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Optimizing Mechanical and Hydraulic Properties of Silica Fume-Modified Pervious Concrete for Urban Flood Management in Northern Peru

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ABSTRACT

This study evaluates the mechanical and hydraulic performance of pervious concrete incorporating silica fume as a partial cement replacement for application in high-intensity rainfall regions. Four mixtures containing 0%, 9%, 10%, and 11% silica fume by cement weight were produced with a water–cement ratio (w/c) of 0.40 and a target void content of 20%, in accordance with American Concrete Institute (ACI) 522R-10 recommendations. Compressive strength, permeability, rainfall simulation, and microstructural analyses were performed to determine the optimal replacement level. At 28 days, the mixture with 10% silica fume achieved the highest compressive strength (238.60 kg/cm²), exceeding the specified design strength (210 kg/cm²). One-way analysis of variance (F = 4.75; p = 0.0347) confirmed statistically significant differences among mixtures. Microstructural analysis showed a reduction in the Ca/Si ratio to 1.47 for the 10% mixture, indicating enhanced pozzolanic reaction and improved matrix densification. Permeability values ranged from 0.510 to 0.518 cm/s across all mixtures, satisfying ACI 522R-10 criteria (≥ 0.3 cm/s). Rainfall simulation at 105 mm/h demonstrated infiltration exceeding 90% of applied water, confirming effective pore connectivity. Results indicate that 10% silica fume provides an optimal balance between strength and hydraulic performance for sustainable urban drainage applications.

1. INTRODUCTION

Concrete remains one of the most widely utilized materials in modern construction due to the sustained global demand for buildings and infrastructure systems. To ensure long-term performance, concrete structures must exhibit high durability and resistance to adverse environmental conditions, including elevated temperatures, high humidity levels, and intense rainfall events [1]. Among the available stormwater management strategies, pervious concrete pavements have gained significant attention because they reduce surface runoff, promote effective water infiltration, and contribute to mitigating urban flooding in densely developed areas [2].

Pervious concrete is a near-zero-slump, open-graded composite material composed of Portland cement, coarse aggregate, minimal or no fine aggregate, water, and chemical admixtures. This specific composition generates a continuous network of interconnected voids, typically ranging from 15% to 35%, which facilitates rapid rainwater percolation into the underlying soil layers, as described in American Concrete Institute (ACI) 522R [3]. Despite its hydraulic advantages, enhancing mechanical strength without substantially compromising permeability remains a major technical challenge in mixture design optimization.

This study postulates that incorporating silica fume at cement replacement levels between 9% and 11% promotes matrix densification and strengthens the paste–aggregate interfacial transition zone (ITZ) while preserving pore connectivity. The research responds to the urgent need for sustainable drainage solutions in northern Peru, where recurrent extreme rainfall events associated with the El Niño phenomenon frequently exceed the capacity of conventional drainage systems [4]. Accordingly, the objective is to evaluate the influence of silica fume incorporation on the mechanical and hydraulic performance of pervious concrete intended for urban applications exposed to high-intensity precipitation.

1.1 Mechanical improvements

Silica fume (microsilica) is a highly reactive pozzolanic by-product generated during the production of silicon and ferrosilicon alloys. It has been incorporated into both conventional and pervious concrete systems to enhance mechanical performance and improve cement matrix densification [5]. Previous research on pervious concrete has primarily focused on mixture design parameters, including the type and proportion of cementitious materials, aggregate characteristics, chemical admixtures, and compaction methods. These parameters significantly influence compressive strength, permeability, and total porosity [6].

Recent investigations have reported substantial mechanical improvements associated with mineral additions. Torres-Ortega et al. [7] achieved compressive strengths of up to 71 MPa through the combined use of silica fume and polypropylene fibers. Caballero Arredondo et al. [8] documented a 72% increase in compressive strength following nanosilica incorporation. In Peru, Saba et al. [9] reported a 25% improvement in compressive strength, while Giménez et al. [10] obtained values reaching 401.91 kg/cm² in mixtures modified with silica fume.

Similarly, Wang et al. [11] observed compressive strength increases exceeding 30% when partially replacing cement with fly ash. Anjos Viana et al. [12] reported satisfactory mechanical performance in pervious concrete mixtures prepared with water–cement ratios of 0.34 and porosity levels ranging between 22% and 35%, demonstrating that optimized mixture design can preserve both strength and hydraulic functionality.

1.2 Hydraulic behavior

Permeability constitutes the primary functional parameter of pervious concrete, as it governs its capacity to infiltrate water and effectively reduce surface runoff [13]. For optimal hydraulic performance, effective porosity is typically maintained between 15% and 25%, ensuring adequate water flow while preserving structural stability and load-bearing capacity. Previous studies have also reported that incorporating reinforcing additives in proportions between 1% and 3% enhances compressive strength and crack resistance, thereby contributing to improved mechanical integrity without severely compromising hydraulic conductivity [14].

Appropriate aggregate gradation and controlled cementitious paste content are essential to achieve a balanced relationship between hydraulic conductivity and mechanical resistance. Permeable pavements are intentionally designed with interconnected void structures or joint spaces that facilitate the downward movement of surface water into the underlying drainage layers [15]. Maintaining this balance is particularly critical in semi-arid regions such as Piura, where high-intensity rainfall events frequently cause soil saturation, structural overstressing, and premature pavement deterioration.

Therefore, this study aims to determine an optimal silica fume replacement level capable of preserving permeability while simultaneously improving compressive strength and load-bearing capacity, thus ensuring both structural reliability and hydraulic efficiency in urban pavements exposed to extreme rainfall conditions.

1.3 Pozzolanic effects

Silica fume is a highly reactive pozzolanic material that promotes the formation of additional calcium silicate hydrate (C–S–H) during cement hydration. This secondary pozzolanic reaction refines the pore structure, densifies the cement matrix, and enhances durability performance [16]. Its incorporation has been shown to significantly increase compressive strength compared with conventional reference mixtures due to its combined filler effect and pozzolanic reactivity.

Replacement levels between 9% and 11% have been reported to achieve uniform matrix densification without obstructing the interconnected macropores necessary for drainage functionality. Preserving pore structure is critical because mesoporosity contributes to strength development, whereas excessive macroporosity reduces compressive resistance and structural cohesion [17].

As an industrial by-product, silica fume also supports sustainability objectives by reducing cement consumption and associated CO$_2$ emissions during production [18]. However, in mixtures with low water–cement ratios, excessive replacement levels may increase autogenous shrinkage if not properly controlled through mixture proportioning. To preserve hydraulic performance, pervious concrete is proportioned primarily with single-sized coarse aggregates and minimal or no fine aggregates, since total porosity directly governs hydraulic conductivity and pavement functionality [19].

Consequently, silica fume-modified pervious concrete represents a technically viable and environmentally sustainable alternative for urban pavements exposed to high-intensity rainfall conditions.

2. METHODOLOGY

This research is classified as applied research because it addresses a specific engineering problem: improving stormwater drainage performance in Piura, a region frequently affected by high-intensity rainfall events, through the development of pervious concrete incorporating silica fume. The study follows a quantitative and experimental approach in which the independent variable (silica fume replacement level) was systematically controlled to evaluate its influence on the dependent variables, namely the mechanical and hydraulic properties of the material.

The experimental design was fully factorial and aimed at establishing causal relationships between silica fume replacement level and concrete performance. Four mixtures were produced with replacement levels of 0%, 9%, 10%, and 11% by weight of cement. The selected range was based on previous studies [3, 5, 6] and preliminary exploratory trials. Replacement levels below 9% did not produce significant matrix densification, whereas levels above 11% reduced workability and increased the risk of partial pore obstruction. Therefore, the 9–11% interval was selected to determine the optimal balance between mechanical resistance and hydraulic functionality while preserving pore connectivity.

The primary tests included compressive strength, permeability coefficient, and rainfall simulation, conducted in accordance with Norma Técnica Peruana (NTP) 339.034 and ACI 522R-10. The complete experimental procedure is presented in Figure 1.

Rainfall data were obtained from SENAMHI (Sondorillo Station) for the period 2006–2015. The records indicate an average daily maximum rainfall of 105.41 mm and an extreme value of 182.20 mm in 2009, supporting the technical need for high-infiltration pavement systems capable of accommodating extreme precipitation events.

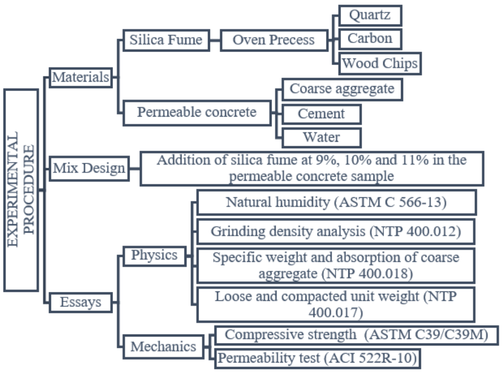


Figure 1. General investigation procedure
Note: Own elaboration.

Table 1. Summary of tests and standards applied

Practice	Technical Standard	Samples	Purpose
Granulometry	NTP 400.012	3	Determine size distribution
Specific gravity and absorption	NTP 400.018	3	Check density and absorption
Loose and compacted unit weight	NTP 400.017	3	Determine bulk density
Compressive strength	ASTM C39/NTP 339.034	36	Evaluate mechanical capacity
Permeability (variable load)	ACI 522R-10 / INEN 2544	12	Determine the K coefficient
Rain simulation	Experimental design	3	Evaluate surface drainage

Note: NTP = Norma Técnica Peruana (Peruvian Technical Standard); ASTM = ASTM International (formerly American Society for Testing and Materials); ACI = American Concrete Institute; INEN = Instituto Ecuatoriano de Normalización (Ecuadorian Standardization Institute).

A total of 36 cylindrical specimens (150 mm × 300 mm) were produced and distributed into four groups according to the silica fume replacement level. Each mixture included nine specimens, with three specimens tested at each curing age (7, 14, and 28 days), ensuring statistical consistency across curing intervals. The materials used in the mixtures were Type I Portland cement, grade microsilica (silica fume), and single-sized coarse aggregate with a nominal maximum size of 1 in. The mixture proportions were maintained constant except for the silica fume replacement percentage in order to isolate its specific effect on performance parameters. The applicable technical standards and testing procedures are summarized in Table 1.

2.1 Physical and mechanical properties of aggregates

The tests performed on the coarse aggregates were conducted to verify compliance with the technical requirements for use in pervious concrete production. The evaluated properties included gradation, particle morphology, mechanical resistance, water absorption, cleanliness, and durability, since these parameters directly influence both hydraulic conductivity and mechanical performance of the mixture. The results obtained were as follows:

- Natural moisture (ASTM C 566-13): 0.46%.
- Particle size analysis (NTP 400.012): Suitable distribution for pervious concrete without fines.
- Specific gravity and absorption (NTP 400.018): 2.68 g/cm³.
- Loose and compacted unit weight (NTP 400.017): 1350 kg/m³ and 1477 kg/m³, respectively.

2.2 Compressive strength of silica fume permeable concrete

Compressive strength and permeability tests were conducted in accordance with ASTM C39/C39M and ACI 522R-10. A total of 36 cylindrical specimens (150 mm × 300 mm) were prepared using a water–cement ratio of 0.40 and a target void content of 20%. This void ratio was selected based on ACI 522R-10 and relevant technical literature, which recommends a range between 15% and 25% to ensure an appropriate balance between hydraulic conductivity and mechanical resistance.

- **Experimental verification of voids:** The saturated surface-dry (SSD) gravimetric method was applied. Specimens were oven-dried to obtain the dry mass (M_{dry}), then immersed in water for 24 h to obtain the saturated mass (M_{ssd}). The void ratio (n) was calculated using: $n = (M_{ssd} - M_{dry}) / (\rho w \cdot V)$, where ρ_w is the density of water and V is the specimen volume. For the tested cylinders ($V = 0.00530144\ m^3$), $M_{ssd} - M_{dry} \approx 1.0603$ kg, resulting in $n \approx 20\%$. Complementary permeability ($K \approx 0.51$ cm/s) and rainfall simulation tests (infiltration > 90%) confirmed adequate pore interconnectivity and hydraulic functionality.
- **Slump test:** Performed in accordance with ASTM C143/NTP 339.035. The measured slump was 0 mm, which is consistent with the absence of fine aggregates and the open-graded, porous structure typical of pervious concrete.
- **Justification of silica fume percentages:** The selected replacement percentages were supported by previous studies and applicable technical standards [20], which indicate that the optimal incorporation range of silica fume lies between 9% and 11% of the cement weight. Accordingly, 10% was selected as the central dosage (theoretical optimum), while 9% and 11% were incorporated as adjacent variations to evaluate the sensitivity of mechanical and hydraulic performance to minor fluctuations in silica fume content. This structured approach enabled a comparative assessment of the influence of each replacement level on compressive strength development and permeability behavior.

2.3 Permeability of permeable concrete with the addition of silica fume

A variable load permeameter (ACI 522R-10) was used, with cylindrical specimens (Ø15 × 30 cm).

Pressure-controlled system: The experimental setup consisted of a pressure-controlled hydraulic system including a 50 L water tank, an adjustable water column up to 0.50 m, a flow-control valve, and a pressure gauge graduated in cm H_2O. A constant hydraulic head of 10 cm H_2O was maintained, equivalent to approximately 0.981 kPa, with a measured variation of ± 0.010 kPa (less than 1%), ensuring stability during testing. Monitoring readings confirmed consistent pressure control throughout the permeability measurements.

The volume of water (Q) was measured, and $K = (Q \cdot L)/(A \cdot h \cdot t)$. Values obtained: 0.48–0.52 cm/s, confirming adequate hydraulic load and laminar flow.

As shown in Table 2, variations in hydraulic pressure remained below 1% for all mixtures, indicating stable testing conditions and consistent permeability measurements. The negligible differences observed between initial and final hydraulic loads suggest that the calculated coefficients accurately reflect the intrinsic pore connectivity of the concrete rather than experimental fluctuations. The measured permeability values (0.48–0.52 cm/s) fall within the range typically reported for pervious concrete under similar void contents. These results demonstrate that the incorporation of silica fume did not significantly alter or obstruct the interconnected macroporous network responsible for water infiltration. Although silica fume refines the cementitious matrix at the microstructural scale through pozzolanic reactions and filler effects, it does not adversely compromise hydraulic conductivity at the macrostructural level.

Overall, the findings indicate that silica fume can be incorporated at replacement levels up to 11% without negatively affecting the balance between mechanical performance and hydraulic functionality. This confirms the material's technical suitability for stormwater management applications in semi-arid regions such as Piura, where maintaining infiltration capacity under extreme rainfall conditions is essential.

Table 2. Hydraulic pressure testing on silica fume permeable concrete

Mixture	Initial Load (cm H_2O)	Final Load (cm H_2O)	Equivalent Pressure (kPa)	Observation
0% silica fume	10	9.9	0.981 → 0.972	Stable flow
9% silica fume	10.1	10	0.990 → 0.981	No losses
10% silica fume	**9.9**	**9.8**	**0.972 → 0.963**	**Constant flow**
11% silica fume	10	10.1	0.981 → 0.990	Total stability

Note: Own elaboration.

2.4 Optimal mixing design

A 10% silica fume replacement level was adopted as the reference mixture, based on the previously established experimental framework. The materials used were Type I Portland cement, silica fume, single-sized coarse aggregate, and potable drinking water. No fine aggregate was incorporated to preserve the interconnected void structure required for pervious concrete performance.

The mixing and specimen preparation process was carried out as follows:

- Selection and preparation of materials: Aggregates were conditioned before mixing, and the mixing water content was adjusted according to the measured moisture to maintain the designed effective water–cement ratio.
- Determination of proportions: A water–cement ratio (w/c) of 0.40 and a target void content of 20% were established to ensure an appropriate balance between mechanical resistance and hydraulic conductivity.
- Mixing sequence: Cement and silica fume were first dry-mixed to guarantee homogeneous dispersion of the pozzolanic material. The coarse aggregate was subsequently incorporated, followed by the gradual addition of water to promote uniform paste coating around aggregate particles.
- Visual verification of fresh state: The mixture was visually inspected to confirm the absence of segregation and to verify the presence of clearly visible interconnected voids, characteristic of pervious concrete.
- Molding: Cylindrical specimens (Ø 15 cm × 30 cm) were cast using light manual compaction applied in layers to avoid excessive densification that could reduce the designed porosity.
- Curing: Specimens were cured in water at controlled temperature conditions for 7, 14, and 28 days before mechanical and hydraulic testing.

2.5 Concrete permeable to rain simulation

The infiltration behavior of the pervious concrete under heavy rainfall conditions (~105 mm/h, representative of events associated with the El Niño phenomenon) was experimentally evaluated.

- Test specimens: Rectangular concrete blocks cured for 28 days were used to simulate surface pavement conditions.
- Simulation system: The experimental setup consisted of an elevated water tank connected to a supply pipe and a spray distribution device equipped with a pressure gauge. The tank height and pipe diameter were selected to ensure sufficient and stable hydraulic pressure throughout the test.
- Execution: A constant flow was applied uniformly over the surface of each block. Hydraulic pressure was continuously monitored and adjusted to maintain steady rainfall intensity during the test period.
- Repetition protocol: At least three blocks per mixture were tested. Each trial was documented through photographic records and detailed visual observations of infiltration performance.

Table 3. Tests carried out and reference standards

Practice	Standard/Reference	Samples	Remarks
Added properties	NTP 400.012 / 400.018 / 400.017	Representative	Gs = 2.68; Loose = 1350 kg/m^3; Compact = 1477 kg/m^3
Slump	ASTM C143/NTP 339.035	1 per mix	Settlement = 0"
Compressive strength	ASTM C39/NTP 339.034	9 specimens per mixture	Ø15 × 30 cm; a/c = 0.40; Empty ≈ 20%
Permeability	ACI 522R-10 (adapted)	3 cores per mix	K ≈ 0.48–0.52 cm/s
Rain simulation	Own procedure	≥ 3 blocks per mix	Intensity ≈ 105 mm/h; Infiltration >90%

Note: NTP = Norma Técnica Peruana (Peruvian Technical Standard); ASTM = ASTM International (formerly American Society for Testing and Materials); ACI = American Concrete Institute; INEN = Instituto Ecuatoriano de Normalización (Ecuadorian Standardization Institute).

Infiltration efficiency exceeded 90%, with no evidence of surface waterlogging. These findings confirm adequate pore interconnectivity and validate the suitability of the mixture design for urban stormwater drainage applications under high-intensity rainfall conditions. As shown in Table 3, the rain simulation tests were conducted under controlled laboratory conditions designed to replicate heavy rainfall events (~105 mm/h), representative of episodes associated with the El Niño phenomenon. All mixtures achieved infiltration rates exceeding 90%, with no evidence of surface water accumulation during testing, thereby confirming effective pore interconnectivity and adequate hydraulic functionality. The absence of surface waterlogging under simulated extreme rainfall conditions demonstrates that the mixture design preserves a stable and continuous macro-void structure, even with the incorporation of silica fume at the evaluated replacement levels. These findings are consistent with the permeability coefficients previously reported and reinforce the reliability of the hydraulic performance results.

Overall, the rain simulation outcomes support the conclusion that silica fume can be incorporated into pervious concrete mixtures without compromising drainage performance. The results confirm the structural and hydraulic suitability of the proposed mixtures for urban stormwater management applications subjected to high-intensity precipitation scenarios.

3. RESULTS

3.1 Determine the physical and mechanical properties of stone aggregates

The tests carried out on the coarse aggregates yielded results that complied with the technical requirements established for pervious concrete production. These properties were verified to ensure adequate mechanical performance and hydraulic stability within the designed mixture.

The concrete mixture was designed according to the following structural and performance requirements:

- Cement: Pacasmayo Type I
- Slump: 0 in
- Specified compressive strength (f’c): 210 kg/cm²
- Dosage Design Parameters
- The mixture design was defined considering the following parameters:
- Design safety factor: 84 kg/cm²
- Required average compressive strength (f’cr): 294 kg/cm²
- Water–cement ratio (w/c): 0.40

The relationship between f’c and f’cr follows conventional mixture design principles, ensuring that the average compressive strength exceeds the specified strength to account for variability and quality control considerations. The selected water–cement ratio (w/c = 0.40) was established to maintain sufficient paste cohesion while preserving the target void content required for hydraulic functionality.

Table 4. Properties of coarse aggregate – Cantera Virgen de la Cocharcas – Avendaño

Property	**Value**	**Unit**
Maximum nominal size	1"	Inch
Dry and loose unit weight	1350	kg/m³
Dry and compacted unit weight	1477	kg/m³
Specific gravity of solids	2.68	-
Natural moisture content (w%)	0.46	%
Absorption percentage	1.31	%

Note: Own elaboration based on field data of the coarse aggregate collected in the Virgen de la Cocharcas – Avendaño quarry.

As shown in Table 4, the coarse aggregate presents a nominal maximum size of 1 in and a specific gravity of 2.68, values that are consistent with aggregates commonly used in pervious concrete applications. The recorded dry loose and compacted unit weights (1350 and 1477 kg/m³, respectively) indicate adequate particle packing potential while preserving the interconnected void structure required to maintain permeability.

The low natural moisture content (0.46%) and moderate water absorption (1.31%) facilitated accurate adjustment of the effective water–cement ratio (w/c = 0.40), thereby ensuring consistency with the target average compressive strength (f’cr = 294 kg/cm²). These aggregate properties confirm their suitability for achieving the required balance between mechanical resistance and interconnected porosity in pervious concrete mixtures.

3.2 Determine the compressive strength of concrete blocks by adding 9%, 10%, and 11% silica fume

The compression test was applied to the specimens at 7, 14, and 28 days. The results were presented as follows:

Table 5. Compressive strength at 7 days pervious concrete f'c 210 kg/cm^2

Mixture	**Diam. (cm)**	**Strength (kgf)**	**Area (cm²)**	**Strength (kg/cm²)**	**% Earned**
0%-01	15.15	24654	180.27	136.8	65.1
0%-02	15.13	24108	179.79	134.1	63.9
0%-03	15.01	23988	176.95	135.6	64.6
9%-01	15.16	23988	180.51	132.9	63.3
9%-02	15.09	22567	178.84	126.2	60.1
9%-03	15.11	20987	179.32	117.0	55.7
10%-01	**15.32**	**26756**	**184.34**	**145.1**	**69.1**
10%-02	**15.12**	**26865**	**179.55**	**149.6**	**71.2**
10%-03	**15.16**	**26809**	**180.51**	**148.5**	**70.7**
11%-01	15.14	25146	180.03	139.7	66.5
11%-02	15.14	24876	180.03	138.2	65.8
11%-03	15.18	23687	180.98	130.9	62.3

Note: Own elaboration based on 7-day compression tests.

Table 6. Compressive strength at 14 days, pervious concrete f'c 210 kg/cm^2

Mixture	**Diam. (cm)**	**Strength (kgf)**	**Area (cm²)**	**Strength (kg/cm²)**	**% Earned**
0%-01	15.18	33218	180.98	183.5	87.4
0%-02	15.03	32567	177.42	183.6	87.4
0%-03	15.04	34607	177.66	194.8	92.8
9%-01	15.05	35987	177.90	202.3	96.3
9%-02	15.02	35289	177.19	199.2	94.8
9%-03	15.02	35209	177.19	198.7	94.6
10%-01	**15.14**	**37890**	**180.03**	**210.5**	**100.2**
10%-02	**15.10**	**37865**	**179.08**	**211.4**	**100.7**
10%-03	**15.60**	**39209**	**191.13**	**205.1**	**97.7**
11%-01	15.12	36988	179.55	206.0	98.1
11%-02	15.12	36754	179.55	204.7	97.5
11%-03	15.14	36888	180.03	204.9	97.6

Note: Prepared by the author based on 14-day compression tests.

Table 7. Compressive strength at 28 days, pervious concrete f'c 210 kg/cm^2

Mixture	**Diam. (cm)**	**Strength (kgf)**	**Area (cm²)**	**Strength (kg/cm²)**	**Average**
0%-01	15.12	39678	180.45	219.88	223.77
0%-02	15.05	40456	181.45	222.96	
0%-03	15.14	41678	182.43	228.46	
9%-01	15.01	41567	183.23	226.86	228.73
9%-02	15.09	40789	180.20	226.35	
9%-03	15.14	41983	180.21	232.97	
10%-01	**15.08**	**42567**	**181.02**	**235.15**	**238.60**
10%-02	**15.08**	**43789**	**180.12**	**243.11**	
10%-03	**15.11**	**43256**	**182.10**	**237.54**	
11%-01	15.12	42867	177.98	240.85	235.21
11%-02	15.11	41987	177.92	235.99	
11%-03	15.12	41234	180.23	228.79	

Note: Prepared by the author based on 28-day compression tests.

As shown in Tables 5-7, the incorporation of silica fume significantly influenced compressive strength development at different curing ages. At 7 days (Table 5), the 10% mixture exhibited the highest early-age strength (≈145 – 150 kg/cm^2), indicating accelerated pozzolanic reactivity and enhanced matrix densification compared with the control mixture and other replacement levels. This early-age performance suggests improved particle packing and ITZ refinement. At 14 days (Table 6), the 10% mixture reached and slightly exceeded the specified design strength (≈210 – 211 kg/cm^2), achieving more than 100% of the target value (f’c = 210 kg/cm^2), while the 9% and 11% mixtures also demonstrated notable improvements compared with the control. This trend indicates enhanced hydration kinetics and improved cementitious bonding attributable to silica fume incorporation.

At 28 days (Table 7), the 10% mixture achieved the highest average compressive strength (238.60 kg/cm^2), followed by the 11% (235.21 kg/cm^2) and 9% (228.73 kg/cm^2) mixtures, all surpassing the control mixture (223.77 kg/cm^2). The differences, although moderate, consistently favor the 10% replacement level, indicating that this proportion provides optimal mechanical enhancement while maintaining the porous structure required for permeability.

Overall, the compressive strength evolution confirms that moderate silica fume incorporation improves the mechanical behavior of pervious concrete. The results support the conclusion that a 10% replacement level represents the optimal dosage under the experimental conditions evaluated.

3.3 Statistical analysis of compressive strength

To evaluate the effect of silica fume on the compressive strength of pervious concrete, mixtures with four different replacement levels (0%, 9%, 10%, and 11%) were produced. Three specimens per mixture were tested at 28 days in accordance with the provisions of NTP 339.034.

It should be noted that the incorporation of ultrafine pozzolanic materials such as silica fume increases the microstructural complexity of cement-based composites, potentially affecting both mechanical and hydraulic performance.

The average compressive strength values were calculated for each mixture, along with their corresponding standard deviations. This statistical treatment allowed assessment of internal variability within each group and facilitated comparison of the influence of silica fume incorporation on compressive strength development. The relatively low dispersion observed among specimens indicates consistency in mixture production and testing procedures. The calculation of standard deviation by group is presented as follows:

- **Group 0% silica fume**

Resistances (kg/cm^2): 219.88, 222.96, 228.46
Average: 223.77
Standard deviation = $\sqrt{[(15.13 + 0.66 + 22.00) / 2]} = \sqrt{(37.78 / 2)} = 4.35$ kg/cm^2

- **Group 9% silica fume**

Resistances (kg/cm^2): 226.86, 226.35, 232.97
Average: 228.73
Standard deviation = $\sqrt{[(3.5 + 5.66 + 17.98) / 2]} = \sqrt{(27.14 / 2)} = 3.69$ kg/cm^2

- **Group 10% silica fume**

Resistances (kg/cm^2): 235.15, 243.11, 237.54
Average: 238.60
Standard deviation = $\sqrt{[(11.9 + 20.34 + 1.12) / 2]} = \sqrt{(33.37 / 2)} = 4.08$ kg/cm^2

- **Group 11% silica fume**

Strengths (kg/cm^2): 240.85, 235.99, 228.79
Average: 235.21
Standard deviation = $\sqrt{[(31.81 + 0.61 + 41.22) / 2]} = \sqrt{(73.63 / 2)} = 6.07$ kg/cm^2

As shown in Table 8, the mixture incorporating 10% silica fume achieved the highest average compressive strength (238.60 kg/cm^2), exceeding the control mixture (223.77 kg/cm^2) by approximately 6.6%. This improvement suggests enhanced matrix densification and improved paste–aggregate interfacial bonding while preserving the interconnected porosity required for permeability. A similar strength development trend was observed at 7 and 14 days, indicating progressive and consistent resistance gain over time.

To evaluate the statistical significance of the observed differences, a one-way analysis of variance (ANOVA) was performed, considering the percentage of silica fume as the independent variable and compressive strength at 28 days as the response variable. The analysis yielded $F = 4.75$ with $p = 0.0347$. Since $p < 0.05$, the differences among the mixtures can be considered statistically significant at the 95% confidence level.

Additionally, 95% confidence intervals were calculated for the 28-day mean compressive strength values in order to assess the precision of the estimates and the variability between mixtures.

Table 8. Average and standard deviation of compressive strength of permeable concrete with different percentages of silica fume

Percent of Silica Fume (%)	Average Resistance (kg/cm^2)	Standard Deviation (kg/cm^2)
0%	223.77	4.35
9%	228.73	3.68
10%	238.60	4.08
11%	235.21	6.07

Note: The values correspond to the average number of specimens tested at 28 days in accordance with NTP 339.034.

Table 9. 95% confidence intervals

Mixture	Average (kg/cm^2)	95% Lower Confidence Interval	95% Higher Confidence Interval
0%	223.8	218.7	228.9
9%	228.7	224.4	233.0
10%	238.6	234.1	243.1
11%	235.2	228.8	241.6

Note: Own elaboration.

As shown in Table 9, the mixture containing 10% silica fume not only achieved the highest average compressive strength but also exhibited a relatively narrow confidence interval, reflecting greater stability and reproducibility of its mechanical behavior. The limited overlap between the 10% mixture interval and the control mixture interval further supports the statistical difference identified by the ANOVA analysis.

3.4 Microstructural analysis (scanning electron microscopy and energy dispersive spectra)

To complement the mechanical findings, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analyses were performed on polished sections of specimens incorporating 0%, 9%, 10%, and 11% silica fume at 28 days of curing.

(a) SEM observations

The micrographs revealed notable differences in the morphology and compactness of the cementitious matrix:

- In the 0% mixture, the ITZ exhibited a porous texture with limited paste–aggregate adhesion and visible hexagonal portlandite crystals ($Ca(OH)_2$).
- In the 9% mixture, a slight reduction in porosity and an increase in finer matrix particles were observed, although some heterogeneous regions remained.
- The 10% mixture presented the densest and most continuous microstructure, characterized by a refined ITZ and a significant reduction in microvoids. The increased presence of C–S–H gel and the reduced amount of free portlandite indicate enhanced pozzolanic reaction.
- In the 11% mixture, a slight increase in interconnected microcracks was observed, likely associated with excess ultrafine content and reduced workability, which may explain the marginal decrease in compressive strength compared with the 10% mixture.

(b) ESD analysis

The EDS spectra confirmed a progressive increase in silica (Si) content and a corresponding decrease in calcium (Ca) content with increasing silica fume incorporation. This trend reflects a reduction in the Ca/Si ratio within the cementitious matrix.

As shown in Table 10, the incorporation of silica fume modified the chemical composition of the cementitious matrix. The progressive reduction in calcium content (Ca%) and the decrease in the Ca/Si ratio from 2.27 (control mixture) to 1.47 (10% mixture) indicate enhanced pozzolanic activity and increased formation of C–S–H.

The 10% mixture exhibited the lowest Ca/Si ratio and the highest Si content, confirming the development of a denser and more homogeneous microstructure. This microstructural refinement provides a mechanistic explanation for the higher compressive strength observed at 28 days.

In contrast, the 11% mixture showed a slight increase in the Ca/Si ratio compared with the 10% mixture, suggesting partial densification but the potential presence of unreacted silica particles, which may limit further mechanical improvement.

Overall, the EDS results corroborate the mechanical findings and confirm that a 10% silica fume replacement provides the optimal balance between chemical reaction, matrix densification, and structural performance.

Table 10. Average results of Energy Dispersive Spectroscopy (EDS) analysis of the cementitious matrix

Mixture	Calcium (Ca) (%)	Silica (Si) (%)	Ca/Si Ratio	Microstructural Observation
0%	42.3	18.6	2.27	High presence of portlandite and open pores
9%	38.7	20.4	1.89	Moderate reduction in $Ca(OH)_2$
10%	34.5	23.5	1.47	Abundant formation of calcium silicate hydrate (C–S–H) and dense matrix
11%	35.9	22.1	1.63	Partial densification with unreacted fines

Note: Own elaboration.

3.5 Effect of silica fume addition (0%, 9%, 10%, and 11%) on the permeability of pervious concrete blocks

The slight reduction in the permeability coefficient (K) observed for the 10% and 11% mixtures can be attributed to matrix densification, which marginally reduces the size of interconnected pores. However, the recorded values remain within the acceptable range for urban drainage applications, demonstrating that the incorporation of silica fume does not compromise hydraulic functionality.

Permeability decreased slightly with increasing silica fume content for the following reasons:

- **Densification of the cementitious matrix:** Silica fume consists of ultrafine particles that fill the voids between cement grains and aggregate surfaces, reducing overall micro-porosity.
- **Refinement of interconnected pores:** While the macroporous network necessary for drainage was preserved, minor narrowing of smaller pore channels resulted in a slight reduction in the permeability coefficient (K ≈ 0.510 – 0.515 cm/s).
- **Balance between strength and permeability:** The observed decrease is minimal, and permeability values remain within the range recommended by ACI 522R-10. Therefore, the pervious concrete maintains its hydraulic function while achieving improved mechanical performance.

Table 11. Permeability of 28-day pervious concrete (ACI 522R-10)

Mixture	Code	t(s)	A (cm²)	K (cm/s)	Q (cm³)	K Avg.
	0% - 01	42.5	180.45	0.514	1308.64	0.517
0%	0% - 02	41.3	181.45	0.530	1322.75	
	0% - 03	43.1	182.43	0.506	1322.91	
	9% - 01	42.1	183.23	0.519	1332.57	0.518
9%	9% - 02	41.7	180.20	0.525	1324.93	
	9% - 03	42.6	180.21	0.511	1304.45	
	10% - 01	43.2	181.02	0.507	1318.13	0.510
10%	10% - 02	42.8	180.12	0.512	1319.75	
	10% - 03	43.0	182.10	0.510	1327.71	
	11% - 01	42.9	177.98	0.518	1315.85	0.515
11%	11% - 02	43.4	177.92	0.513	1313.91	
	11% - 03	43.1	180.23	0.515	1332.46	

Note: Prepared by the author based on the permeability tests carried out on permeable concrete with the addition of silica fume.
t = time (s); A = specimen cross-sectional area (cm²); Q = discharge volume (cm³); K = permeability coefficient (cm/s) determined in accordance with ACI 522R-10; K Avg. denotes the mean value of three replicates.

Table 12. Recommended dosage for 1 m³ of permeable concrete with the addition of 10% silica fume

Material	Dry Weight (kg/m³)	Wet Weight (kg/m³)	Volume (m³)	Dosage (vol.)
Cement	349.50	349.50	0.233	1.00
Silica fume 10%	34.95	34.95	0.016	0.07
Coarse aggregate	1892.55	1911.48	1.304	6.00
Water	154.00	154.00	0.154	0.66

Note: Own elaboration based on the design prepared for this research.

As shown in Table 11, the permeability coefficients at 28 days ranged between 0.510 and 0.518 cm/s for all mixtures, indicating minimal variation attributable to silica fume incorporation. The control mixture presented an average K value of 0.517 cm/s, while the 10% mixture exhibited a slightly lower average (0.510 cm/s). This confirms that matrix densification did not significantly obstruct the interconnected pore system responsible for water infiltration. The small differences among mixtures indicate that silica fume primarily improved the microstructure of the cementitious matrix without substantially altering the macroporous network that governs hydraulic conductivity. Therefore, even at the optimal 10% replacement level, where compressive strength was maximized, the permeability remained within the typical range reported for pervious concrete. These findings demonstrate that mechanical enhancement was achieved without compromising permeability, reinforcing the balance between structural performance and drainage capacity established in this study.

As shown in Table 12, the recommended dosage for 1 m³ of pervious concrete with 10% silica fume was established based on the optimal mechanical and hydraulic performance observed in previous tests. The water–cement ratio (w/c = 0.40) and the cementitious content—including the 10% silica fume replacement—ensured adequate matrix densification while preserving the interconnected void structure. The slight difference between dry and wet aggregate weight reflects moisture correction to maintain mixture consistency. The volumetric proportion (1:6 cementitious material to coarse aggregate) confirms that the design prioritizes macroporosity, which is essential for permeability. This dosage represents the optimal balance between strength enhancement and hydraulic efficiency, validating the 10% silica fume mixture as the most suitable formulation for pervious concrete applications under high rainfall conditions.

Table 13. Recommended dosage in relative weight (kg)

Cement	Silica Fume	Coarse Aggregate	Water
1.00	0.10	5.41	0.44

Note: Own elaboration based on the design prepared for this research.

As shown in Table 13, the recommended mix proportion in relative weight (1:0.10:5.41:0.44) confirms that the 10% silica fume replacement was incorporated within a controlled water–cement ratio of 0.40.

3.6 Determine the optimal permeable concrete mix design with the addition of silica fume

The mixture incorporating 10% silica fume achieved the optimal balance between compressive strength and permeability, maintaining a water–cement ratio of 0.40 and preserving the porous structure recommended by ACI 522R-10. The defined relative dosage facilitates practical field implementation while ensuring structural reliability and drainage efficiency.

3.7 Determine the permeability of concrete in the simulation of rainfall in prototyping

To evaluate the hydraulic performance of pervious concrete under extreme rainfall conditions, a simulation test was conducted using an experimental system designed to replicate a rainfall intensity of 105 mm/h, representative of severe precipitation events recorded in the city of Piura.

The test enabled direct observation and quantification of the hydraulic behavior of pervious concrete blocks manufactured with the optimized mixture. During the simulation, water from an elevated tank was distributed uniformly through a piping system and spray nozzles onto the block surface. The system pressure was maintained constant and monitored using a calibrated pressure gauge (0–60 psi), ensuring homogeneous testing conditions. The quantification procedure is presented as follows:

- An elevated tank with a capacity of 1050 L was connected to a piping system equipped with uniform nozzles to simulate a rainfall intensity of 105 mm/h over an effective exposure area of 0.25 m².
- The applied water volume was measured using a calibrated volumetric indicator.
- Infiltrated water was collected beneath the block and weighed using precision scales, yielding 947 L of infiltrated volume.

The infiltration percentage was calculated as:

$$\text{Infiltration } (\%) = \frac{\text{Infiltration volume (L)}}{\text{Applied water volume (L)}} \times 100$$
$$= \frac{947}{1050} \times 100 \approx 90\%$$

3.8 Calibration and validation of the simulation system

Although the rainfall simulation system was developed specifically for this research, it was experimentally calibrated to ensure reproducibility and reliability. Calibration consisted of adjusting the outlet flow using a rotameter and regulating nozzle distribution until a rainfall intensity equivalent to 105 mm/h was achieved.

To validate correspondence with standardized methods, results were compared with ASTM C1701 – Standard Test Method for Infiltration Rate of In-Place Pervious Concrete [21]. The infiltration rate was calculated according to the standard equation:

$$I = \frac{K \times M}{D^2 \times t}$$

where,

- I = infiltration rate (mm/h),
- K = calibration constant of the equipment (4,583 × 10^6 for units in mm, s, and m²),
- M = mass of infiltrated water (kg),
- D = diameter of the application area (mm),
- t = infiltration time (s).

Table 14. Comparison between simulation system results and ASTM C1701

Parameter Evaluated	Simulation System (Prototype)	ASTM C1701 [21]	Difference (%)
Applied precipitation (mm/h)	105	102 ± 5	+2.9
Infiltrated Volume (L)	947	920–960	+1.7
Infiltration rate (mm/h)	92.4	90–100	–2.6
Pressure Variation (psi)	±0.3	±0.2	+0.1
Estimated total error	—	—	4.7

Note: ASTM = ASTM International (formerly American Society for Testing and Materials).

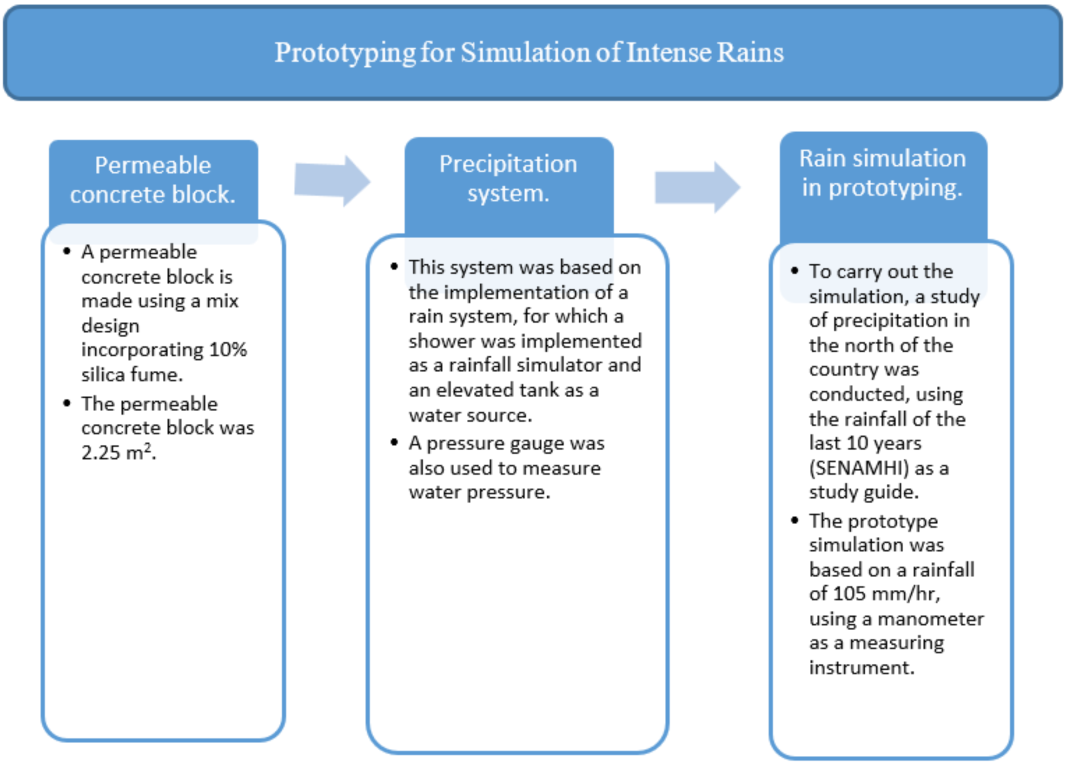
Applying the experimental data of the prototyped system, a mean rate of 92.4 mm/h was obtained, which was compared with the characteristic ranges reported by ASTM C1701 in Table 14.

The calibration results demonstrate that the prototype system exhibits less than 5% variation relative to ASTM reference values, with an estimated total error of 4.7%. This confirms the accuracy and reproducibility of the experimental setup.

The agreement between both methods validates the system's capacity to simulate heavy rainfall conditions in a controlled and reliable manner, reproducing the hydraulic behavior experienced by pervious concrete under field conditions.

The optimized 10% silica fume mixture achieved a hydraulic efficiency of approximately 90%, with an average infiltration rate of 92.4 mm/h, remaining within the optimal range established by ASTM C1701. These results confirm that permeability was preserved while mechanical strength was enhanced, demonstrating the technical feasibility of the proposed formulation for high-intensity rainfall environments.

The experimental setup and hydraulic flow distribution are illustrated in Figure 2.



- A permeable concrete block is made using a mix design incorporating 10% silica fume.
- The permeable concrete block was 2.25 m^2.

- This system was based on the implementation of a rain system, for which a shower was implemented as a rainfall simulator and an elevated tank as a water source.
- A pressure gauge was also used to measure water pressure.

- To carry out the simulation, a study of precipitation in the north of the country was conducted, using the rainfall of the last 10 years (SENAMHI) as a study guide.
- The prototype simulation was based on a rainfall of 105 mm/hr, using a manometer as a measuring instrument.

Figure 2. Rain prototyping procedure

Note: Own elaboration.

4. DISCUSSIONS

4.1 Physical and mechanical properties of coarse aggregates

The aggregate test results confirm that the selected materials provide suitable conditions for pervious concrete production, consistent with ACI 522R-10. The 1-in nominal maximum size coarse aggregate from the Virgen de la Cocharcas–Avendaño quarry supports the formation of stable interconnected voids, which are essential for functional permeability. The dry loose unit weight (1350 kg/m³) and compacted unit weight (1477 kg/m³) indicate adequate packing capacity and stability within the mixture, while the low moisture content (0.46%) and absorption (1.31%) facilitate precise control of the water–cement ratio (w/c = 0.40), minimizing segregation and maintaining mixture homogeneity.

When compared with results reported in the study [12], both studies employ 1-in aggregates and low w/c ratios, reinforcing that aggregate gradation and water–cement ratio are critical factors governing hydraulic behavior. In the present study, the 1:6 cementitious-to-aggregate proportion supports a balance between mechanical strength and permeability, making the mixture suitable for pedestrian areas and light vehicular traffic.

Overall, the granulometric and physical properties of the selected aggregates ensure structural stability and hydraulic performance of the pervious concrete, in alignment with international technical guidance.

4.2 Effect of silica fume (0%, 9%, 10%, and 11%) on compressive strength

The results indicate that silica fume incorporation enhances the compressive strength of pervious concrete, which is consistent with its high pozzolanic reactivity. At 28 days, the mixture containing 10% silica fume achieved a compressive strength of 238.60 kg/cm².

At the microstructural level, silica fume contributes through two complementary mechanisms:

- Pozzolanic reaction: Amorphous silicon dioxide reacts with calcium hydroxide ($Ca(OH)_2$) to form additional calcium silicate hydrate (C–S–H), increasing matrix densification and strength.
- Refinement of the ITZ: Ultrafine silica fume particles improve paste–aggregate contact and reduce micro-defects, enhancing adhesion and limiting microcrack development.

SEM observations and the microstructural discussion supported by Saba et al. [9] are consistent with this interpretation, showing a denser and more homogeneous cementitious matrix for moderate silica fume contents (9–10%), with reduced microvoids and a more continuous ITZ.

However, the 11% silica fume mixture exhibited a smaller strength gain. This behavior may be associated with reduced workability and more difficult compaction due to excess ultrafine content, which can introduce localized micro-defects. The larger standard deviation at 28 days (6.07 kg/cm²) is consistent with increased variability under these conditions.

From a practical standpoint, future applications should consider using plasticizing or water-reducing admixtures to maintain workability and uniformity while preserving a low w/c ratio.

4.3 Sustainability and cost analysis of silica fume pervious concrete

Using silica fume as a partial cement replacement can improve sustainability by reducing cement consumption. In this study, the 10% replacement corresponds to 34.95 kg/m³ of cement substituted. The manuscript estimates a reduction of approximately 28 kg CO_2/m³ (8–10% reduction compared to conventional concrete) and reports a moderate increase in initial cost (≈ S/60–70/60–70/m³), equivalent to ≈ S/6–7/m² for a 10 cm slab thickness.

Although silica fume has a higher unit cost (S/ 2.50/kg) than cement (S/ 0.73/kg), the life cycle cost analysis indicates that the total 20-year life cycle cost may be reduced due to lower maintenance and replacement needs, as summarized in Table 15.

4.3.1 Extended life cycle cost assessment

To complement the economic analysis, the indirect costs associated with the life cycle of the material were considered, including transportation, labor, maintenance, and replacement over 20 years of service. The results are summarized in Table 15.

4.3.2 Interpretation and benefit-cost ratio

The analysis shows that, despite the slight initial increase in the cost of materials (≈ S/ 6–7 /m²), the total life cycle cost of concrete with silica fume is reduced by more than 40%, due to its greater durability, less deterioration due to infiltration, and less frequent maintenance.

In addition, the benefit/cost ratio (B/C) considering the savings for durability and maintenance is estimated between 2.5 and 7.8, which demonstrates the technical, economic, and environmental feasibility of its application in urban permeable pavements.

Table 15. Life cycle cost assessment (LCCA) comparison between conventional concrete and pervious concrete with 10% silica fume

Concept	Conventional Concrete (S/ /m²)	Pervious Concrete with 10% Silica Fume (S/m²)	Change (%)
Materials (cement, aggregates, additives)	68	74	+8.8
Labor and transportation	52	54	+3.8
Maintenance (20 years)	310	120	-61.3
Replacement /rehabilitation	85	40	-52.9
Total life cycle cost (20 years)	**515**	**288**	**-44.1**

Note: Own elaboration.

4.4 Determine the addition of cement by 0%, 9, 10%, and 11% silica fume on the permeability of concrete blocks

The permeability values obtained (0.518 cm/s, 0.510 cm/s, and 0.515 cm/s for 9%, 10%, and 11% silica fume, respectively) confirm that the pervious concrete maintains effective infiltration capacity and satisfies the ACI 522R-10 criterion (≥ 0.3 cm/s).

The slight reduction in permeability with increasing silica fume content is attributed to matrix densification and refinement of smaller pore channels due to ultrafine particle filling and additional C–S–H formation. Importantly, the primary flow channels remain interconnected, maintaining hydraulic functionality.

Synthesis: Moderate silica fume addition (9–10%) densifies the cementitious matrix without clogging the interconnected pore network, sustaining stable hydraulic behavior while improving mechanical performance.

4.5 Optimal pervious concrete mix design with silica fume

Considering both compressive strength and permeability, the 10% silica fume mixture provides the most favorable balance under the tested conditions. The mixture maintains w/c = 0.40 and preserves the porous structure recommended by ACI 522R-10 while delivering the highest compressive strength among the evaluated mixtures.

4.6 Determine the permeability of the concrete in the simulation of rainfall in prototyping

The rainfall simulation conducted at 105 mm/h confirmed the high infiltration capacity of the designed pervious concrete. The prototype testing reported infiltration exceeding 90% of the applied water volume, indicating strong pore connectivity and integrity of the porous structure.

These results support the practical applicability of the 10% silica fume pervious concrete mixture for sustainable urban drainage systems (SUDS), including pedestrian pavements, parking areas, and low-traffic driveways. Field implementation should emphasize consistent workability control and uniform compaction; the use of plasticizing admixtures and surface vibration techniques may reduce variability and prevent surface defects while maintaining hydraulic performance.

5. CONCLUSIONS

The coarse aggregates exhibited adequate physical and mechanical properties for the production of pervious concrete. The 1-in nominal maximum size aggregate presented a specific gravity of 2.68 and an absorption of 1.31%, enabling a stable mixture with controlled porosity and interconnected void structure favorable for infiltration performance.

The adopted mixture design (w/c = 0.40, zero slump, and 1:6 cementitious-to-aggregate ratio) aligns with ACI 522R-10 recommendations and enabled the development of pervious concrete with balanced mechanical strength and hydraulic performance.

Silica fume incorporation at levels between 9% and 11% by cement weight enhanced compressive strength development. The 10% silica fume mixture achieved the highest 28-day compressive strength (238.60 kg/cm²). The one-way ANOVA results ($F = 4.75$; $p = 0.0347$) confirmed statistically significant differences among mixtures at the 95% confidence level, validating the influence of silica fume content on mechanical performance.

Microstructural observations obtained through SEM and EDS analyses supported these findings. The reduction in the Ca/Si ratio to 1.47 in the 10% mixture indicates intensified pozzolanic activity and greater C–S–H formation, which are consistent with matrix densification and improved continuity of the ITZ.

Permeability at 28 days remained within a narrow range (approximately 0.510–0.518 cm/s) across all mixtures, satisfying ACI 522R-10 criteria and demonstrating that silica fume incorporation did not compromise hydraulic performance. The slight reduction in K observed at higher replacement levels is attributable to microstructural refinement while preserving the primary interconnected macropore network responsible for water flow.

Rainfall simulation tests conducted at 105 mm/h confirmed infiltration exceeding 90% of the applied water volume, demonstrating effective pore connectivity and hydraulic efficiency under extreme precipitation conditions. These results support the technical feasibility of implementing the optimized 10% silica fume mixture for sustainable stormwater management in regions exposed to high-intensity rainfall, such as Piura.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results obtained, complementary lines of research are identified aimed at strengthening knowledge about the behavior of pervious concrete with the addition of silica fume:

- **Long-term durability:** Evaluate the performance of concrete with 10% silica fume against moisture-drying, freeze-thaw, and surface abrasion cycles, using ASTM standardized tests that allow estimating mass loss, dynamic modulus variation, and wear resistance.
- **Application of shrinkage-reducing additives:** To delve into their combined effect with silica fume, as they were mentioned in the literature but not experimentally analyzed in this study.
- **Full-scale tests:** Implement test sections in urban pavements in Piura to monitor the behavior of concrete in the face of heavy rains and thermal variations, validating its hydraulic and structural performance in real conditions.
- **Microstructural analysis (SEM–EDS):** Examine the formation and distribution of C–S–H gel, the densification of the ZTI, and its effect on connected porosity, to correlate microstructural properties with the overall durability of the material.
- **Economic and environmental assessment:** Expand the quantification of benefits derived from the use of silica fume as an industrial by-product, considering the reduction of cement content, CO_2 emissions, and maintenance LCCA compared to alternative materials.

To strengthen the experimental validation of durability, it is suggested to incorporate the following complementary tests, which will determine the useful life of concrete permeable with silica fume under different environmental conditions, as shown in Table 16.

Table 16. Proposed tests for the evaluation of the durability of silica fume permeable concrete

Practice	Norm	Main Variable	Purpose
Freeze-thaw	ASTM C666 / C666M	Mass loss, dynamic modulus	Assesses resistance to thermal cycling (-18 °C to +4 °C).
Wetting–drying	ASTM D559 / D559M	Mass loss, cracking	Determines stability against variations in humidity.
Surface abrasion	ASTM C944 / C944M	Wear (mm or %)	Measures resistance to pedestrian or vehicular traffic.
Chemical attack	ASTM C267 / C1012	Mass and strength variation	Evaluates durability against sulfates and chlorides.
Carbonation (optional)	RILEM CPC-18 / ISO 1920-12	Depth (mm)	Estimates resistance to CO_2 penetration.

Note: Prepared by the author based on the methodological proposal for durability assessment.

Pervious concrete with 10% silica fume presents optimal performance by combining high strength (238.6 kg/cm²), functional permeability (0.510 cm/s), and hydraulic efficiency greater than 90%, consolidating itself as a technical and sustainable alternative to traditional concrete.

Its application in the Piura region, where torrential rains generate recurrent floods, constitutes an effective strategy for mitigating rainfall risk and improving urban drainage, aligned with the objectives of resilient infrastructure and environmental sustainability.

The future incorporation of durability tests, microstructural analysis, and life cycle assessment will allow consolidating a comprehensive characterization of the material, guaranteeing its long-term performance both in structural and ecological terms.

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