Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 1, 2025

Analysis of the Influence of Polypropylene Fiber Addition on Pervious Concrete

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Submissão: 08/08/2024
Aceite: 05/11/2024
ROCHA, Guilherme Augusto Donegá; SANTANA, Anderson Mauricio Carvalho; FELIPE, Alexsandro dos Santos; GONÇALVES, Aparecido Carlos; ALBUQUERQUE, Maria da Consolação Fonseca de. Análise da influência da adição de fibras de polipropileno no concreto permeável. **Periódico Eletrônico Fórum Ambiental da Alta Paulista**, *[S. l.]*, v. 21, n. 1, 2025. DOI: 10.17271/1980082721120255596.
Disponível em: https://publicacoes.amigosdanatureza.org.br/index.php/forum_ambiental/article/view/5596

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Análise da influência da adição de fibras de polipropileno no concreto permeável

RESUMO

Objetivo - Este estudo tem como objetivo investigar a influência da adição de fibras de polipropileno nas propriedades mecânicas e funcionais de concretos permeáveis contendo 10% de sílica ativa, visando avaliar seu potencial para aplicação em pavimentos urbanos sustentáveis. Para isso, avalia-se a influência da incorporação de diferentes teores de fibras (1, 2, 3 e 4 kg/m³) na permeabilidade, índice de vazios e resistências mecânicas (compressão axial, compressão diametral e tração na flexão). Além disso, busca-se compreender a variação do módulo de elasticidade e da capacidade de deformação pós-pico, comparando os resultados obtidos com a mistura de referência para verificar a viabilidade do uso dessas composições em infraestrutura urbana.
Metodologia – O estudo foi conduzido em laboratório e seguiu uma abordagem experimental para avaliar os efeitos da adição de fibras de polipropileno em concretos permeáveis contendo 10% de sílica ativa. Inicialmente, foram selecionados os materiais constituintes, incluindo cimento Portland, agregados, sílica ativa e fibras de polipropileno. As misturas foram preparadas com diferentes teores de fibras (1, 2, 3 e 4 kg/m³), além de uma mistura de referência sem fibras para comparação. Os corpos de prova foram moldados e submetidos a ensaios para determinar suas propriedades físicas e mecânicas. A massa específica, permeabilidade e índice de vazios foram avaliados para caracterizar a estrutura porosa do concreto. A resistência mecânica foi analisada por meio de ensaios de compressão axial, compressão diametral e tração na flexão. O módulo de elasticidade e a capacidade de deformação pós-pico também foram investigados para compreender o comportamento estrutural das amostras. Os resultados foram comparados entre as diferentes misturas, permitindo avaliar a influência da incorporação das fibras na resistência mecânica e na funcionalidade do concreto permeável. Os achados contribuem para o desenvolvimento de pavimentos urbanos mais sustentáveis e duráveis.
Originalidade/relevância - A crescente urbanização tem intensificado problemas como a impermeabilização do solo, aumento do escoamento pluvial e o efeito de ilha de calor urbano, demandando soluções sustentáveis para a drenagem urbana. No Brasil, a drenagem urbana prioriza a eficiência hidráulica, frequentemente em detrimento dos impactos ambientais. O concreto permeável surge como uma alternativa viável, pois contribui para a redução do escoamento superficial e melhora a qualidade da água. No entanto, sua alta porosidade compromete a resistência mecânica, limitando sua aplicação em áreas de tráfego veicular. Estudos recentes têm explorado modificações nos compósitos cimentícios para superar essa limitação, como o uso de sílica e fibras poliméricas. No entanto, há uma lacuna na literatura sobre o impacto da incorporação de fibras de polipropileno em concretos permeáveis contendo sílica ativa, especialmente em relação ao equilíbrio entre permeabilidade, resistência mecânica e comportamento pós-fissuração. Assim, este estudo contribui para o avanço do conhecimento ao investigar diferentes dosagens de fibras de polipropileno (1, 2, 3 e 4 kg/m³) em concretos permeáveis com 10% de substituição de cimento por sílica ativa, avaliando sua influência no desempenho mecânico e funcional. Os resultados podem subsidiar o desenvolvimento de concretos mais resistentes e duráveis, ampliando sua aplicação prática em infraestrutura urbana sustentável.
Resultados - Os resultados obtidos demonstraram que a adição de fibras de polipropileno impactou significativamente as propriedades físicas e mecânicas do concreto permeável. A adição de fibras reduziu a massa específica e aumentou a permeabilidade e o índice de vazios, evidenciando maior conectividade entre os poros. Nos ensaios mecânicos, a resistência à compressão axial e compressão diametral não apresentaram variações significativas entre as diferentes dosagens de fibras. No entanto, a resistência à tração na flexão aumentou com a adição de 1 kg/m³ de fibras, sugerindo um efeito positivo na capacidade do concreto de resistir a esforços de flexão. Com maiores teores de fibras (2, 3 e 4 kg/m³), observou-se uma leve redução na resistência à flexão, possivelmente devido ao aumento da porosidade e à dificuldade de dispersão homogênea das fibras na matriz cimentícia.
Contribuições teóricas/metodológicas - Este estudo contribui para a literatura científica ao aprofundar a compreensão sobre o impacto da adição de fibras de polipropileno em concretos permeáveis modificados com sílica ativa. A análise detalhada das propriedades físicas e mecânicas do material, especialmente em relação à permeabilidade, resistência à flexão e módulo de elasticidade, preenche uma lacuna na pesquisa sobre a viabilidade estrutural desse tipo de concreto em aplicações de infraestrutura urbana. Do ponto de vista metodológico, a pesquisa se destaca pela abordagem experimental sistemática, avaliando diferentes teores de fibras (1, 2, 3 e 4 kg/m³) e comparando seu efeito na estrutura porosa e no comportamento mecânico do concreto permeável. O uso combinado de ensaios de resistência, módulo de elasticidade e capacidade de deformação pós-pico fornece uma visão mais abrangente sobre a interação entre fibras e matriz cimentícia, permitindo um entendimento mais preciso das condições ótimas para o reforço do material. Além disso, os resultados deste estudo oferecem uma base

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metodológica para futuras pesquisas que busquem otimizar concretos permeáveis com reforços poliméricos, auxiliando no desenvolvimento de materiais mais eficientes e sustentáveis para o setor da construção civil.

Contribuições sociais e ambientais - O uso de concreto permeável com fibras de polipropileno contribui para a sustentabilidade urbana, reduzindo o escoamento superficial, ajudando no controle de enchentes e melhorando a recarga dos lençóis freáticos. Além disso, sua aplicação pode minimizar o efeito de ilha de calor urbano, promovendo maior conforto térmico. Socialmente, a adoção desse material favorece cidades mais resilientes, reduzindo a necessidade de infraestrutura de drenagem convencional e seus custos de manutenção. O estudo fomenta o desenvolvimento de tecnologias sustentáveis na construção civil, alinhadas aos princípios da sustentabilidade.

PALAVRAS-CHAVE: Concreto Permeável. Fibra de Polipropileno. Resistência Mecânica.

Analysis of the Influence of Polypropylene Fiber Addition on Permeable Concrete

ABSTRACT

Objective – This study aims to investigate the influence of polypropylene fiber addition on the mechanical and functional properties of permeable concretes containing 10% silica fume, assessing their potential for application in sustainable urban pavements. To this end, the effects of incorporating different fiber contents (1, 2, 3, and 4 kg/m³) on permeability, void content, and mechanical strengths (axial compression, splitting tensile strength, and flexural tensile strength) were evaluated. Furthermore, variations in the modulus of elasticity and post-peak deformation capacity were analyzed, comparing the results with a reference mixture to determine the feasibility of using these compositions in urban infrastructure.

Methodology – The study was conducted in a laboratory setting following an experimental approach to assess the effects of polypropylene fiber addition in permeable concretes containing 10% silica fume. Initially, the constituent materials were selected, including Portland cement, aggregates, silica fume, and polypropylene fibers. The mixtures were prepared with varying fiber contents (1, 2, 3, and 4 kg/m³), along with a reference mixture without fibers for comparison. Specimens were cast and subjected to tests to determine their physical and mechanical properties. Bulk density, permeability, and void content were evaluated to characterize the porous structure of the concrete. Mechanical strength was analyzed through axial compression, splitting tensile, and flexural tensile strength tests. The modulus of elasticity and post-peak deformation capacity were also investigated to understand the structural behavior of the samples. The results were compared among the different mixtures, allowing an assessment of the influence of fiber incorporation on the mechanical strength and functionality of permeable concrete. The findings contribute to the development of more sustainable and durable urban pavements.

Originality/Relevance – The rapid urbanization process has exacerbated issues such as soil impermeabilization, increased stormwater runoff, and the urban heat island effect, necessitating sustainable solutions for urban drainage. In Brazil, urban drainage prioritizes hydraulic efficiency, often at the expense of environmental impacts. Permeable concrete emerges as a viable alternative, as it reduces surface runoff and improves water quality. However, its high porosity compromises mechanical strength, limiting its application in traffic areas. Recent studies have explored modifications in cementitious composites to address this limitation, such as the use of silica fume and polymeric fibers. Nevertheless, there is a gap in the literature regarding the impact of polypropylene fiber incorporation in permeable concretes containing silica fume, particularly in relation to the balance between permeability, mechanical strength, and post-cracking behavior. This study contributes to advancing knowledge by investigating different dosages of polypropylene fibers (1, 2, 3, and 4 kg/m³) in permeable concretes with 10% cement replacement by silica fume, evaluating their influence on mechanical and functional performance. The results may support the development of stronger and more durable concretes, expanding their practical application in sustainable urban infrastructure.

Results – The results demonstrated that the addition of polypropylene fibers significantly influenced the physical and mechanical properties of permeable concrete. The incorporation of fibers reduced bulk density while increasing permeability and void content, indicating greater pore connectivity. In mechanical tests, axial compressive strength and splitting tensile strength did not exhibit significant variations among different fiber dosages. However, flexural tensile strength increased with the addition of 1 kg/m³ of fibers, suggesting a positive effect on the concrete's ability to withstand bending stresses. For higher fiber dosages (2, 3, and 4 kg/m³), a slight reduction in flexural strength was observed, possibly due to increased porosity and difficulties in achieving homogeneous fiber dispersion within the cementitious matrix.

Theoretical/Methodological Contributions – This study contributes to the scientific literature by deepening the understanding of the impact of polypropylene fiber addition in permeable concretes modified with silica fume. The

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detailed analysis of the material's physical and mechanical properties, particularly concerning permeability, flexural strength, and modulus of elasticity, fills a research gap regarding the structural viability of this type of concrete for urban infrastructure applications. From a methodological perspective, the research stands out for its systematic experimental approach, evaluating different fiber contents (1, 2, 3, and 4 kg/m³) and comparing their effects on the porous structure and mechanical behavior of permeable concrete. The combined use of strength tests, modulus of elasticity assessment, and post-peak deformation capacity analysis provides a more comprehensive understanding of fiber-matrix interactions, enabling a more precise determination of optimal reinforcement conditions. Additionally, the results of this study offer a methodological foundation for future research aimed at optimizing permeable concretes with polymeric reinforcements, contributing to the development of more efficient and sustainable materials for the construction sector.
Social and Environmental Contributions – The use of permeable concrete with polypropylene fibers contributes to urban sustainability by reducing surface runoff, aiding in flood control, and enhancing groundwater recharge. Additionally, its application can mitigate the urban heat island effect, promoting improved thermal comfort. Socially, the adoption of this material supports the development of more resilient cities, reducing the need for conventional drainage infrastructure and its associated maintenance costs. This study fosters the advancement of sustainable construction technologies aligned with sustainability principles.

KEYWORDS: Permeable Concrete. Polypropylene Fiber. Mechanical Strength.

Análisis de la Influencia de la Adición de Fibras de Polipropileno en el Hormigón Permeable

RESUMEN
Objetivo – Este estudio tiene como objetivo investigar la influencia de la adición de fibras de polipropileno en las propiedades mecánicas y funcionales de los hormigones permeables que contienen un 10% de sílice activa, con el fin de evaluar su potencial para su aplicación en pavimentos urbanos sostenibles. Para ello, se analiza la influencia de la incorporación de diferentes contenidos de fibras (1, 2, 3 y 4 kg/m³) en la permeabilidad, el índice de vacíos y las resistencias mecánicas (compresión axial, compresión diametral y tracción en flexión). Además, se busca comprender la variación del módulo de elasticidad y la capacidad de deformación post-pico, comparando los resultados obtenidos con la mezcla de referencia para verificar la viabilidad del uso de estas composiciones en infraestructura urbana.
Metodología – El estudio se llevó a cabo en laboratorio y siguió un enfoque experimental para evaluar los efectos de la adición de fibras de polipropileno en hormigones permeables con un 10% de sílice activa. Inicialmente, se seleccionaron los materiales constituyentes, incluyendo cemento Portland, agregados, sílice activa y fibras de polipropileno. Las mezclas se prepararon con diferentes contenidos de fibras (1, 2, 3 y 4 kg/m³), además de una mezda de referencia sin fibras para comparación. Se moldearon los especímenes y se sometieron a ensayos para determinar sus propiedades físicas y mecánicas. Se evaluaron la masa específica, la permeabilidad y el índice de vacíos para caracterizar la estructura porosa del hormigón. La resistencia mecánica se analizó mediante ensayos de compresión axial, compresión diametral y tracción en flexión. También se investigaron el módulo de elasticidad y la capacidad de deformación post-pico para comprender el comportamiento estructural de las muestras. Los resultados se compararon entre las diferentes mezclas, permitiendo evaluar la influencia de la incorporación de fibras en la resistencia mecánica y la funcionalidad del hormigón permeable. Los hallazgos contribuyen al desarrollo de pavimentos urbanos más sostenibles y duraderos.
Originalidad/Relevancia – La creciente urbanización ha intensificado problemas como la impermeabilización del suelo, el aumento de la escorrentía pluvial y el efecto de isla de calor urbano, lo que exige soluciones sostenibles para el drenaje urbano. En Brasil, el drenaje urbano prioriza la eficiencia hidráulica, con frecuencia en detrimento de los impactos ambientales. El hormigón permeable surge como una alternativa viable, ya que contribuye a la reducción de la escorrentía superficial y mejora la calidad del agua. Sin embargo, su alta porosidad compromete la resistencia mecánica, limitando su aplicación en áreas de tráfico vehicular. Estudios recientes han explorado modificaciones en los compuestos cementosos para superar esta limitación, como el uso de sílice y fibras poliméricas. No obstante, existe una laguna en la literatura sobre el impacto de la incorporación de fibras de polipropileno en hormigones permeables que contienen sílice activa, especialmente en lo que respecta al equilibrio entre permeabilidad, resistencia mecánica y comportamiento post-fisuración. Así, este estudio contribuye al avance del conocimiento al investigar diferentes dosificaciones de fibras de polipropileno (1, 2, 3 y 4 kg/m³) en hormigones permeables con un 10% de sustitución de cemento por sílice activa, evaluando su influencia en el desempeño mecánico y funcional. Los resultados pueden respaldar el desarrollo de hormigones más resistentes y duraderos, ampliando su aplicación práctica en infraestructura urbana sostenible.

Resultados – Los resultados obtenidos demostraron que la adición de fibras de polipropileno impactó significativamente las propiedades físicas y mecánicas del hormigón permeable. La adición de fibras redujo la masa específica y aumentó la permeabilidad y el índice de vacíos, evidenciando una mayor conectividad entre los poros. En los ensayos mecánicos, la resistencia a la compresión axial y a la compresión diametral no presentaron variaciones significativas entre las diferentes dosificaciones de fibras. Sin embargo, la resistencia a la tracción en flexión aumentó con la adición de 1 kg/m³ de fibras, lo que sugiere un efecto positivo en la capacidad del hormigón para resistir esfuerzos de flexión. Con mayores contenidos de fibras (2, 3 y 4 kg/m³), se observó una ligera reducción en la resistencia a la flexión, posiblemente debido al aumento de la porosidad y a la dificultad de lograr una dispersión homogénea de las fibras en la matriz cementosa.

Contribuciones teóricas/metodológicas – Este estudio contribuye a la literatura científica al profundizar en la comprensión sobre el impacto de la adición de fibras de polipropileno en hormigones permeables modificados con sílice activa. El análisis detallado de las propiedades físicas y mecánicas del material, especialmente en relación con la permeabilidad, la resistencia a la flexión y el módulo de elasticidad, llena un vacío en la investigación sobre la viabilidad estructural de este tipo de hormigón en aplicaciones de infraestructura urbana. Desde el punto de vista metodológico, la investigación se destaca por su enfoque experimental sistemático, evaluando diferentes contenidos de fibras (1, 2, 3 y 4 kg/m³) y comparando su efecto en la estructura porosa y el comportamiento mecánico del hormigón permeable. El uso combinado de ensayos de resistencia, módulo de elasticidad y capacidad de deformación post-pico proporciona una visión más amplia sobre la interacción entre las fibras y la matriz cementosa, permitiendo una comprensión más precisa de las condiciones óptimas para el refuerzo del material.

Además, los resultados de este estudio ofrecen una base metodológica para futuras investigaciones que busquen optimizar hormigones permeables con refuerzos poliméricos, contribuyendo al desarrollo de materiales más eficientes y sostenibles para el sector de la construcción.

Contribuciones sociales y ambientales – El uso de hormigón permeable con fibras de polipropileno contribuye a la sostenibilidad urbana, reduciendo la escorrentía superficial, ayudando en el control de inundaciones y mejorando la recarga de los acuíferos. Además, su aplicación puede minimizar el efecto de isla de calor urbano, promoviendo un mayor confort térmico. Socialmente, la adopción de este material favorece ciudades más resilientes, reduciendo la necesidad de infraestructura de drenaje convencional y sus costos de mantenimiento. Este estudio fomenta el desarrollo de tecnologías sostenibles en la construcción civil, alineadas con los principios de sostenibilidad.

PALABRAS CLAVE: Hormigón Permeable. Fibra de Polipropileno. Resistencia Mecánica.

1 INTRODUCTION

Elango et al. (2021) analyzed the properties of porous concrete made with Portland cement, concluding that the compressive strength of pervious concrete with void ratios of 15%, 20%, and 25% ranges between 38 and 44 MPa, 29 and 35 MPa, and 15 and 22 MPa, respectively. Adamu et al. (2021) studied the durability performance of pervious concrete containing rice husk ash and calcium carbide waste (CCW) as partial replacements for Portland cement at rates of 5%, 10%, 15%, and 20%. Their research showed that both rice husk ash and calcium carbide waste had a negative effect on the durability of pervious concrete.

Ibrahim et al. (2014) estimated that for pervious concrete to perform well in water drainage, its void content should be between 15% and 35%. The authors explained that this range of voids in the concrete volume allows the pores to remain interconnected, thereby facilitating water passage.

Kistan et al. (2023) analyzed the inclusion of 0.4% polypropylene fibers in concrete along with a 30% replacement of cement with fly ash. This study demonstrated an increase in both compressive strength and flexural tensile strength from the early stages compared to fiber-free concrete.

In the literature, several authors have studied pervious concrete, focusing primarily on flexural tensile strength, a crucial property for pavements. For example, Batezini (2013) investigated the flexural tensile strength of pervious concrete samples without additives, varying the proportions of cement, aggregates, and water.

Fei et al. (2024) analyzed high-performance pervious concrete using a low-cost modified vinyl ester as a binder, conducting flexural tensile tests. Similarly, Brasileiro et al. (2024) investigated the influence of recycled aggregates and silica fume on the performance of pervious concrete. They observed a decrease in flexural tensile strength in samples containing 40%, 50%, and 60% recycled aggregates compared to samples with natural aggregates, with reductions of 5%, 27%, and 13%, respectively, at 28 days.

In this context, it is essential to advance the technology of pervious concrete pavements to mitigate the issues associated with impermeable urban areas while ensuring adequate mechanical strength. Therefore, this research aims to analyze pervious concrete with the addition of polypropylene fibers, seeking to evaluate new materials that contribute to the broader use of pervious pavements.

2 MATERIALS AND METHODS

2.1 Materials

The binder used was Portland Composite Cement with Filler (CP II-F-32) from the Itaú brand, as specified in its technical datasheets for application in various types of construction and manufactured in accordance with NBR 16697 (ABNT, 2018). The average specific mass of the cement was 3.02 g/cm³, as reported by the supplier.

For coarse aggregate, basalt crushed stone was used, sourced from a quarry located in the municipality of Itapura – SP, with a particle size ranging from 1 to 12 mm. The aggregate met the granulometric limits specified in NBR 7211 (ABNT, 2009). The maximum dimension, absorption, and specific mass characteristics were determined according to the same standard and are detailed in Table 1.

Table 1 - Physical Properties of Aggregates

Material	μ (g/cm³)	Absorção (%)	Dimensão Máxima (mm)
Agregado Graúdo	2,82 ± 0,03 [NBR NM 53 (ABNT, 2009)]	2,55 ± 0,05 [NBR NM 53 (ABNT, 2009)]	12,50

Source: Author (2023).

To compensate for the low water/cement ratio used in the mix design, the Tec-Flow 7000 superplasticizer was incorporated. This admixture complies with NBR 11768 (ABNT, 2019) and has a specific mass of 1.09 g/cm³, as reported by the manufacturer. It has a viscous appearance, with colors ranging from yellow to amber. The dosage was set at 0.5% of the cement weight, following the manufacturer's recommendation, which specifies a range of 0.5% to 1.5%.

The water used in the mixture was sourced from the municipal distribution network of Ilha Solteira – SP, extracted from deep wells in the São José dos Dourados hydrographic basin.

Additionally, Tecnosil silica fume was added to the mixtures containing coarse aggregate at a 10% proportion relative to the cement weight. The manufacturer ensures that the silica complies with NBR 13956 (ABNT, 2012). The physical properties of the silica used are detailed in Table 2.

Table 2 - Characteristics of Silica Fume

Massa Específica (g/cm³)	Teor de SiO2	Superfície Específica (m²/kg)	Formato da Partícula	Diâmetro Médio (mm)
2,22	≥ 90%	19.000	Esférico	0,0002

Source: Author (2023).

The Duristeel FF54 structural macrofiber was used to reinforce the pervious concrete, in compliance with ASTM C-116. The characteristics of this macrofiber are detailed in Table 3.

Table 3 - Characteristics of Duristeel FF54 Structural Macrofiber

Material	Módulo de Elasticidade	Peso Específico	Comprimento	Resistência a Tração	Absorção de água
Polipropileno	9,0 GPa	0,97 g/cm³	54 mm	850 MPa	Zero

Source: Author (2023).

The manufacturer recommends a minimum dosage of 1 kg/m³ and a maximum of 6 kg/m³ to improve the tensile strength of the concrete. Based on these guidelines and considering the total volume of 0.0157 m³ for the sample preparation, the following macrofiber contents were added for a comprehensive analysis: 1 kg/m³, 2 kg/m³, 3 kg/m³, and 4 kg/m³.

2.2 Physical and Mechanical Characterization of Pervious Concrete

The apparent density and the average void percentage were determined following the procedure described by ASTM C1688/C1688M (2014). The void ratio was calculated as the ratio between the volume of permeable pores and the total volume of the sample.

Although the void ratio is directly related to the permeability of the concrete, there is no specific normative limit for this characteristic. Studies, such as the one by Tennis et al. (2004), recommend a void ratio range between 15% and 25%. In this study, the range recommended by Tennis was adopted, as ratios below 15% may compromise the permeability of the concrete, while ratios above 25% may harm its structural strength.

The permeability coefficient represents the rate at which a certain amount of water percolates through a permeable element or structure and is the most important factor in evaluating porous concrete, which is typically designed to meet the demands of the environment where the pavement will be installed.

The permeability coefficient in this study was measured according to ISO 17875-1 (ISO, 2016), which, in simplified terms, employs the constant head method for the calculation, as per Equation 1.

$$\boldsymbol{K = \frac{m}{a.t}} \qquad (1)$$

Where:
K = permeability coefficient (mm/s)
m = mass of water (in mm³)
a = area of the test specimen's cylinder (in mm²)
t = time taken for the volume of water to percolate through the specimen (in seconds)

Over time, the permeability of concrete can be reduced due to the accumulation of solid particles carried by water and air. This accumulation tends to block the pores of the concrete, gradually decreasing its ability to allow water passage. To ensure that the pavement remains within performance standards throughout its lifespan, it was designed with a permeability coefficient higher than the minimum required by the NBR 16416 standard, which is 1 mm/s.

A slump test was also performed on all mixtures, following NBR 16889 (ABNT, 2020) and the procedure outlined in NBR 16886 (ABNT, 2020). None of the mixes exhibited a slump greater than two centimeters, which is in compliance with the guidelines described by Silva (2019).

2.3 Mechanical Tests

The following tests were conducted in the laboratory, according to the relevant technical standards, using a universal testing machine (Emic brand) with a capacity of 200 tons, ensuring the precision and reliability of the results obtained from the tests:

Axial compressive strength (NBR 5739, ABNT, 2018) on cylindrical specimens.

Diametral compression tensile strength (NBR 7222, ABNT, 2011) on cylindrical specimens.

Flexural tensile strength (NBR 12142, ABNT, 2010) on prismatic specimens.

A flexural tensile strength test (ASTM E855-90) was also performed on prismatic specimens to obtain the modulus of elasticity, as shown in Equation 2.

$$E = \frac{\mathrm{Pa}(3L^2-4a^2)}{4\mathrm{b}h^3\mathrm{v}} \qquad (2)$$

Where:
E = Modulus of Elasticity (GPa)
P = Load at 70% of failure (kN)
L = Span from support to load application (mm)
a = Base of the cross-sectional area (mm)

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Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 1, 2025

h = Height of the cross-sectional area (mm)
v = Deflection at the midspan (mm)

3. RESULTS AND DISCUSSION

3.1 Density, Void Index, and Permeability

Table 4 presents the average values of density and void index, along with their respective standard deviation (SD) and coefficient of variation (CV) obtained for the reference specimens and those with fiber addition.

The results showed that the dry apparent density of the hardened pervious concrete samples varied between 1900 and 1970 kg/m³. This range is in line with the values obtained by Batezini (2013) for pervious concretes, which range from 1700 to 2000 kg/m³.

Both mixtures, the reference mixture and those with fiber addition, presented densities greater than 1600 kg/m³, meeting the minimum required by the NBR 16416 standard (ABNT, 2015). This requirement is essential to ensure that the pervious concrete has the necessary density for its structural applications.

In Table 4, it can also be observed that the coefficient of variation for the results did not exceed 2%, both for density and void index. This low coefficient of variation suggests that the method employed in the mix design was efficient, resulting in minimal variability and confirming the consistency and uniformity of the mixtures. The consistency in the density values reflects good homogeneity in the mixture and the incorporation of the fibers.

Tabela 4 - Average Values of Density and Void Index

Mix Design	Density (Kg/m³)	CV(%)	DP (Kg/m³)	Void Index (%)	CV (%)	DP (Kg/m³)
Reference	1963,04	1,42	27,82	28,82	2,02	1,42
1Kg/m³	1904,06	1,61	30,78	29,86	1,61	2,46
2Kg/m³	1901,20	1,55	29,57	30,63	1,55	1,93
3Kg/m³	1897,4	1,49	30,12	31,9	1,93	1,7
4Kg/m³	1892,63	1,53	28,91	32,62	1,71	2,12

Source: Author (2023).

Furthermore, upon examining Table 4, it is clear that the void indices of the analyzed mixes were higher than 15%, aligning with the recommendations in the literature for pervious concretes, as suggested by Tennis et al. (2004). According to the American Concrete Institute (ACI, 2010), the void index of pervious concrete should range between 15% and 25% to ensure its drainage functionality. The void index of pervious concrete is critical for evaluating its effectiveness in allowing water to flow through its matrix, maintaining the expected functionality in pervious pavement applications.

In this study, the reference mix had a void index above the maximum suggested by ACI (2010), with a value of 28.8%. With the addition of 1 kg/m³ of fiber, the void index increased to 29.86%. Increasing the fiber addition to 2 kg/m³ raised the void index to an average of 30.63%. In the mixes with 3 kg/m³ and 4 kg/m³ fiber addition, the results increased to 31.9% and 32.62%, respectively.

As expected, the addition of polypropylene fiber to the pervious concrete mixes resulted in an increase in the void index of the samples. This phenomenon can be explained by the formation of additional spaces between the aggregates and the polypropylene fibers, which are

Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / Online Support - ISSN 1980-0827 Suporte CD-ROM / CD-ROM Support

Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 1, 2025

not filled by the hydrated cement. Toghroli et al. (2020) discuss that the increase in the void index in pervious concretes results from the accumulation of air in the concrete matrix, especially at the interfaces between the cementitious mix and the polypropylene fibers.

This increase in the void index is consistent with the literature and reflects the influence of the fibers on the porous structure of the pervious concrete. The presence of fibers provides additional channels for air retention, contributing to the elevation of the void index and potentially influencing the permeability and other physical properties of the concrete.

Table 5 presents the average values of the permeability coefficients (K) and their respective standard deviations and coefficient of variation. For each specimen, the permeability coefficient determination test was performed twice, and the average of the times was calculated for each sample.

Tabela 5 - Average Values of Permeability Coefficients

Mx	K	(DV) (%)	(CV) %
Reference	9,84	6,35	22,83
1Kg/m³	11,06	4,3	18,6
2Kg/m³	11,56	2,67	13,33
3Kg/m³	12,03	4,65	14,68
4Kg/m³	12,65	3,18	13,94

Source: Author (2023).

The proposed reference mix showed excellent drainage capabilities, with a permeability coefficient of 9.83 mm/s. According to Elango et al. (2020), the ideal permeable concrete should have a permeability coefficient in the medium range of 2 to 8 mm/s.

3.2 Mechanical Tests

The mechanical tests were conducted at 28 days, including tests for axial compressive strength, diametral compression, and flexural tensile strength (four-point bending), on the permeable concrete mixes with and without polypropylene fibers. The average results, along with the standard deviation and coefficient of variation, are presented in Table 6.

Tabela 6 - Average Values of Axial Compressive Strength, Diametral Compression, Flexural Tensile Strength, and Modulus of Elasticity

	REFERENCE	1Kg	2Kg	3Kg	4Kg
Compressão axial (MPa)	15,96	14,32	12,04	9,85	10,08
CV (%)	7,82	1,39	1,96	0,28	0,012
DP (MPa)	3,84	1,34	1,21	0,46	0,1
Compressão Diametral (MPa)	2	1,66	1,5	1,34	1,4
CV (%)	0,125	0,018	0,013	0,004	0,0013
DP (MPa)	0,61	0,11	0,1	0,058	0,032
Tração na Flexão (MPa)	1,38	1,5	1,34	1,26	1,17
CV (%)	0,4	0,4	0,52	0,12	0,03
DP (%)	0,48	0,14	0,1	0,3	0,17

Source: Author (2023).

As observed in Table 6, the reference mix showed the highest axial compressive strength compared to the samples containing the addition of polypropylene fibers. This suggests that the inclusion of fibers did not contribute to an increase in the axial compressive strength of the mix. Santana (2024) investigated the incorporation of glass fibers (AR) in permeable concrete using the same reference mix. A comparison between the results of adding glass fibers (AR) and polypropylene fibers (PP) is presented in Table 7.

Tabela 7 - Comparison of Axial Compressive Strength with Literature Values

REFERENCE	10% AR (MPa)	20% AR (MPa)	1Kg/m3 PP (MPa)	2Kg/m3 PP (MPa)	3Kg/m3 PP (MPa)	4Kg/m3 PP (MPa)
15,96	14,83	11,6	14,55	12,32	9,85	10,08

Source: Author (2023).

When examining Table 7, it can be observed that both polypropylene fibers and glass fibers (AR) resulted in a reduction in axial compressive strength compared to the concrete without fibers.

Regarding the tensile strength by diametral compression (Table 6), the addition of polypropylene fiber also showed a decrease in values compared to the reference mix, with this decrease increasing as the amount of fiber added increased.

The mix containing 1 kg/m³ of fiber showed a 17% reduction in tensile strength by diametral compression compared to the reference mix, while the mix with 2 kg/m³ reduced by 25%. The mixes with 3 kg/m³ and 4 kg/m³ of polypropylene fiber showed reductions of 33% and 31.5%, respectively.

Santana (2024) also investigated the same reference mix of permeable concrete with the addition of glass fibers (AR) to evaluate the tensile strength by diametral compression. Table 8 presents a comparison between the effects of adding polypropylene fiber and glass fiber, where 10% and 20% additions of glass fiber were used relative to the mass of the mix.

Tabela 8 - Comparison of Diametral Compression Strength with Literature Values

REFERENCE	10% AR (MPa)	20% AR (MPa)	1Kg/m3 PP (MPa)	2Kg/m3 PP (MPa)	3Kg/m3 PP (MPa)	4Kg/m3 PP (MPa)
2	2,41	1,74	1,65	1,5	1,33	1,39

Source: Author (2023).

A discrepancy is observed in the diametral compression tensile strength values, where the mixture with the addition of 10% glass fiber (AR) reached 2.41 MPa, showing higher strength compared to the reference mixture. On the other hand, the addition of polypropylene fiber resulted in a reduction in strength. The highest strength obtained with the glass fiber (AR) was 31.5% higher than the highest value achieved with the addition of polypropylene fiber.

In the flexural tensile test (Table 6), the addition of 1 kg/m³ of fiber proved beneficial. The average strength value for the reference mixture was 1.38 MPa, with a standard deviation of 0.48. The average values obtained for the mixtures with the addition of 1 kg/m³, 2 kg/m³, 3 kg/m³, and 4 kg/m³ of fiber were 1.5 MPa, 1.34 MPa, 1.26 MPa, and 1.17 MPa, respectively.

The addition of 1 kg/m³ resulted in an 8.7% increase in flexural strength, while the addition of 2 kg/m³ showed a 2.9% reduction. The greatest reduction in strength was observed with the addition of 4 kg/m³ of fiber, resulting in a 15.2% decrease, and with the addition of 3 kg/m³, the reduction was 8.9%.

Table 9 presents a comparison of the results from this study with some data found in the literature for permeable concrete.

Tabela 9 - Comparison of flexural tensile strength results with the literature

Flexural Tensile Strength Present Study (Mpa)	Flexural Tensile Strength Batezine (2013) (Mpa)	Flexural Tensile Strength Brasileiro (2024) (Mpa)	Flexural Tensile Strength Lin e Yu (2022) (Mpa)	Flexural Tensile Strength Santana (2024) (Mpa)	Flexural Tensile Strength Fei (2024) (Mpa)
1,38	2,16	2,46	2,61	2,41	8,86
1,5	2,03	2,33	11,11	1,74	
1,34	2,22	1,78	4,36		
1,26	1,38	2,12			
1,17	1,5				
	1,34				
	1,26				
	1,17				

Fonte: Autor (2023).

In the literature, the results are generally higher than those of the present study; however, the literature results have lower void indexes than those in this study. Brasileiro et al., 2024, worked with void indexes in the range of 12% to 16%; Fei et al., 11%; and Batezini, from 24% to 25%. It is noted that resistance decreases with an increase in the void index, while permeability decreases with the same increase. Santana et al., 2024, worked with similar void indexes and also found higher values. However, it should be noted that these values were obtained using a three-point bending test, which results in higher resistance values.

Table 10 presents the results for the modulus of elasticity, deflection value, and the percentage difference between the values for the reference concrete and the concrete with added fiber.

From Table 10, it can be observed that the maximum deflection occurred in the sample without fiber, while the sample with 1 kg/m³ of fiber showed the lowest deflection, with a value very close to the sample with 2 kg/m³. The samples with 3 kg/m³ and 4 kg/m³ exhibited higher deflections. The mixtures with 1 and 2 kg/m³ of fiber showed the greatest differences in both deflection and modulus of elasticity compared to the concrete without fiber. This is consistent with Equation 2, where the modulus of elasticity is directly proportional to the load and inversely proportional to the deflection.

Tabela 10 - Deflection, Modulus of Elasticity, and the Difference Between Reference and Fiber-Added Values:

Mix	Maximum deflection (mm)	Difference in maximum deflection (%)	Elastic Modulus (MPa)	Difference E (%)
Reference	1,54	-	124	-
1Kg/m³	1,12	- 27,27	200	+ 61
2Kg/m³	1,14	- 25,97	175	+ 45
3Kg/m³	1,4	- 9,1	130	+ 6
4Kg/m³	1,53	- 0,65	123	0

Source: Author (2023).

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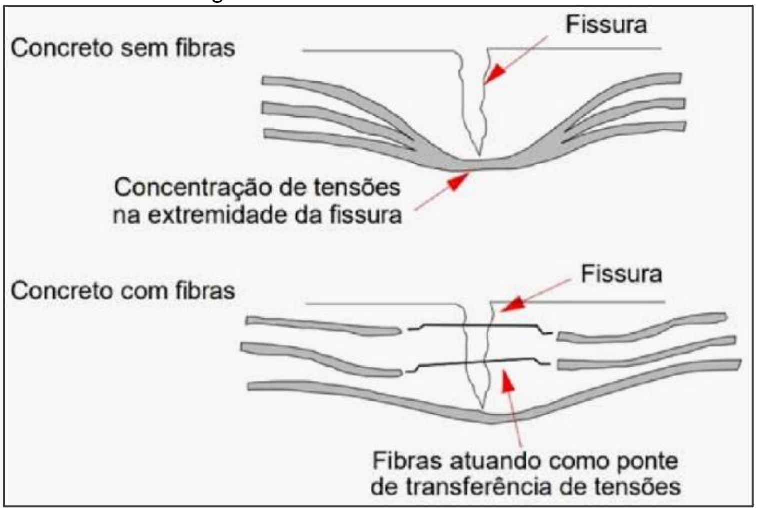
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 1, 2025

This relationship occurs because the fibers restrict crack opening, making it harder for the crack to propagate, as illustrated in Figure 1 (Silva et al., 2019), which reduces the deflection value at the center of the specimen. However, after a certain amount of fiber, the resistance begins to decrease enough for the fiber to no longer prevent crack propagation and, consequently, the deflection deformation.

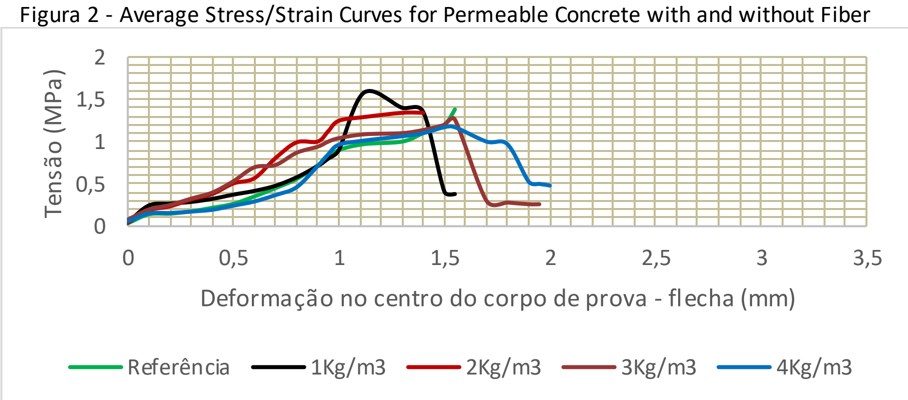
Figure 2 presents the average stress/strain curves for permeable concrete with and without fiber. It is possible to observe the sudden rupture of the concrete without fiber, as it does not exhibit a post-peak stress drop, as occurs in concretes with fiber addition. The reference mix showed an average deformation of 1.54 mm at rupture, while the mix with the addition of 1 kg/m³ of polypropylene fiber recorded an average deformation at rupture, measured by the LVDT, of 1.12 mm, representing a reduction of 27.27%.

Figura 1 - Action of Fibers in Concrete



Source: Silva *et al.*, 2019.

Figura 2 - Average Stress/Strain Curves for Permeable Concrete with and without Fiber



Source: Autor (2023).

4. CONCLUSION

The research was conducted with the aim of evaluating the mechanical properties of permeable concrete, including axial compression strength, diametral tensile strength, flexural tensile strength, and modulus of elasticity. Permeability, void index, and specific mass were also assessed.

The results allowed for the following conclusions: The addition of polypropylene fibers resulted in a decrease in axial and diametral compressive strength. This decrease increased with the amount of fiber added. The reduction in axial and diametral compressive strength may be directly related to the increase in the void index of the permeable concrete with the addition of polypropylene fibers.

The flexural tensile strength varied with the addition of polypropylene fibers. The mixture with 1 kg/m³ of fiber showed an increase in strength compared to the reference mix. The mixture with the addition of 2 kg/m³ of fiber obtained a value very close to the concrete without fibers. However, the mixtures with 3 and 4 kg/m³ of fiber showed a decrease in flexural strength. Therefore, there is an "ideal" amount of fiber for it to act as a stress transfer source; beyond this amount, the matrix begins to lose strength, and the stress transfer is no longer sufficient to produce higher values than the permeable concrete without fiber.

The flexural modulus of elasticity showed an increase with the inclusion of polypropylene fibers, compared to the reference concrete, for fiber amounts of 1, 2, and 3 kg/m³. However, increasing fiber content led to a decrease in the modulus of elasticity, with the mixture containing 4 kg/m³ presenting a value equal to the reference mixture.

The fibers directly influenced the deformation of the permeable concrete, resulting in a reduction in maximum deflection, mainly in the mixtures with 1 and 2 kg/m³, which directly impacted the increase in the modulus of elasticity, as it is directly proportional to the load and inversely proportional to the displacement at the center of the specimen (deflection).

This occurs because the fiber holds the crack opening, making its propagation more difficult, which reduces the deflection value at the center of the specimen. Beyond a certain amount of fiber, the strength starts to decrease enough that the fiber can no longer hold the crack propagation and, consequently, the deflection deformation.

The addition of fibers also resulted in a decrease in density and an increase in the void index and permeability coefficient, which became more evident with higher fiber additions. All mixtures showed excellent drainage capacities, greater than those suggested by the literature.

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ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - v. 21, n. 1, 2025

DECLARAÇÕES

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Ao descrever a participação de cada autor no manuscrito, utilize os seguintes critérios:

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DECLARAÇÃO DE CONFLITOS DE INTERESSE

Eu/Nós, Guilherme Augusto Donegá Rocha, Maria da Consolação Fonseca de Albuquerque, Anderson Mauricio Carvalho Santana, Alexsandro dos Santos Felipe, Aparecido Carlos Gonçalves, declaramos que o manuscrito intitulado Análise da influência da adição de fibras de polipropileno no concreto permeável:

1. **Vínculos Financeiros**: Não possui vínculos financeiros que possam influenciar os resultados ou interpretação do trabalho. Nenhuma instituição ou entidade financiadora esteve envolvida no desenvolvimento deste estudo.
2. **Relações Profissionais**: Não possui relações profissionais que possam impactar na análise, interpretação ou apresentação dos resultados. Nenhuma relação profissional relevante ao conteúdo deste manuscrito foi estabelecida.
3. **Conflitos Pessoais**: Não possui conflitos de interesse pessoais relacionados ao conteúdo do manuscrito. Nenhum conflito pessoal relacionado ao conteúdo foi identificado.