Periódico Eletrônico "Fórum Ambiental da Alta Paulista"
Electronic Journal "Environmental Forum of Alta Paulista"

ISSN 1980-0827 – Volume 20, Number 3, Year 2024

Study on the influence of alkali-resistant glass fiber additions on the properties of pervious concrete

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SUMMARY
The soil waterproofing process results in negative consequences for urban drainage management. In this context, pervious concrete, the subject of this study, emerges as a solution to mitigate impacts from waterproofing. However, due to its high porosity, this type of concrete exhibits lower strength compared to conventional concrete. The objective of this research was to investigate the influence of adding alkali-resistant glass fibers (AR glass fiber) on the strength and permeability of pervious concrete. Pervious concrete mixes were prepared using a ratio of 1:4.6, with the addition of 10% silica, 0.5% superplasticizer additive, and 0.34% water relative to the weight of cement. To assess the influence of fibers, two different percentages of AR glass fiber were added: 10% and 20% (by volume of concrete). The methodological approach included tests for axial compressive strength, split tensile strength, three-point flexural strength, as well as determining bulk density, voids ratio, and permeability coefficient. The results revealed that the addition of fibers led to a decrease in axial compressive strength. However, the mix with 10% fiber showed an increase in split tensile and flexural strengths, which are critical in pavement applications. Dry bulk density and permeability coefficient decreased with fiber inclusion, while the voids ratio increased. It is concluded that adding 10% fiber was beneficial; however, subsequent increases did not yield significant gains.

KEYWORDS: Permeable Concrete. Alkali-Resistant Glass Fiber. Mechanical Properties

1 INTRODUCTION

The phenomenon of urbanization in Brazil originated primarily in the 1940s, experiencing notable intensification in the subsequent decades. The transition from traditional agriculture to more mechanized production, combined with government policies promoting the modernization of the rural sector, caused a significant exodus of workers from the countryside to urban centers.

According to data from the 2015 National Household Sample Survey (PNAD), about 84.72% of the Brazilian population resides in urban areas, while only 15.28% remain in rural zones, as indicated by the Brazilian Institute of Geography and Statistics (IBGE, 2015).

Rapid population growth and uncontrolled urban expansion have led to extensive paving of roads, sidewalks, and subdivisions, causing significant changes in the original vegetation cover. This process brings various environmental problems and implications, notably the increase in soil impermeabilization, which results in a substantial reduction in the soil's water absorption capacity, leading to events such as floods, the formation of heat islands, among other adversities (Lopes et al., 2020).

It is crucial to find methods and construction practices that minimize impermeable areas. The use of pervious concrete in pavements plays a fundamental role in meeting this demand, significantly contributing to the reduction of impermeable areas. This is because this type of pavement has a high permeability due to its high porosity. Additionally, it consists of a large amount of coarse aggregates and contains little to no fine materials.

Pervious concrete pavement typically consists of a layer of pervious concrete on the surface, followed by a base, and finally a subgrade (soil). A permeable geotextile fabric can also be included, although it is not mandatory (Ferguson, 2005).

Xie et al. (2019) enumerate the main advantages of using pervious concrete in pavements: reduction of surface stormwater runoff; replenishment of groundwater; increased skid resistance on the concrete surface; improvement of groundwater quality; reduction of hydroplaning; minimization of the heat island effect; and reduction of traffic noise.

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Silva (2019) lists the main disadvantages associated with the use of pervious concrete in pavement, highlighting:

- Risk of pore clogging;
- Low strength compared to conventional concrete;
- Limitations in the durability of pervious concrete.

The lower strength of pervious concrete emerges as a limiting factor for its application. Both the Brazilian Standard NBR 16416 (ABNT, 2015) and the American Concrete Institute (ACI) 522 (ACI, 2010) outline some recommended applications for pervious concrete, such as:

- Sidewalks;
- Parking lots;
- Pavements intended for light vehicle traffic;
- Tennis courts;
- Base layers for pavements;
- Sound barrier walls;
- Bridge abutments;
- Pool decks.

Hesami et al. (2014) state that the inclusion of fibers in the composition of pervious pavement enhances both tensile and flexural strength. This increase is attributed to the elastic capacity provided by the fibrous material, substantially reducing the risk of sudden rupture of pervious concrete.

Alkali-resistant glass fibers (AR glass fibers) consist of fibers coated with materials capable of resisting alkalinity, such as zirconium oxide, which helps preserve the mechanical properties of the fibers during their service life in concrete (MANZIONE, 2019).

In light of these considerations, the present study aims to primarily evaluate and compare the mechanical properties of pervious concrete, with and without fiber additions, including axial compressive strength, split tensile strength, and flexural tensile strength using three-point bending. Additionally, void content, dry bulk density, and permeability coefficient of the mixtures were analyzed and compared, both for the control and mixes with 10% and 20% fiber additions by volume of cubic concrete, with tests conducted after 28 days of sample curing.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in the mixes of the pervious concrete under study were: Portland cement CP II-F-32, water, superplasticizer additive (Tec-Flow 7000), silica fume (TECNOSIL), coarse aggregate with particle size of 4.75/12.5mm (known as crushed stone 0), and alkali-resistant glass fibers (FIBERGLASS YUNIU).

For the specimen preparation process, a concrete mixer, cylindrical plastic molds with dimensions of 10x20 cm, and wooden prism molds with dimensions of 10x10x40 cm were used. Three different mixtures were produced, named as follows: reference (without the addition of alkali-resistant glass fibers) and with the addition of 10% and 20% alkali-resistant glass fibers. For each mixture, 16 samples were prepared: 12 cylindrical specimens and 4 prism specimens.

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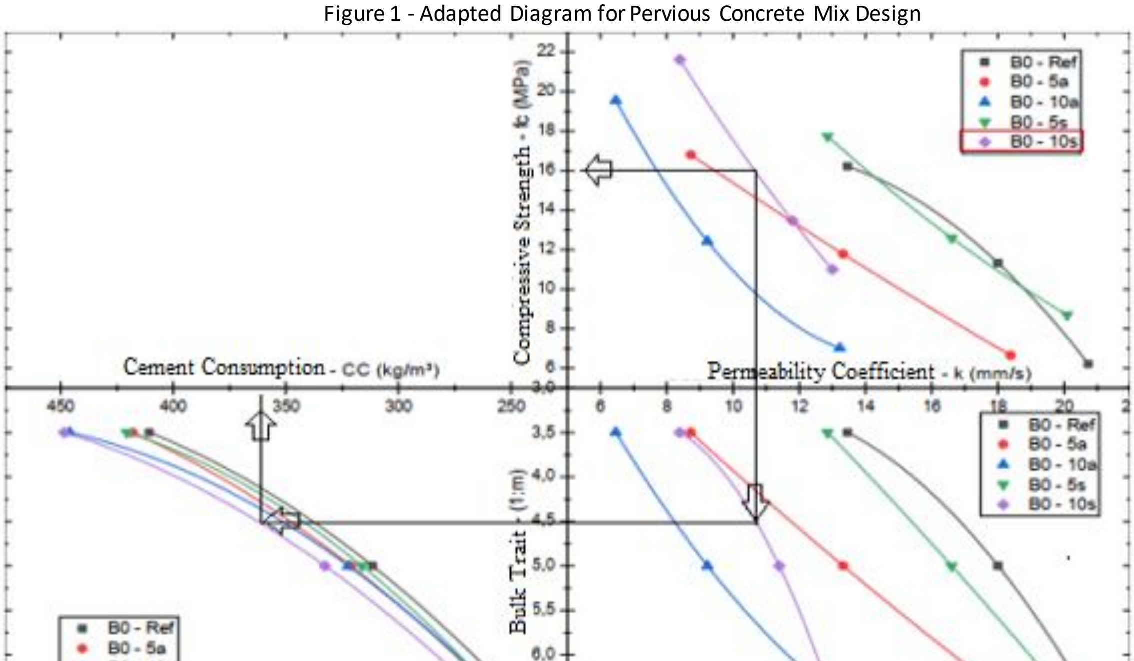
The cylindrical specimens were allocated as follows: 4 samples for axial compressive strength testing, 4 samples for split tensile strength testing, and 4 samples for specific gravity testing. Additionally, 4 prism specimens were reserved for each mixture to perform three-point bending tests.

2.2 Methods

2.2.1 Mix design and production of pervious concrete

The mix design followed the procedures from the diagram adapted by Bigotto (2021). The mix proportion obtained through this method was 1 part cement to 4.6 parts coarse aggregate, with a cement consumption of 440.18 kg/m³. The total water/cement ratio was 0.34, with 0.28 allocated for cement hydration and the remainder for aggregate absorption. Additionally, 0.5% of superplasticizer additive was added relative to the cement mass, along with 10% silica, also based on the cement mass. Figure 1 shows the diagram adapted by Bigotto (2021) from Helene and Terzian (2001). In this experimentally obtained diagram, the water-to-cement ratio axis was replaced with the permeability coefficient.

Figure 1 - Adapted Diagram for Pervious Concrete Mix Design



Source: (BIGOTTO, 2021)

According to Bigotto's mix design diagram (2021), it is possible to input an estimated value of axial compressive strength to determine the permeability coefficient in mm/s, the mass ratio 1:m, and finally, the cement consumption in kg/m³. As indicated by the line drawn in Figure 1.

To determine the amount of water absorbed by the aggregate, the aggregate absorption percentage test was conducted according to the American Society for Testing and

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Materials ASTM C 127-15 (ASTM, 2016). A water/cement ratio of 0.28 was used (for cement hydration), in addition to the inclusion of absorption water to complete the saturation process of the crushed stone 0, resulting in a total water/cement ratio of 0.34.

Subsequently, the slump cone test was performed, as described in the Brazilian standard NBR 16889 (ABNT, 2020). Additionally, a tactile and visual analysis was conducted, as reported by Batezini (2013) and Silva (2019). These authors mention that there is no standardized method to verify the consistency of pervious concrete.

For the specific gravity test, the American standard ASTM C1754/C1754M-12 (ASTM, 2021) was used. Fifteen cylindrical specimens were tested at 28 days. The specimens used in the specific gravity tests were discarded according to the standard after undergoing the high-temperature drying process.

The void index test was conducted as recommended by ASTM C1754/C1754M-12 (ASTM, 2021).

For the determination of permeability coefficient, 15 cylindrical samples were used following the specifications of the International Organization for Standardization ISO 17875-1 (ISO, 2016). This is a constant head permeability test.

The test involves wrapping the samples with plastic film and then using a heat gun to seal the sides of the sample, preventing water from leaking. A small excess of approximately 5 cm of plastic should be left between the top surface and the end of the plastic. Next, two markings should be made: one at a distance of 1.5 cm from the top surface and another at a distance of 2.5 cm. One liter of water is poured onto the sample to moisten it, followed by adding two liters of water in a container and pouring it onto the sample. The timing starts when the water contacts the top surface of the concrete, maintaining a constant water level between the markings. Figure 2 illustrates the test.

Figure 2 - Sample wrapped in plastic film

Source: Own elaboration (2024).

Next, Equation 1 is used to calculate the permeability coefficient.

$$K = \frac{W}{A.t} \qquad (1)$$

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Where:
K is the permeability coefficient (mm/s);
W is the volume of water poured onto the pervious concrete sample (mm³);
A is the cross-sectional area of the pervious concrete sample (mm/s²);
t is the time taken for the water to infiltrate into the pervious concrete sample (s).

Also at 28 days, tests were conducted for: axial compressive strength, following Brazilian standard NBR 5739 (ABNT, 2018); split tensile strength, according to NBR 7222 (ABNT, 2011); and flexural strength, in accordance with the American standard ASTM C293/C293M-16 (ASTM, 2016).

Flexural strength, according to ASTM, is determined by testing a beam with load applied at the center, i.e., through a three-point bending test. The flexural strength value is calculated according to Equation 2:

$$R = \frac{PL}{2\,b.d^2} \qquad (2)$$

Where:
R is the modulus of rupture (MPa);
P is the maximum load applied as indicated by the testing machine (N);
L is the span length (mm);
b is the average width of the specimen (mm);
d is the depth of the specimen (mm).

Due to the difficulty of adhering the extensometer to pervious concrete due to its high porosity, the static modulus of elasticity was obtained as a function of axial compressive strength, according to Equation 3, developed by Goede (2009).

$$E = 36{,}1 \times \rho_c 1{,}5 \times \sqrt{f_c} \qquad (3)$$

Sendo:
E = Modulus of elasticity (Ibf/in²)
ρ_c = Density of concrete (Ib/ft³)
f_c = Compressive strength of concrete (Ibf/in²)

3 RESULTS AND DISCUSSION

3.1 Slump cone test and tactile and visual analysis

The result of the slump cone test was 1.8 cm, indicating very minimal slump. Batezini (2013) and Bigotto (2021) highlight that this result is due to the low water-to-cement ratio, contributing to the porosity of pervious concrete. Through tactile and visual analysis, it was noted that the mixture exhibited a hand-moldable consistency and a glossy appearance, as

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illustrated in Figure 3. This appearance is consistent with observations by Tennis et al. (2004) and Silva (2019).

Figure 3 - Mixture with ideal content

Source: Own elaboration (2024).

3.2 Dry bulk density

All specimens (both reference and with fibers) exhibited apparent bulk density ranging from 1600 kg/m³ to 2000 kg/m³, as recommended by authors Pinheiro and Salomão (2020) and Brazilian standard NBR 16416 (ABNT, 2015). Batezini (2013) states that pervious concrete typically has a bulk density of approximately 80% of regular concrete, which is around 2400 kg/m³. Table 1 presents the average values, standard deviation, and coefficient of variation of the bulk density of the mixes.

Table 1 – Mixtures – Bulk Density

MIXTURE	BULK DENSITY (kg/m³)	STANDARD DEVIATION (%)	COEFFICIENT OF VARIATION (%)
Reference	1963,04	27,82	1,42
10% (AR) fiber addition	1926,71	36,36	1,89
20% (AR) fiber addition	1902,11	12,52	0,66

Source: Own elaboration (2024).

It is noted that the dry bulk density of the mixture with 10% and 20% fiber addition shows a decrease of 1.86% and 3.1%, respectively, compared to the value of the reference mixture. Therefore, the increase in fiber content resulted in a decrease in bulk density. This finding aligns with Toghroli et al. (2020), who explain that the decrease in bulk density occurs due to the accumulation of air between the pervious concrete mixture and the fibers.

3.3 Void index

Table 2 illustrates the void index results of the samples.

Table 2 – Mixtures – Void Index

MIXTURE	VOID INDEX (%)	STANDARD DEVIATION (%)	COEFFICIENT OF VARIATION (%)
Reference	28,82	1,42	2,02
10% (AR) fiber addition	31,12	1,79	5,75
20% (AR) fiber addition	33,00	0,56	1,68

Source: Own elaboration (2024).

According to Table 2, it is noted that all mixtures exhibited a void index above 15%, as recommended by Elango et al. (2021), Fu et al. (2023), and Kia et al. (2017) for pervious concrete. There is also an increase compared to the reference samples, with an increment of 7.94% and 14.5% for the samples with 10% and 20% fiber, respectively. These results align with those of Toghroli et al. (2020), who concluded that the increase in void index in pervious concrete mixtures is due to the entrapment of air between the concrete mixture and the fiber.

3.4 Permeability Coefficient

Table 3 presents the results of the permeability coefficient, along with the standard deviation and coefficient of variation of the mixtures.

Table 3 – Mixtures vs Permeability Coefficient

MIXTURE	PERMEABILITY (%)	STANDARD DEVIATION (%)	COEFFICIENT OF VARIATION (%)
Reference	27,74	6,35	22,89
10% (AR) fiber Addition	25,89	3,66	14,13
20% (AR) fiber Addition	23,92	2,54	10,63

Source: Own elaboration (2024).

All mixtures exhibited a permeability coefficient higher than the 1 mm/s value recommended by ABNT NBR 16416. The values obtained in the research ranged from 23.92 to 27.74 mm/s.

According to Table 3, it can be observed that the addition of fiberglass in permeable concrete mixtures decreases its permeability coefficient. However, this decrease is small (6.7%) for the 10% fiber composition compared to the reference sample, while the standard deviation and coefficient of variation were much higher for the reference sample. Philip et al. (2023) mention that fiber addition reduces the permeability coefficient due to the distribution of fibers in the concrete pores, resulting in more closed and compact pores that impede water flow. In the concrete pores.

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Figure 4 – Sample of permeable concrete with fiberglass

Source: Own elaboration (2024).

3.5 Axial compressive strength

The Table 4 presents the results of the axial compressive strength tests with their respective standard deviations and coefficient of variation.

Table – 4 Axial Compression Strength Test Results

MIXTURES	TEST	AGE (DAYS)	MEAN AXIAL COMPRESSION (MPa)	STANDARD DEVIATION (MPa)	COEFFICIENT OF VARIATION (%)
Reference	Axial Compression	28	15,96	2,80	17,52
10% (AR) fiber addition	Axial Compression	28	14,55	1,90	13,04
20% (AR) fiber addition	Axial Compression	28	12,32	1,82	14,79

Source: Own elaboration (2024).

It is noted that the reference mixture showed the highest axial compression strength compared to the other mixtures. This indicates that the addition of fiber did not contribute to an increase in axial compression strength. Sharma and Mehta (2023) concluded that this reduction could be attributed to an increase in voids content in the concrete samples, as also shown here in Table 2, weakening the concrete structure.

3.6 Diametral compression strength

The results of the tests for diametral compression tensile strength are presented in Table 5.

Table 5 – Average result of diametral compression strength test

MIXTURES	TEST	AGE (DAYS)	MEAN DIAMETRAL COMPRESSION TENSILE STRENGTH (MPa)	STANDARD DEVIATION (MPa)	COEFFICIENT OF VARIATION (%)
Reference	Diametral Compression	28	2,00	0,35	17,68
10% (AR) fiber addition	Diametral Compression	28	2,41	0,44	18,16
20% (AR) fiber addition	Diametral Compression	28	1,74	0,17	9,50

Source: Own elaboration (2024).

It can be observed from Table 5 that the mixture with 10% fiber addition showed the highest value of diametral compression tensile strength. The mixture with 10% fiber addition exhibited a diametral compression strength 17% and 28% higher than the reference mixture and the mixture with 20% fiber addition, respectively. This result demonstrates that fiber enhances tensile strength under compression up to a certain content, after which the increase tends to diminish this strength.

This finding aligns with the results of Sharma and Mehta (2023), indicating that there is an "optimal" content of glass fiber that provides the greatest increase in diametral compression strength.

3.7 Flexural strength

In Table 6, average flexural strength values are presented alongside standard deviations and coefficients of variation for each mixture.

Table 6 – Average result of 3- point flexural test

MIXTURES	TEST	AGE (DAYS)	MEAN FLEXURAL STRENGTH (MPa)	STANDARD DEVIATION (MPa)	COEFFICIENT OF VARIATION (%)
Reference	3 Point flexural	28	4,09	0,44	10,65
10% (AR) fiber addition	3 Point flexural	28	5,09	0,39	7,62
20% (AR) fiber addition	3 Point flexural	28	3,18	1,12	35,28

Source: Own elaboration (2024).

The mixture with 10% volume fiber addition achieved the highest flexural strength result. Values 24% and 37.6% higher were observed compared to the reference mixture and the mixture with 20% fiber addition, respectively. Similar to the findings in the diametral compression tensile strength test, the addition of fiber increased flexural strength up to a certain content, after which the increment tends to decrease this strength.

Hesami et al. (2014) mention that the increase in diametral tensile strength and flexural strength occurs due to the elasticity imparted by the material due to the presence of fibers, significantly reducing the possibility of sudden rupture of permeable concrete.

3.8 Modulus of elasticity

The results of the modulus of elasticity obtained using the Goede Equation (2009) are presented in Table 7.

Table 7 – Static of elasticity results obtained using the Goede Equation (2009) are presented in table7.

MIXTURES	COMPRESSIVE STRENGTH (MPa)	APPARENT DRY DENSITY (kg/m³)	MODULUS OF ELASTICITY (MPa)
Reference	15,96	1963,04	13.570
10% (AR) fiber addition	14,55	1926,72	12.610
20% (AR) fiber addition	12,32	1920,12	11.540

Source: Own elaboration (2024).

Goede (2009) worked with pervious concrete and when substituting axial compression results into his equation to obtain the modulus of elasticity, they observed that their results varied between 12,100 MPa and 15,100 MPa. It is observed that the modulus of elasticity obtained by the equation in the present study closely matched Goede's results, both for the reference mixtures and for mixtures with 10% and 20% fiber addition.

Silva (2019) also used Equation 3 in their research and obtained a modulus of elasticity result of 15,105 MPa for fiber-free pervious concrete. Thus, the values are close to those found in the literature.

For almost all mechanical tests and the permeability coefficient test, the reference samples showed higher standard deviation values and coefficients of variation.

4 CONCLUSION

Based on the results obtained, it is observed that:

a) All mixtures of hardened pervious concrete samples achieved dry apparent density values between 1900 and 1970 kg/m³, as recommended by Batezini (2013). It was also observed that the apparent density of the pervious concrete samples with 10% and 20% fiber addition decreased compared to the reference mixture.

b) The pervious concrete sample mixtures had a void index above 15%. It is noted that the addition of fibers in the pervious concrete mixtures increases the void index and decreases axial compression strength. The increase in the void index occurs due to air accumulation caused by the presence of the fibers.

c) All concrete mixtures achieved a permeability coefficient above the recommendation of ABNT NBR 16416, which is 1 mm/s. The addition of fiber resulted in a decrease in the permeability coefficient, and the higher the fiber content, the lower the permeability coefficient. According to Philip et al. (2023), the reduction in the permeability coefficient occurs due to the distribution of fibers within the pores of the pervious concrete, making the pores more closed and compact, thus reducing water percolation. This was evident in the photograph presented from a sample in the present work.

d) Although the addition of AR glass fiber showed a decrease in compressive strength, the same did not occur for the tensile strength in compression and flexural strength. In these tests, the addition of fiber also increased the strength up to a certain content, after which the increase in fiber tends to decrease this strength value. The increase in tensile and flexural strength occurs due to the elongation of the fibers in the concrete, reducing sudden rupture, i.e., increasing the ductility of the concrete, up to a certain fiber content.

e) In the present study, the mixture that showed the best results for application in pavement was the one with an addition of 10% of fiber, because although the axial compression strength was lower compared to the reference sample, this geometry is not the most requested in pavement, with flexion and traction being the main solicitations.

f) Regarding the decrease in the permeability coefficient, which was observed in the sample with 10% fiber compared to the reference sample, it can be said that this decrease was very small, especially when comparing the standard deviation. In other words, the reference sample had a lower value than the sample with 10% fiber, however, the average was higher.

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