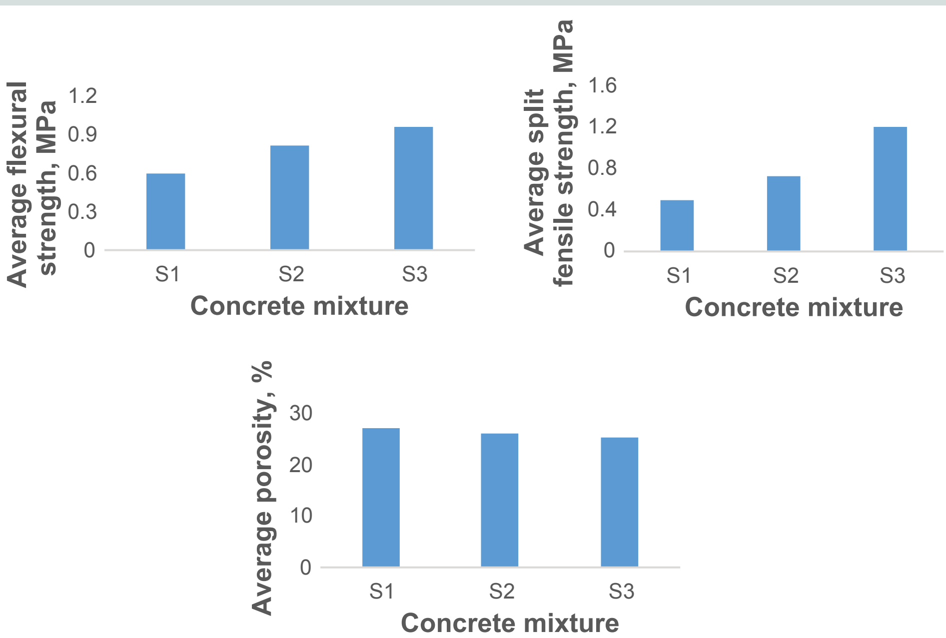

Figure 4. Comparison of flexural strength, split tensile strength, and porosity for concrete mixtures S1, S2, and S3. Note: 1 MPa = 0.145 ksi.

Table 3. Test results for mixtures S4, S5, and S6

Mixture designation	Average density, kg/m³	Average 7-day compressive strength, MPa	Average 28-day compressive strength, MPa	Average permeability coefficient, mm/sec	Average porosity, %	Average flexural strength, MPa	Average split tensile strength, MPa
S4	2203.66	7.81	11.813	5.56	24.163	1.198	1.368
S5	2206.33	9.31	13.71	5.38	21.863	1.406	1.577
S6	2195.33	8.47	12.651	5.18	24.271	1.28	1.395

Note: 1 mm/sec = 0.0384 in./sec; 1 kg/m³ = 1.6875 lb/yd³; 1 MPa = 0.145 ksi.

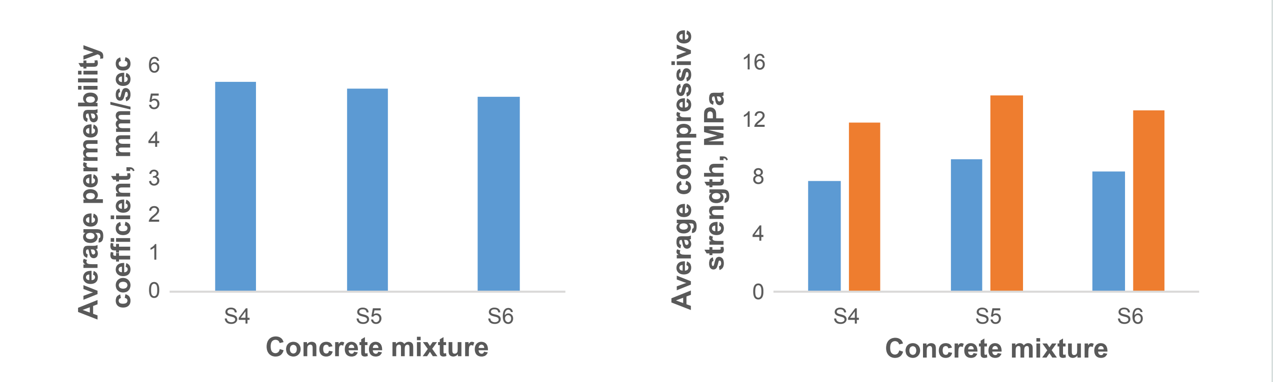

Figure 5. Comparison of compressive strength and permeability coefficient for concrete mixtures S4, S5, and S6. Note: 1 mm/sec = 0.0384 in./sec; 1 MPa = 0.145 ksi.

Mixtures S4, S5, and S6 all demonstrated permeability values within the acceptable range for porous concrete applications. S4 had the highest permeability coefficient (5.56 mm/sec [0.22 in./sec]). The permeability coefficient of S5 was slightly lower (5.38 mm/sec [0.21 in./sec]). This concrete mixture provided both strength and water permeability. S6 also met permeability criteria, supporting its application in structures that need controlled water flow and strength.[30] The findings from this phase of the investigation highlight the importance of optimized aggregate distribution in achieving a concrete mixture that delivers both high compressive strength and effective permeability for sustainable infrastructure and urban drainage solutions.[31]

Effect of aggregate sizes on flexural strength, split tensile strength, and porosity

Specimens made with mixture S5 achieved the highest average flexural and split tensile strengths. The optimal proportions of smaller aggregates in S5 enhanced interlocking and matrix compactness (Table 3 and **Fig. 6**). In contrast, the average flexural and split tensile strengths of S4 and S6 were slightly lower, reflecting less-effective aggregate packing in these mixtures.

Specimens made with S5 also had the lowest porosity (21.83%), indicating a denser structure with fewer internal voids. The maximum average 28-day compressive strengths for specimens in this second series of mixtures (S4, S5, and S6) of the study were significantly higher than their respective maximum flexural strengths. This finding reflects the typical behavior of concrete, where compressive capacity greatly exceeds its resistance to bending stresses. The comparison underscores the importance of mixture optimization for structural durability, especially in applications subjected to tension or flexure.

Effects of silica fume and high-range water-reducing admixture on compressive strength and permeability

Mixtures S7 through S15 were developed from the S5 mixture proportions, which were determined to be the optimal choice from the second specimen series of the study. These nine mixtures incorporated varying proportions of silica fume (2.5% to 10%) and HRWRA (0.5% to 1.5%), which supported assessing the influence of these admixtures on compressive strength and permeability (**Table 4** and **Fig. 7**).

The results of the third series of specimens confirm that silica fume positively affects compressive strength, primarily through enhanced pozzolanic activity and microstructural densification. Moderate dosages of HRWRA 1% improved cement particle dispersion and reduced water demand, further contributing to strength gains, as observed in specimens

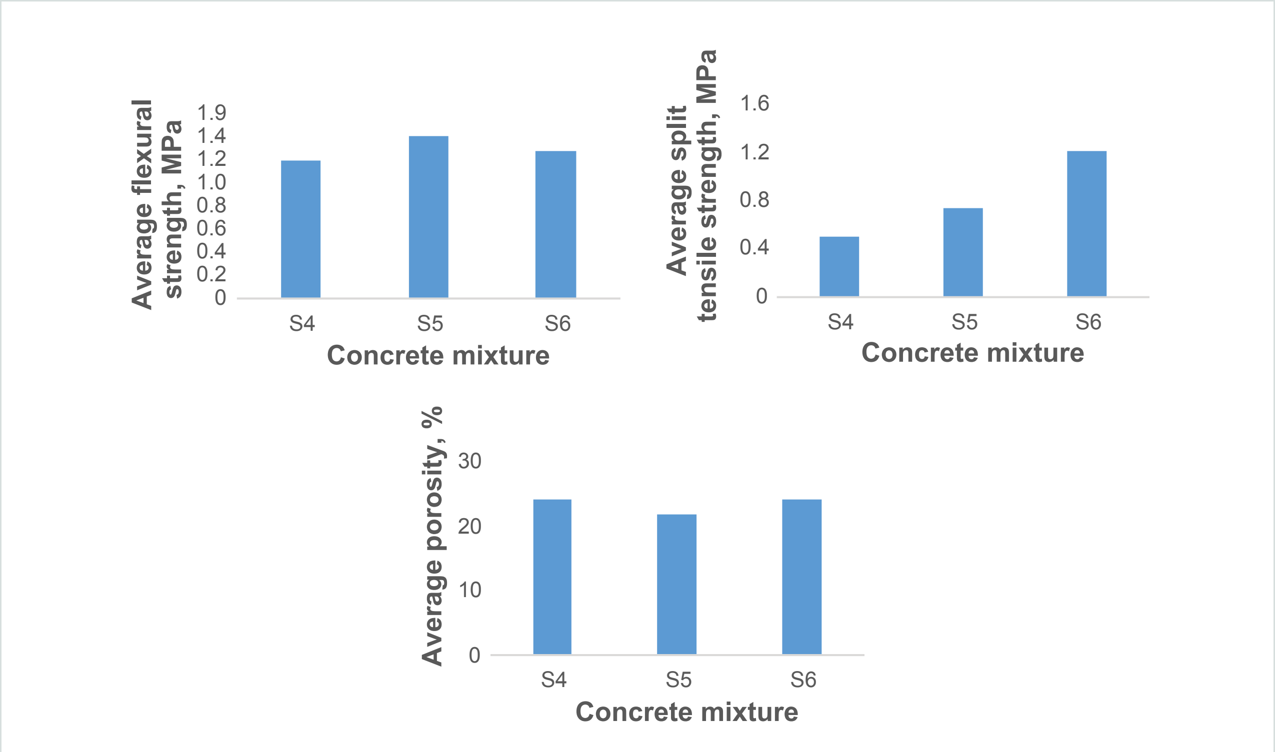

Figure 6. Comparison of flexural strength, split tensile strength, and porosity for concrete mixtures S4, S5, and S6.
Note: 1 MPa = 0.145 ksi.

Table 4. Test results for mixtures S7–S15

Mixture designation	Average density, kg/m³	Average 7-day compressive strength, MPa	Average 28-day compressive strength, MPa	Average permeability coefficient, mm/sec	Average porosity, %	Average flexural strength, MPa	Average split tensile strength, MPa
S7	2045.16	10.28	15.588	4.14	19.211	1.608	2.476
S8	2056.33	11.09	16.938	4.7	19.328	1.618	3.018
S9	2048.83	10.88	16.741	4.77	19.69	1.383	2.741
S10	2074	10.76	16.598	3.12	18.551	1.713	2.756
S11	2121	12.07	18.48	3.41	18.415	1.713	3.701
S12	2104.16	11.16	17.175	3.91	17.596	1.653	2.795
S13	2111.83	10.38	15.798	2.94	17.56	1.498	2.308
S14	2116.67	11.10	16.828	3.12	17.48	1.7	2.788
S15	2120	10.642	16.125	3.19	17.15	1.611	2.38

Note: 1 mm/sec = 0.0384 in./sec; 1 kg/m³ = 1.6875 lb/yd³; 1 MPa = 0.145 ksi.

made with mixtures S8 or S9. The optimal performance was achieved with mixture S11, which contained 5% silica fume and 1% HRWRA. Specimens made from mixture S11 had the highest average 28-day compressive strength. This finding can be attributed to the synergistic effect of the silica fume and HRWRA, which improves particle packing, reduces porosity, and enhances workability without compromising strength.

Increasing the HRWRA dosage beyond optimal levels, however, as was tested in S10, S13, S14, and S15, did not yield proportional strength improvements and reduced performance, indicating diminishing returns. Similarly, compared with the mixtures

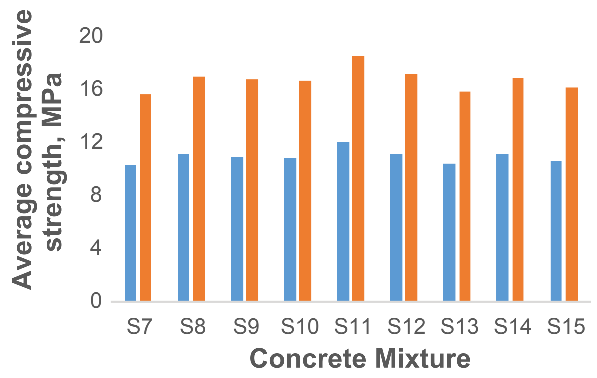

Figure 7. Comparison of compressive strength for concrete mixtures S7, S8, S9, S10, S11, S12, S13, S14, and S15. Note: 1 MPa = 0.145 ksi.

with 5% silica fume, the mixtures with 10% silica fume had lower compressive strengths, a finding that highlights the importance of dosage optimization. As silica fume and HRWRA dosages increased in mixtures S7 through S11, permeability decreased (**Fig. 8**). The permeability coefficient of S11 was 3.33mm/sec (0.13 in./sec), which is well within the acceptable range for pervious concrete. Of the three mixtures with 10% silica fume, S13 and S14 also remained within acceptable permeability limits for pervious concrete; however, S15 exceeded the permissible threshold, suggesting that excessive admixture content may disrupt matrix integrity. Overall, the study demonstrates that the combined use of silica fume and HRWRA can significantly enhance the strength and permeability performance of concrete when applied in controlled proportions.

The addition of silica fume to the concrete reduced the porosity between the cement paste and the aggregates, resulting in a denser microstructure and a stronger bond in the interface region.[32] Silica fume, known for its high pozzolanic activity and extremely fine particles, contributes significantly to producing concrete with low permeability. Because permeability plays a key role in determining how well a structure can resist the penetration of harmful substances, it is considered a vital factor in durability evaluation.[33]

Effect on flexural strength, split tensile strength, and porosity by incorporation of mineral and chemical admixture

Table 4 and **Fig. 9** illustrate trends in flexural strength, split tensile strength, and porosity for mixtures S7 through S15. Flexural strength values for S7, S8, and S9 ranged from 1.38 to 1.60 MPa (0.20 to 0.23 ksi), generally increasing strength alongside silica fume content. However, excessive silica fume combined with insufficient HRWRA reduced workability, negatively affecting strength. Of the mixtures evaluated in the third series of test specimens, S11 achieved the highest flexural strength because its balanced proportions of silica fume and HRWRA promoted optimal particle bonding and workability.

Split tensile strength followed a similar pattern. S8 and S11 exhibited the highest values, 3.08 and 3.701 MPa (0.45 and 0.54 ksi), respectively. This finding highlights the importance

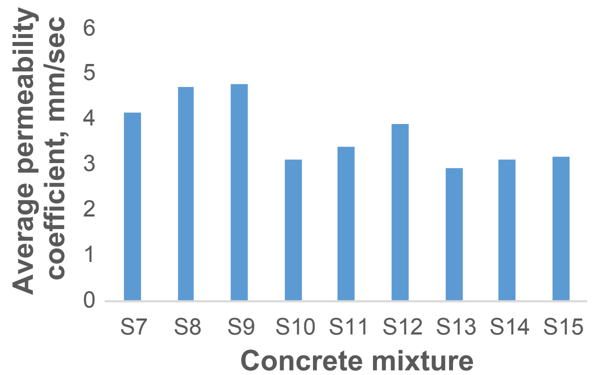

Figure 8. Comparison of permeability coefficient for concrete mixtures S7, S8, S9, S10, S11, S12, S13, S14, and S15. Note: 1 mm/sec = 0.0384 in./sec.

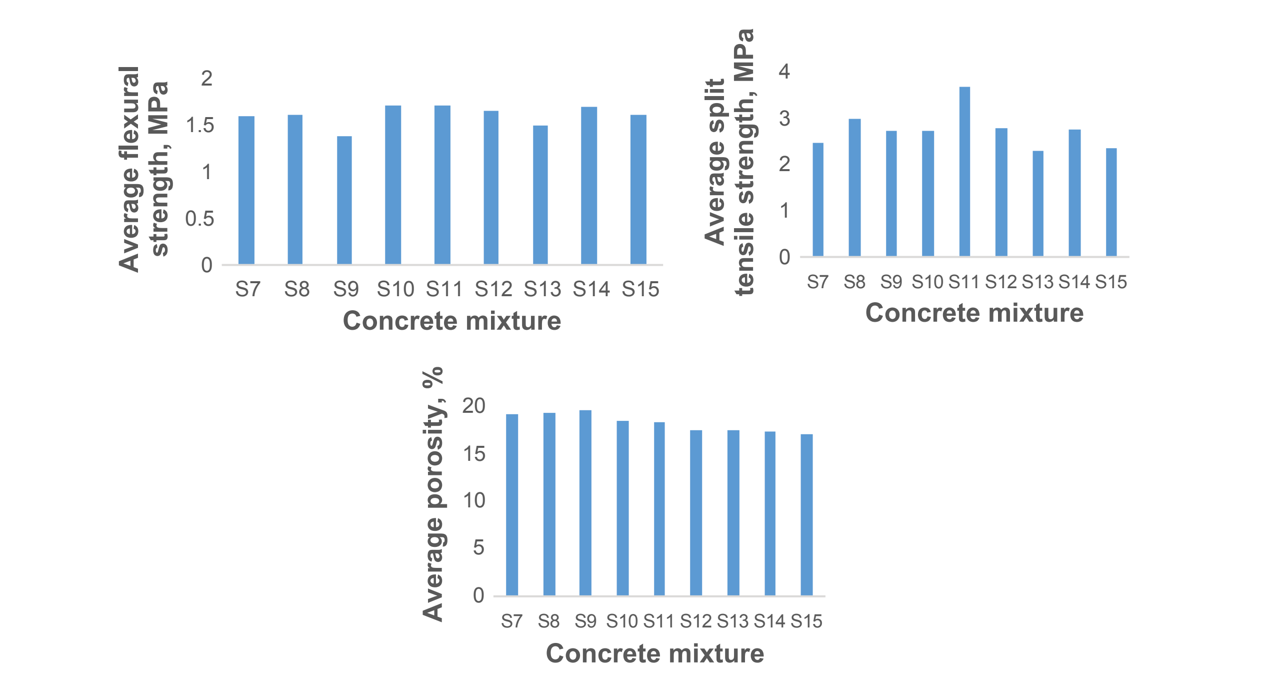

Figure 9. Comparison of flexural strength, split tensile strength, and porosity for concrete mixtures S7, S8, S9, S10, S11, S12, S13, S14, and S15. Note: 1 MPa = 0.145 ksi.

of optimal mixture composition and effective particle dispersion. S13, S14, and S15 (mixtures with 10% silica fume) had relatively lower tensile strengths than the other mixtures evaluated in this phase. The variation was attributed to differences in aggregate proportions and mixture homogeneity.

Overall, the results emphasize the importance of optimized admixture dosage for enhancing tensile performance. Porosity measurements for all mixtures in this phase were relatively consistent, with minor reductions observed in S10, S11, and S12 (5% silica fume) and further decreases in S13, S14, and S15. The latter three mixtures had the lowest porosity levels, reflecting improved particle packing and reduced voids due to higher silica fume content. These findings reinforce the significance of designing mixtures to control pore structure and permeability. Because they are very fine, silica fume particles help fill the voids within the concrete mixture, increasing bulk density, a phenomenon known as the microfiller effect.[34]

Conclusion

Permeable concrete represents an innovative development in the world of construction, defined by its aptitude for facilitating the passage of water through its structure. The objective of this study is to advance the understanding of optimal mixture proportions for sustainable permeable concrete.

The research findings support the following conclusions:

- The aggregate-to-cement ratio plays a crucial role in influencing both the compressive strength and permeability of concrete. Increasing cement content reduced permeability and increased compressive strength.

- The incorporation of 9.5 mm (0.375 in.) aggregates resulted in higher compressive strength compared with the use of 12.5 and 4.75 mm (0.492 and 0.187 in.) aggregates. This improvement is attributed to better interlocking and reduced void content associated with the 9.5 mm aggregates.

- Adding silica fume together with HRWRA, up to an optimum level (10% silica fume and 1% HRWRA by weight of cement), led to a rise in compressive strength and a decrease in permeability. The reduced permeability is attributed to the development of a more-compact and finer matrix resulting from the inclusion of silica fume and HRWRA.

- Among the mixtures evaluated in the third series of study specimens (S7 through S15), S11 yielded compressive strength that increased to 34.8% and permeability that decreased by 57.77%. Flexural strength increased by 21.83%, and split tensile strength increased by 134.68%. The addition of silica fume led to the refinement of pore sizes inside the porous concrete, thereby yielding an increase in compressive strength, and incorporating HRWRA resulted in an enhanced level of workability for the concrete.

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Notation

A = specimen surface area

H = water head height

K = water permeability coefficient

L = specimen length

Q = volume of flow

T = time the measurement

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Abstract

The use of permeable concrete represents a significant development in sustainable urban infrastructure. The primary characteristic of this material is its porous structure, which is attained by precisely combining coarse aggregates, cement, and water. Implementing permeable surfaces within urban environments enables the adoption of sustainable methods for water management aimed at mitigating the risks associated with flooding. This study investigated permeable concrete mixtures to determine the optimum aggregate-to-cement ratio, evaluate the effects associated with variations in aggregate sizes, and consider the impact of a high-range water-reducing admixture and silica fume on concrete strength, permeability, and porosity. Fifteen concrete mixtures were designed, cast, and tested to analyze compressive strength and permeability characteristics. The results are displayed graphically and discussed in detail with a focus on optimal concrete mixture to achieve maximum strength while remaining within acceptable limits for permeability. The study demonstrates that future permeable concrete can achieve remarkable strength and permeability characteristics.

Keywords

Compressive strength, mechanical performance, permeability, permeable concrete, optimum aggregate-to-cement ratio, sustainability.

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