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Impact of PET and microfiber fibers on the mechanical properties of pervious concrete: a canonical correlation approach.

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ABSTRACT
The objective of this work was to analyze the effect of polypropylene microfibers and PET fibers on the mechanical properties and electrical resistivity (ER) of pervious concrete. Three mixtures were designed—control, with microfibers, and with PET—and tested in compression, tension, flexure, ER, and resonance frequency. The results were integrated through a Canonical Correlation Analysis (CCA) to identify multivariate relationships between fiber reinforcement and material performance. CCA revealed significant correlations between fiber incorporation and increases in mechanical strength, as well as their relationship with variations in ER. This study is original in applying CCA to pervious concrete: fibers improve structural behavior, and CCA provides a precise and comprehensive multivariable interpretation.
Keywords: multivariate analysis, structural behavior, resonance frequency, experimental characterization, dynamic modulus of elasticity.

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Contribution of each author
In this work, author M. G. Gómez-Valdovinos contributed to the experimental development (50%) and writing of the paper (75%); author W. Martínez-Molina contributed to the definition of the experimental methodology (50%), as well as its review and follow-up (75%); author A. Muciño-Velez contributed to data collection (25%) and experimental development (50%); author M. Arreola-Sánchez contributed to data collection (75%) and the analysis and interpretation of the mechanical analysis (50%); author H. L. Chávez-García contributed to the analysis and interpretation of the mechanical analysis (50%); M. A. Navarrete-Seras contributed to the definition of the experimental methodology (50%), as well as its review and follow-up (25%); J. P. Molina-Aguilar carried out the discussion of the application of the canonical method (75%), and E. M. Alonso-Guzman contributed the original idea (100%), discussion of the application of the canonical method (25%), and writing of the paper (25%).

Impacto de fibras de PET y microfibras en las propiedades mecánicas de concreto permeable: una aproximación con correlación canónica.

RESUMEN

El objetivo de este trabajo fue analizar el efecto de microfibras de polipropileno y fibras de PET en las propiedades mecánicas y en la resistividad eléctrica (RE) del concreto permeable. Se diseñaron tres mezclas —control, con microfibras y con PET— y se evaluaron compresión, tensión, flexión, RE y frecuencia de resonancia. Los resultados se integraron mediante un Análisis de Correlación Canónica (ACC) para identificar relaciones multivariadas entre el refuerzo y el desempeño del material. El ACC mostró correlaciones significativas entre la incorporación de fibras y el incremento de resistencia mecánica, así como su relación con la variación en RE. El estudio es original porque al aplicar ACC a concretos permeables las fibras mejoran el comportamiento estructural y el ACC aporta una interpretación integral precisa.

Palabras clave: análisis multivariado, comportamiento estructural, frecuencia de resonancia, caracterización experimental, módulo de elasticidad dinámico.

Impacto das fibras e microfibras de PET nas propriedades mecânicas do betão permeável: uma abordagem de correlação canónica.

RESUMO

O objetivo foi analisar o efeito de microfibras de polipropileno e fibras de PET nas propriedades mecânicas e na resistividade elétrica (RE) do concreto permeável. Três misturas foram elaboradas—controle, com microfibras e com PET—e avaliadas em compressão, tração, flexão, RE e frequência de ressonância. Os resultados foram integrados por meio da Análise de Correlação Canônica (ACC) para identificar relações multivariadas entre o reforço fibroso e o desempenho do material. A ACC mostrou correlações significativas entre a incorporação de fibras e o aumento da resistência mecânica, bem como sua relação com a variação da RE. O estudo é original ao aplicar ACC a concretos permeáveis: as fibras melhoram o comportamento estrutural e a ACC fornece uma interpretação multivariada precisa e abrangente.

Palavras-chave: análise multivariada, comportamento estrutural, frequência de ressonância, caracterização experimental, módulo de elasticidade dinâmico

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1. INTRODUCTION

Pervious concrete is a material with multiple environmental benefits. It is a hydraulic concrete made with materials similar to those used in conventional concrete, but with special care taken in the grain size of the stone aggregate and with less water. (Rangelov et al. 2016). The control of particle size aims to produce a material with an open structure and connectivity between pores that allows water and air to flow through the voids present in it; to achieve this, coarse aggregates with little or no fines are used (Hesami et al. 2014).
Porosity between 15 and 30% is the main characteristic that has led to pervious concrete being used to reduce stormwater runoff, mitigate the heat island effect in urban areas, allow water to pass through to the water table, and minimize noise caused by tire-pavement interaction thanks to sound absorption (Park et al. 2022; Nazeer et al. 2023). According to Oni et. al. (2020) the use of pervious concrete brings environmental, economic, and social benefits. The higher the percentage of pores inside the concrete, the greater the water permeability, sound absorption, and lower thermal capacity (Park et al. 2022), for example, a pore percentage between 15% and 30% allows for water permeability of approximately 2 to 6 mm/s (Zhong et. al., 2018); however, with increased porosity and heterogeneity, the mechanical properties of the material decrease. Unlike conventional concrete, in pervious concrete, the strength properties are more closely linked to the aggregate-cement ratio than to the water-cement ratio (Chandrappa and Biligiri 2016). Pervious concrete designed for 15, 20, or 25% porosity typically has compressive strengths of 38-44 MPa, 29-35 MPa, and 15-22 MPa, respectively (Zhong et. al. 2018); its flexural strength is between 1 and 6 MPa, depending on the design (Nguyen, Tran, and Vu 2022); and, it has water/cement ratios in the range of 0.26 to 0.45 to maintain the stability of the cement paste without compromising mechanical strength too much (Zhong et al. 2018).
The ability to move a high volume of water through its interconnected pores into the subsoil is the main environmental benefit offered by pervious concrete, resulting in groundwater recharge, reducing flooding due to a lack of percolation areas in urban areas, and decreasing or eliminating problems related to rainwater (Sherwani et al. 2021). When used as a wearing course in pavement, the U.S. Environmental Protection Agency lists the following advantages: natural filtration removes contaminants, resulting in natural water treatment, less need for drainage works alongside roads (curbs and storm drains), increased driving safety due to greater skid resistance, and, if properly designed granular layers are used, recharge of local aquifers (Giustozzi 2016).
Certainly, all the benefits mentioned are linked to the number of pores in the material. However, this internal porosity compromises homogeneity when distributing internal stresses due to external forces, resulting in lower mechanical strength than conventional concrete (Song et. al. 2022). Improving mechanical performance is one of the major challenges for pervious concrete; Zhou et al. (2016) indicate that, with the intention of obtaining the required continuous voids and sufficient mechanical strength, several studies have evaluated the performance of this concrete modified with polymer fibers, reporting an increase in void content, permeability, and compressive strength with such incorporation. Juradin et al. (2021) investigated the incorporation of fibers and the compaction method in the properties of pervious concrete, concluding that the addition of fibers improves mechanical properties while negatively affecting the porosity and permeability of the mixtures. Based on an analysis of the incorporation of fibers obtained from solid waste in hydraulic concrete, Blancas-Herrera et al. (2020) conclude that this type of addition is a great alternative for creating a material with greater mechanical responses to tensile, flexural, and ductility forces, as well as being a more homogeneous material with greater energy absorption. With regard to durability, J. T. Kevern and D. Biddle (2017) designed a test plan to verify the effects of pervious concrete with macro synthetic fibers on its structure in terms of its durability properties. a reduction in surface abrasion, permeability, and filtration rate was obtained, with an improvement in resistance to the

freezing and thawing process. In line with the ideas outlined above, T.K.M Ali and N. Hilal (2020) proposed the idea of incorporating PET into concrete as an ideal option due to the non-degradable characteristics of this plastic, since, after an experiment in which they added this waste to reinforced concrete, they observed improved behavior against cracking in beams, as well as improved tensile strength, drying shrinkage, creep, chemical resistance, and a change in the type of failure from brittle to ductile.

The multivariate method Canonical Correlation Analysis (CCA) can be defined as a linear mathematical method used to compare two groups of data: an independent set called "X" and a dependent set called "Y" with a quantity p of variables x_i and q of variables y_i, respectively (D. Díaz 2015). The main objective of the method is to quantify the validity of the relationship between the two sets of variables mentioned above. For this reason, it is applied in many areas such as meteorology, demography, biology, chemistry, political science, knowledge sciences, psychometrics, sociology, administrative sciences, pedagogy, and even artificial intelligence (Badii and Castillo 2017).

ACC is a multivariate method to be solved using numerical linear algebra techniques, as it is a maximum problem with constraints, which can be solved with eigenvalues and eigenvectors if the Lagrange multiplier method is applied for its analysis (B.C. Matías Castillo et. al. 2017). The remarkable thing about ACC is that multiple dependent variables can be predicted simultaneously from the set of independent variables; this analysis is carried out by creating several canonical functions (theoretical canonical values) that maximize the correlation between the two linear combinations. In addition, this technique allows both dependent and independent variables to be metric and non-metric, continuous and discrete (R.A. Viana Marcelo and J. L. Navarro España 2012).

The method has the following three objectives (Badii and Castillo 2017):

1. To establish whether two sets of variables quantified in the same sample or population are independent of each other or, if not, to find the magnitude of the relationships that may exist between them.
2. Assign a weight or relative value to each set of criterion variables and predictor variables in order to achieve the maximum correlation between the linear combinations of each set.
3. Declare the nature of all relationships found between the sets of dependent and independent variables.

The advantage of ACC over Principal Component Analysis (PCA) or multivariate regression is that it focuses on simultaneously exploring the relationship between two sets of multivariate variables, establishing their interrelationship. It also identifies linear combinations, making it possible to maximize their correlation, which reduces the dimensionality of the study while preserving relevant information. This makes it easier to work with large and complex data sets.

Based on the ideas developed in the previous paragraphs and with the aim of further expanding knowledge about pervious concrete with different fiber additives, this study analyzes three pervious concrete mixtures: a control mixture without additives, a second mixture with polypropylene microfibers added, and, finally, a mixture with PET macrofibers added (Gómez Valdovinos et al. 2025).

The analysis of the mechanical properties of pervious concrete is more complex than that of conventional hydraulic concrete due to the heterogeneity of its internal structure of interconnected pores and the small amount of cement paste that binds the edges of the aggregate geomaterials.

The objective of this study is to adequately define the variables that delimit and define the mechanical properties in pervious concrete, and then apply a multivariate technique to these variables to enable a different analysis of the material.

Despite extensive research on pervious concrete, there is no evidence of the application of a multivariate technique for its analysis; therefore, a more in-depth analysis of the results obtained in the mechanical tests carried out on pervious concrete with added fibers is performed using the ACC multivariate technique.

2. MATERIALS AND METHODS

2.1 Materials

The materials used to make pervious concrete were water, Portland cement, gravel only or coarse geomaterial without fine aggregate, and an air-entraining additive, in order to obtain a workable mixture:

- Drinking water.
- Portland cement composite, strength class 30 MPa, rapid strength, and sulfate resistance (CPC 30 R RS) in accordance with Mexican standard NMX-C-414-ONNCCE-2017 established by the National Organization for Standardization and Certification in Construction and Building (ONNCCE) (ONNCCE 2017), equivalent to Type II of the classification presented by international standard ASTM C 150 (ASTM C150/C150M-24).
- Crushed basalt gravel with sizes ranging from 19 mm (3/4“) to 4.76 mm (mesh no. 4), homogeneous granulometry, from the “TRACSA" material bank located in the state of Michoacán, Mexico (Figure 1). Its characteristics are presented in Table 1.
- Air-entraining additive based on synthetic surfactants.
- Ground PET flakes with the highest percentage of particles passing through mesh no. 4 and retained in mesh no. 8. Waste collected specifically for this purpose (Figure 1).
- Structural synthetic polypropylene microfibers for concrete with a size of approximately 20 mm long, 0.5 mm wide, and 0.19 mm thick (Figure 1).

a) Crushed Gravel b) PET flakes c) Microfibers

Figure 1. Materials used to make the different mixtures.

The mix design was prepared in accordance with the parameters indicated in the report on pervious concrete (ACI 2010) of the American Concrete Institute (ACI), and following the procedure dictated in standard ACI 211.3 (ACI 2002) for zero slump concrete.

Table 1. Characteristics of coarse geomaterial aggregate

Material	**Nominal Maximum Size (NMS)**	**Density**	**Compacted dry volumetric mass (MVSC)**	**Absorption**
	(pulg)	(kg/m^3)	(kg/m^3)	%
Gravel	3/4"	2632.5	1675	1.50

Three mixtures of pervious concrete were prepared with a water/cement mass ratio of 0.4 and 6 ml of air-entraining additive per kilogram of cement. Table 2 provides the necessary dosages of the different materials for the preparation of 1 m³ of each mixture. The control mixture is designated TP-6, the mixture with PET is designated TP-6PET, and the mixture with microfibers is designated TP-6M.

Table 2. Dosage of materials in the mixtures produced.

Mixture	**Cement** (kg/m^3)	**Gravel** (kg/m^3)	**Water** (kg/m^3)	**Additive** (ml/m^3)	**PET** (kg/m^3)	**Microfibers** (kg/m^3)
TP-6	271.423	1658.250	133.776	1628.538	-	-
TP-6PET	271.423	1658.250	133.776	1628.538	1.651	-
TP-6-M	271.423	1658.250	133.776	1628.538	-	1.651

For the electrical resistivity and compressive strength tests performed on pervious concrete, cylindrical specimens with a diameter of 15 cm and a height of 30 cm were prepared; cylindrical specimens measuring 10 cm in diameter and 20 cm in height were prepared for the indirect tensile test, as well as prisms measuring 15 cm x 15 cm x 60 cm to carry out the flexural and resonance frequency tests. Three specimens were cast to be subjected to the aforementioned mechanical tests at each of the ages of 7, 14, 28, 90, 120, and 180 days.

2.2 Methodology for physical-mechanical analysis

The following tests were performed to determine the physical and mechanical characteristics: electrical resistivity (RE); resonance frequency to obtain the dynamic modulus of elasticity (Ed); simple compression (f'c); indirect tensile strength, Brazilian or Joao Carneiro test, TI; and beam bending, or modulus of rupture (MR).

The electrical resistivity (RE) test was carried out according to the procedure and instructions given in Mexican standardNMX-C-514-ONNCCE-2019 “Electrical Resistivity of Hydraulic Concrete” (ONNCCE 2019c) in order to complement the experimental mechanical analysis with a physical test on the material under study. Thus, RE was included in the experimental characterization because it is a physical indicator sensitive to the microstructure, void continuity, and moisture content of pervious concrete. Although this type of concrete has an open porous network, RE allows the identification of changes associated with the incorporation of fibers and the modification of the cement paste, providing complementary information to the mechanical tests. Given that ACC requires independent and physically linked variables to explain the overall response of the material, RE was essential to strengthen the integrative analysis of the properties studied. The resonance frequency test was carried out using the procedure established by standard NMX-C-089-ONNCCE-2019 “Determination of fundamental, transverse, longitudinal, and torsional frequencies of concrete specimens” (ONNCCE 2019a) to determine the dynamic modulus of elasticity in the three mixtures. Compressive strength was obtained using the specifications set forth in Mexican standard NMX-C-083-ONNCCE-2014 “Determination of compressive strength” (ONNCCE 2014). The method indicated in standard NMX-C-163-ONNCCE-2019 “Determination of tensile strength by diametral compression of concrete cylinders—test method” (ONNCCE 2019b) was used. The modulus of rupture of each of the mixtures was quantified using the three-point method with a beam loaded at the middle third of the span, in accordance with standard NMX-C-191-ONNCCE-2015 “Determination of the flexural strength of concrete using a simple beam with load applied at one-third of the span” (ONNCCE 2015).

2.3 Multivariate analysis methodology

he development of the multivariate Canonical Correlation Analysis method, mathematically speaking, was developed by Hotelling in 1936 (Hotelling 1936). The following paragraphs describe an adaptation of the original method (Ouarda et al. 2001):

If we consider that the independent variables are grouped in a matrix X = (x_1, x_2, … , x_p) and the dependent variables in another matrix called Y = (y_1, y_2, … , y_q), we can define the composite variables U and W, called canonical variables, a form of latent variables, which correlate the two sets of variables mentioned above and are defined as the linear combination of the set of original variables. To obtain the canonical variables that will represent the linear combination with maximum variance, it is necessary to multiply the transpose of weight vectors a = (a_1, a_2, … , a_p) y b = (b_1, b_2, … , b_q) by the matrices of dependent and independent variables, respectively, as shown in formulas (1) y (2).

$$U = (a_1, a_2, \dots, a_p)(x_1, x_2, \dots, x_p) = a_1x_1 + a_2x_2 + \cdots + a_px_p = a^Tx \tag{1}$$

$$W = (b_1, b_2, \dots, b_q)(y_1, y_2, \dots, y_q) = b_1y_1 + b_2y_2 + \cdots + b_qy_q = b^Ty \tag{2}$$

Since the p x q variance-covariance matrix corresponding to both sets is symmetric, the covariance matrices between the sets of independent variables with respect to the dependent variables satisfy $C_{YX} = C_{XY}^T$, so the canonical correlation coefficient will be:

$$corr\,(U,W) = \frac{cov(U,W)}{\sqrt{var(U)}\sqrt{var(W)}} = \frac{a^TC_{XY}b}{\sqrt{a^TC_{XX}a}\sqrt{b^TC_{YY}b}} \tag{3}$$

Since equation (3) is a rational function with radicals in its denominator, to find its solution it is necessary that $\boldsymbol{var(U) = a^TC_{XX}a}$ and $\boldsymbol{var(W) = b^TC_{YY}b}$ are equal to 1, considering respectively the variances of the sets of independent (C_{XX}) nd dependent (C_{YY}) variables.

This implies two normalization constraints, in addition to the fact that the solution must be such that it favors maximization. If the Lagrange multiplier method is applied to maximize the above equation with both constraints, τ_1 and τ_2 represent the scalar coefficients that weight both terms. It is necessary to solve the following Lagrangian equation:

$$L(a,b) = a^TC_{XY}b - \tau_1(a^TC_{Xx}a - 1) - \tau_2(b^TC_{YY}b - 1) \tag{4}$$

Since both normalization constraints must be satisfied simultaneously, the scalar coefficients must have the same magnitude associated with an eigenvalue λ that defines the respective linear transformation, given that the aim is to optimize equation 4, which is made up of square matrices. By obtaining the multivariate gradients of both sets of variables, the Lagrangian function generates equations (5) and (6), whose solutions allow us to obtain the weight vectors a and b.

$$C_{YY}^{-1}C_{XY}^{T}C_{XX}^{-1}C_{XY}b-\lambda^2 b=0 \tag{5}$$

$$C_{XX}^{-1}C_{XY}C_{YY}^{-1}C_{XY}^{T}a-\lambda^2 a=0 \tag{6}$$

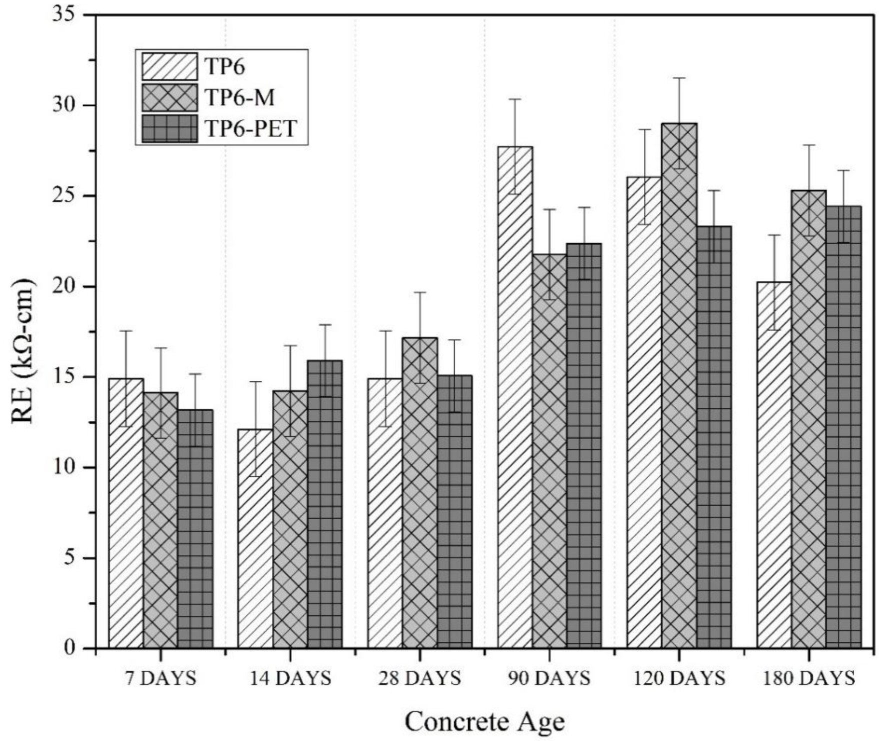
For the particular case of this work, the calculation of the weight vectors a = (a_1, a_2, … , a_p) and b = (b_1, b_2, … , b_q) was performed using the “STATISTICA” software, which analyzes the information, processes it, and outputs factors that only need to be destandardized and denormalized to define the weight vectors a and b, these being the core part of the procedure when defining the linear equation that correlates all the variables under analysis.

2.4 Definition of variables for multivariate analysis

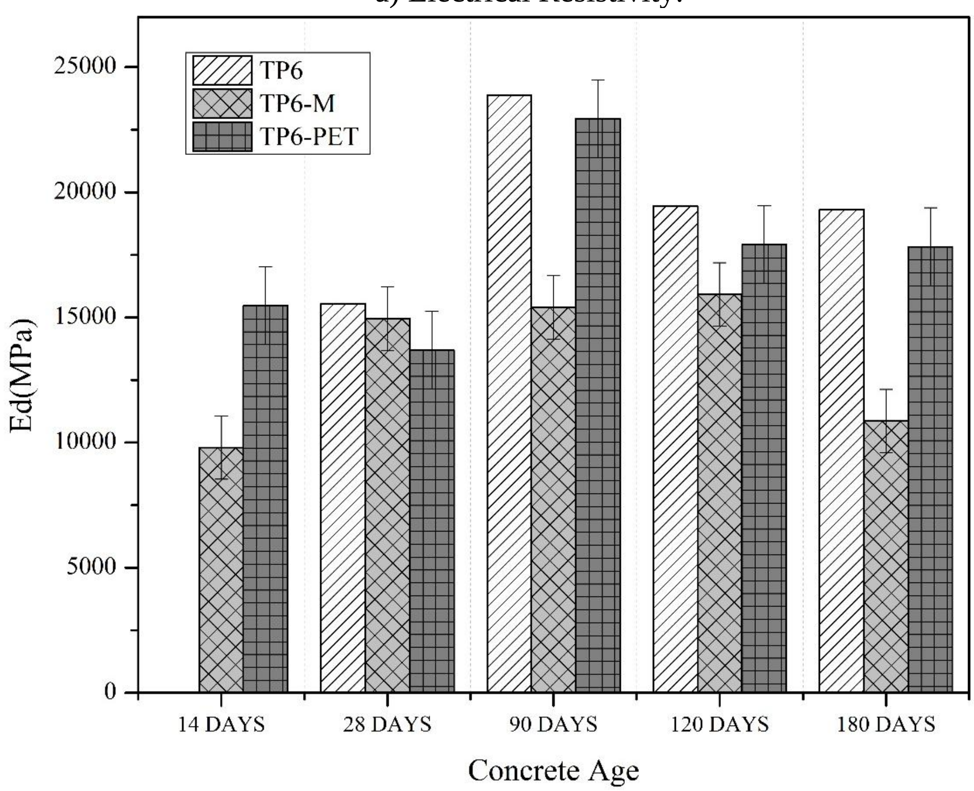
In this study, the dependent variables were defined by the results of the physical-mechanical tests carried out on the specimens of each mixture, that is, electrical resistivity, dynamic modulus of elasticity, compressive strength, indirect tensile strength, and modulus of rupture; these results are recorded in Table 3. The group of independent variables (Table 3) consists of two variables: one that defines the test age (7 days, 14 days, 28 days, 90 days, 120 days, or 180 days) called Age, and another that defines the type of mixture 1, 2, or 3 (1-TP6, 2-TP6M, 3-TP6PET) which was called T-add. The definition of this last variable was carried out with the aim of including the type of addition in the Canonical Correlation Analysis to verify whether the added fibers have an influence on the mechanical properties of a pervious concrete, so it was decided to use quantitative values (1, 2, and 3) to define each mixture made. The data matrix containing the union of the dependent and independent variables created to perform the analysis is shown in Table 4 in “Results,” since it was defined with the results of the physical-mechanical tests performed on the three mixtures prepared at the established test ages.

3. RESULTS AND DISCUSSIONS

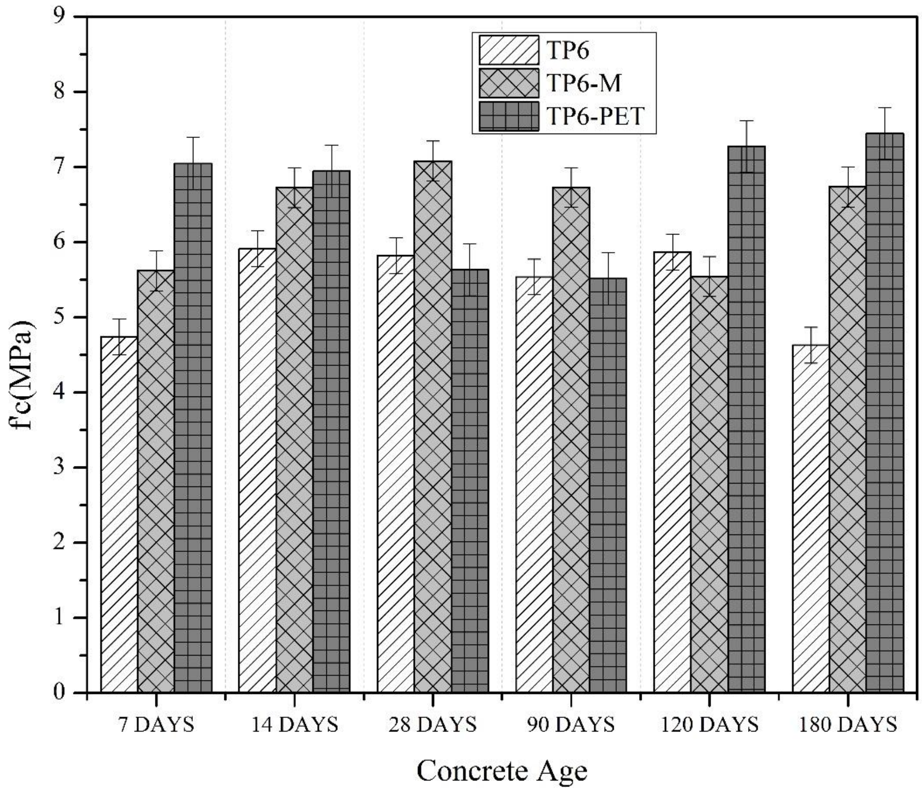
3.1 Physical-mechanical analysis



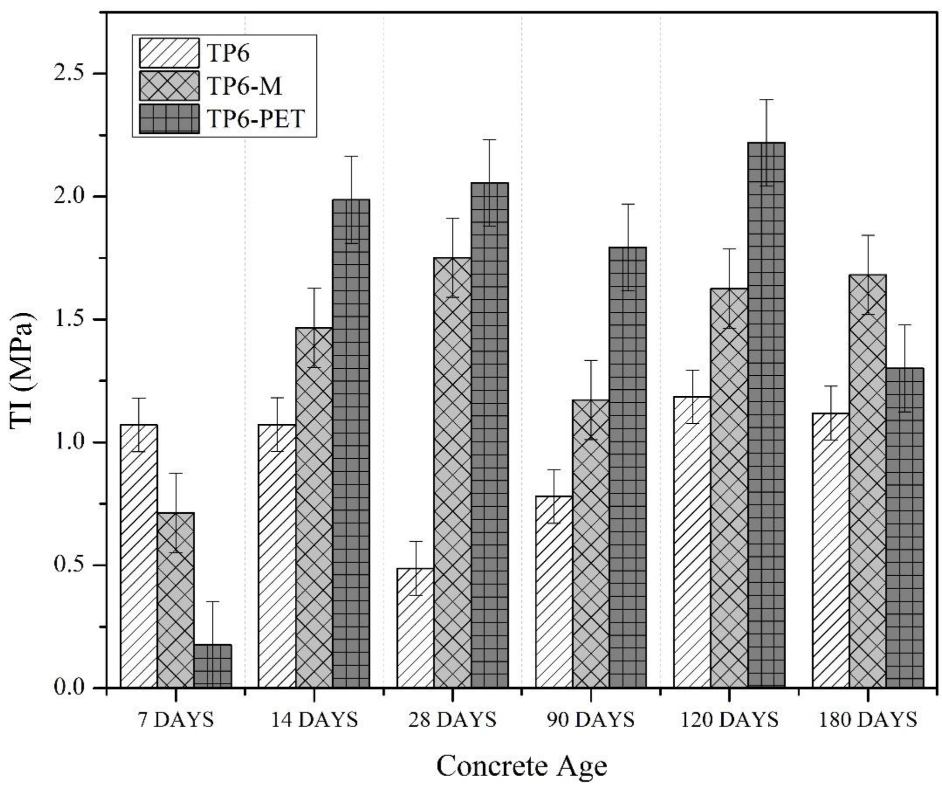
a) Electrical Resistivity.



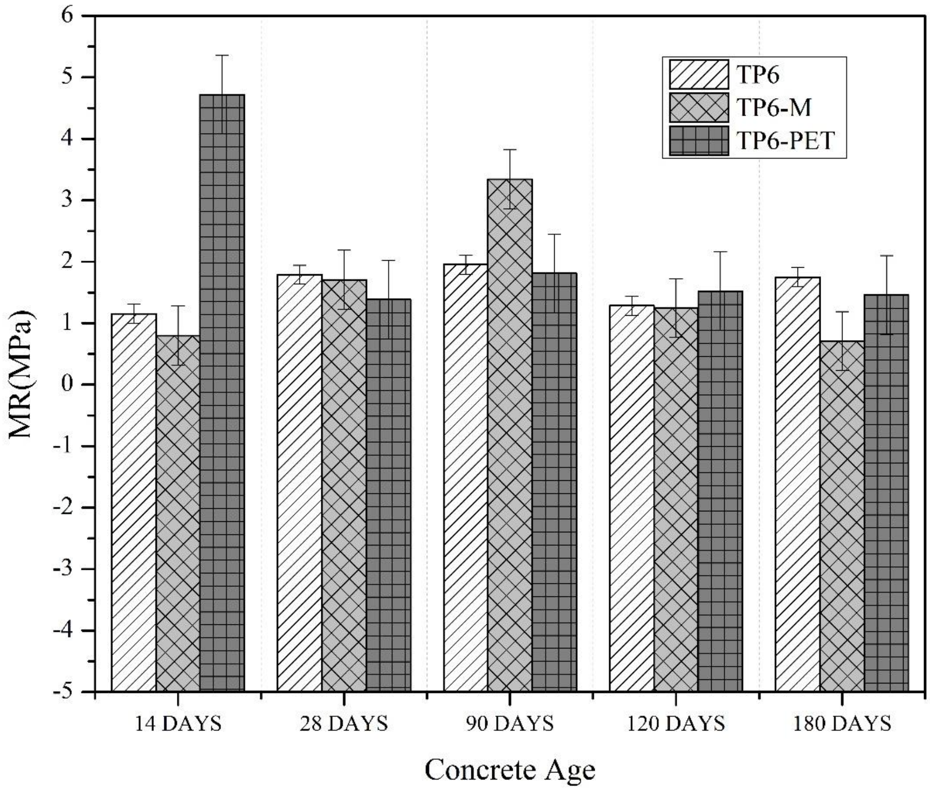
b) Modulus of elasticity.



c) Compressive Strength.



d) Indirect Tensile Strength.



e) Flexural strength module.
Figure 3. Mechanical test results

Table 3. Definition of dependent variables and independent variables

Name	Definition	Descripction	Unity	Obtention	Type (Discrete or Continuous)	Type (Metric or Non-Metric)
Dependent variables						
Electrical Resistivity	RE	Electrical property of a material that measures its ability to oppose the flow of an electric current	kΩ-cm	Based on standard NMX-C-514-ONNCCE-2019, with a resistometer	Continuous	Metric
Dynamic elasticity module	Ed	The fundamental resonance frequency of a concrete specimen is obtained for the purpose of calculating Young's dynamic modulus of elasticity	MPa	Based on standard NMX-C-089-ONNCCE-2019, using an e-meter	Continuous	Metric
Compressive strength	f’c	Compressive strength is the	MPa	Based on standard	Continuous	Metric

		resistance of a specimen under axial loading expressed as force per unit area		NMX-C-083-ONNCCE-2014, with the Forney universal machine		
Indirect Tensile Strength	TI	The maximum unit stress that a material can withstand under an axial tensile load is called tensile strength	MPa	Based on standard NMX-C-163-ONNCCE-2019, with the Forney universal machine	Continuous	Metric
Flexural strength	MR	The flexural strength is the value obtained by applying normal load to the axis, causing flexural compression in the fibers of the simply supported prismatic element.	MPa	Based on standard NMX-C-191-ONNCCE-2015, with the Forney universal machine	Continuous	Metric

Independent variables

Concrete Age	Age	Days after casting, during which various tests were carried out	S/U	S/M	Discrete	Non Metric
Type of mixture	T-add	Type of blend according to its addition (PET or microfibers)	S/U	S/M	Discrete	Non Metric

Once all the physical and mechanical tests had been carried out at the defined test ages, the results shown in Figure 3 were obtained. The trend over time in the electrical resistivity results differs for each mixture (Figure 3a). The mixture without additives does not show a defined trend as the test age increases; initially, the resistivity value decreases, but it increases from the third age onwards and decreases again from 120 days, ending with a resistivity of 20.23 kΩ-cm at 180 days. On the other hand, the mixture with microfibers has an upward trend at first, ending with a downward trend and higher resistivity at the penultimate test age. Only the mixture with PET maintains a constant and upward trend, ending with the highest resistivity value at 180 days, equal to 24.42 kΩ-cm. The dynamic modulus of elasticity values found from the magnetic resonance test are plotted in Figure 3b. All mixtures show the same trend once they reach late ages. The highest dynamic modulus of elasticity value for the TP6 and TP6-PET mixtures was obtained at 90 days of testing, after which this parameter decreased as the testing time increased. The highest values are represented by the TP-6 mixture, with a maximum value of 23.887 MPa at 90 days and a minimum value of 19.306 MPa at 180 days of testing. The lowest values are for the TP6-M mixture, with a dynamic elastic modulus of 10.854 MPa at 180 days. The mixture with microfibers maintained a relatively constant value at all test ages; however, the lowest values of the modulus of elasticity in the mixture are found at the first and last test ages.

Compressive strength is the index property for characterizing unreinforced concrete. From the results obtained for this property for the material produced in this research work, it is noteworthy, first of all, that the mixture without addition has a reduction in compressive strength from 14 days onwards as the test age increases, presenting a compressive strength of 4.63 MPa at 180 days, which is the lowest average strength per age found in the three mixtures. The mixture with microfibers shows average results at most ages, with compressive strength values that do not vary much at different test ages, compared to the other two mixtures. On the other hand, the mixture with PET, although it shows a decreasing trend in the early test ages (7, 14, and 28 days), ends with a completely upward trend and has the highest values in four of the six test ages, including the last one (Figure 3c). The results of the indirect tensile test are shown in Figure 3d. The control mixture shows a decreasing behavior up to 28 days, from which point the TI value begins to increase, reaching a value of 1.12 MPa. The lowest tensile strength value is for the TP-6 mixture, followed by the TP6-M mixture, and the maximum value is for the PET specimen, with the exception of the last test age. The mixture with microfibers does not show a specific trend, and in the TP6-PET mixture, at 180 days of testing, the values decrease compared to 120 days. However, the values obtained for the tensile strength of the two mixtures with fibers (microfibers and PET) are higher than those of the control mixture without addition for all test ages. Reviewing the MR values calculated from the flexural test and plotted in Figure 3e, the TP6-M blend has its highest value at 90 days with 3.34 MPa. however, at 120 and 180 days, the strength decreases considerably, becoming lower than the other two mixtures with a modulus of rupture of 0.71 MPa. The TP6-PET mixture performs best in this test, as its MR remains with little variation in the last 3 test ages.

As described in the previous paragraphs, variability was found in the data for each of the mixtures in all the properties analyzed experimentally. Pervious concrete is a more heterogeneous material than conventional concrete, as it has less cohesion between aggregates than conventional concrete, mainly due to the small contact area between these aggregates because of the reduced amount of cement paste and little or no use of fine aggregates. In addition, as the stone material used in the production of this material is large in size, the arrangement of the particles is difficult to control in the test tubes. Therefore, specimens made with the same mixture, but with different particle arrangements and a high degree of heterogeneity, exhibit variable characteristics.

The incorporation of microfiber in the pervious concrete under analysis reported a 46% increase in compressive strength compared to the control at the last test age, as well as a 50% increase in tensile strength. This improvement in the microfiber mixture is greater than that reported in the research by J. T. Kevern et. al (2017) who reported that the compressive and tensile strength of conventional concrete to which fibers were added was not significantly affected. For its part, the incorporation of PET in pervious concrete resulted in a 61% increase in compressive strength at the last test age compared to the control pervious concrete, and a 16% increase in tensile strength T. K. M. Ali et. al. (2020) reported that the addition of 2% PET to pervious concrete reduced compressive strength by 72%, with 0.75% being the optimal percentage for obtaining sufficient strength values. Contrasting these results with those obtained in the present investigation, where 0.08% PET is added to pervious concrete, it can be inferred that the optimal substitution percentages should be low, since the addition of 0.08% PET to the pervious concrete produced an increase in the compressive and tensile strength of the material. This is one of the limitations of the study, since the incorporation of waste is at a low percentage. However, it is expected that in large-scale construction projects, this percentage will become significant.

3.2 Multivariate analysis.

The initial data matrix required by the multivariate method chosen to initiate the analysis was created using all the results of the tests performed on the different specimens, and is presented in Table 4. An important aspect to consider is that the technique does not process cases where the information for all the variables considered is incomplete. Therefore, the results obtained in the first two test ages for the TP-6 mixture and the first test age for the TP6-M and TP6-PET mixtures were not used in the canonical correlation analysis, as neither the modulus of elasticity nor the modulus of rupture were obtained.

Table 4. Data matrix for multivariate analysis.

Independent variables		**Dependent variables**				
Age (days)	***T-add (adm)***	**RE (kΩ-cm)**	**Ed (kgf/cm²)**	**f'c (kgf/cm²)**	**TI (kgf/cm²)**	**MR (kgf/cm²)**
28	1.00	14.90	158554.40	59.35	4.97	18.23
90	1.00	27.72	243587.87	56.46	7.95	19.94
120	1.00	26.05	198374.40	59.85	12.08	13.10
180	1.00	20.23	196876.41	47.21	11.41	17.83
14	2.00	14.23	99995.88	68.59	14.96	8.15
28	2.00	17.17	152455.61	72.18	17.86	17.40
90	2.00	21.76	157122.68	68.60	11.96	34.07
120	2.00	29.01	162272.60	56.51	16.57	12.71
180	2.00	25.30	110686.68	68.69	17.14	7.23
14	3.00	15.90	157735.78	70.80	20.26	48.10
28	3.00	15.07	139682.57	57.42	20.95	14.12
90	3.00	22.37	233878.59	56.22	18.29	18.48
120	3.00	23.31	182632.14	74.16	22.62	15.50
180	3.00	24.42	181707.95	75.94	13.27	14.88

Once the canonical analysis has been performed, it is possible to verify the statistical correlation between variables, such as Pearson's correlation, with a correlation between independent variables (Table 5), a correlation between dependent variables (Table 6), and a correlation between both groups (Table 7).

Table 5. Correlation between independent variables.

Variable	**Age**	**T-add**
Age	1.0000	0.0000
T-add	0.0000	1.0000

Table 6. Correlation between independent variables and dependent variables.

Variable	**RE**	**Ed**	**f'c**	**TI**	**MR**
Age	1.0000	0.4879	-0.1243	-0.1068	-0.2424
T-add	0.4879	1.0000	-0.4250	-0.2585	0.1577

Table 7. Correlation between dependent variables.

Variable	**RE**	**Ed**	**f'c**	**TI**	**MR**
RE	1.0000	0.4879	-0.1243	-0.1068	-0.2424
Ed	0.4879	1.0000	-0.4250	-0.2585	0.1577
f'c	-0.1243	-0.4250	1.0000	0.3682	0.1575
TI	-0.1068	-0.2585	0.3682	1.0000	0.0581
MR	-0.2424	0.1577	0.1575	0.0581	1.0000

In the results, a correlation of 100% is represented by 1.000, while an inverse proportion is represented by -1.000. The two variables that are independent in the analysis are the test age and the type of additive in the mixtures. There should be no correlation between these independent variables, since they are defined in the experimental program (which is why they were defined as independent variables). Therefore, in the correlation of these variables in Table 5, it can be seen how these variables are not related to each other, that is, the test age is not related to the type of mixture. As shown in Table 7, in the correlation of dependent variables, all the values of the matrix trace are 1.000 because it is the correlation of the variables with themselves; other than that, the only noteworthy thing is that compressive strength (f'c) has a slight relationship with indirect tension (TI) and electrical resistivity (RE) with dynamic modulus of elasticity (Ed); on the other hand, electrical resistivity (RE) and breaking modulus (MR) show a slight inverse correlation, with a negative correlation value, since the lowest MR values are found at ages with higher RE. Likewise, if f'c or TI increase, Ed decreases, which may be due to the fact that, even when high compressive or tensile strengths are present, the concrete remains relatively inflexible (and therefore has a low modulus of elasticity) due to the low bonding strength between the aggregates and the low cement paste content. The correlation analysis of independent variables against dependent variables shown in Table 6 revealed the following:

1. The independent variable "Age" is related to the variables RE (Electrical Resistivity) and MR (Modulus of Rupture). The information obtained indicates that as age increases, the RE value increases and the MR decreases.
2. The independent variable T-add (Type of Addition) was found to be directly and generally related to the dependent variables TI (Indirect Tensile Strength) and f´c (Compressive Strength), and to a lesser extent, to MR (Modulus of Rupture). The results show that higher values of T-add increase both f'c and indirect stress, i.e., mixtures with microfiber or PET additions show higher values than the control sample without additions (the sample without additions was given a value of 1 for the variable T-add, the sample with microfiber was given a value of 2, and the sample with PET was given a value of 3). This is corroborated by Figure 3d, which shows that, at all ages except 7 days, the TI value is higher for mixtures with additions than for the control mixture, with age being a factor that does not influence this scenario.

The scatter plot in Figure 4 was created using the canonical variables calculated by the STATISTICA software. To create this graph, of the two eigenvalues found (λ_1=0.781691, λ_2=0.512213) the first was chosen, which provides the highest canonical correlation value. The equation representing the trend line of the graphed data is:

$$Y = -3.4059E - 9 + 0.8841X \quad (7)$$

According to equations 1 and 2, the canonical variable X (U) is made up of the weight vector **a** and the set of independent variables **x**, while the canonical variable Y(W) corresponds to the weight vector **b** and the set of dependent variables **y**.

Table 8 shows the values that make up the two weight vectors and the two sets **x** and **y** that integrate the canonical variables to form the linear equation.

Table 8. Definition of weight vectors and variables that constitute the linear correlation equation for λ_1=0.781691.

Independent canonical variable $X(U) = a^T x$		**Dependent canonical variable** $Y(W) = b^T y$	
a = (a_1, a_2)	**x = (x_1, x_2)**	**b= (b_1, b_2, b_3, b_4, b_5)**	**y= (y_1, y_2, y_3, y_4, y_5)**
(-0.3256046, 0.9084772)	(Age, T-add)	(-0.4187563, 0.2575633, 0.3322778, 0.7624729, 0.0984120)	(RE, Ed, f'c, TI, MR)

Therefore, equation 7) can also be expressed as:

$$0.4187563\,RE + 0.2575633\,Ed + 0.3322778\,f'c + 0.7624729\,TI + 0.0984120MR = -3.4059E-9 + 0.8841(-0.3256046\,Age + 0.9084772\,T-add) \quad (8)$$

The values of the Cartesian axes in the graph represent the best linear combination of the dependent variables (-0.4187563 RE + 0.2575633 Ed + 0.3322778 f'c + 0.7624729 TI + 0.0984120MR) with respect to the independent variables (-0.3256046 Age + 0.9084772 T-add) considering the first eigenvalue λ resulting from the process that defines the respective linear transformation, that is, this equation is a function that integrates all the properties obtained in the experimental analysis of the research.

It is important to mention that the modulus of the weight coefficients indicates which variable has a greater impact on the proposed linear combination with the canonical variables ***X*** and ***Y***. On the other hand, the positive or negative sign indicates the direction of the relationship between each original variable and the canonical combination. Thus, a positive coefficient indicates that as the variable x_i increases, the canonical variable U_i will also increase, and a negative coefficient indicates the inverse relationship. Considering this point, the results of the weight vectors suggest that f'c, TI, and RE have the greatest impact on the dependent canonical variable with respect to the independent variable (which contains the variables Tadd and Age), with a relationship in the same direction when it comes to f'c and TI, while the impact of RE is negative. In the independent canonical variable, the T-add type of addition is the component with the greatest impact. This indicates that the type of addition (T-add) has a greater influence on the response of indirect tensile strength and compressive strength than in the case of the electrical resistivity of the mixtures. From the scatter plot created with the two canonical variables (Figure 2), the value of R= λ canonical is obtained for the analysis created. This is the canonical correlation value between the two sets of variables used in the analysis (set of independent variables and set of dependent variables), that is, it numerically represents the linear correlation between these sets (Hotelling 1936). The value ranges from 0 to 1, where 0 indicates no correlation and 1 indicates a perfect correlation. As the correlation value for the analysis carried out in this study is 0.7817, the % of reproduction that can be achieved from the canonical variables found with the correlation analysis performed and, therefore, with the equation that integrates the five properties analyzed experimentally is 78.17%, which is a promising reproducibility percentage, presenting an opportunity to define or project some specific property of the material under study (previously established as a variable in the equation). On the other hand, if Pearson's correlation is calculated, the result of R^2 is 0.7817, which is basically the same as canonical R. To verify the level of reproducibility given by the linear correlation equation found, the electrical resistivity for all mixtures at all test ages was calculated using it. The equality expressed in equation (8) represents the line of best linear correlation between the values of the canonical variables, which is why it can be used to establish an estimate of a dependent variable based on the other dependent variables and the independent variables within the canonical variables X (U) and Y(W).

The RE values estimated with the linear equation, as well as the RE values obtained from the laboratory test, are shown in Table 9. A column with the percentage error between the value found in the experiment and the estimate is also added.

Table 9. Comparison between actual electrical resistivity and electrical resistivity estimated from the linear correlation equation.

Age (days)	**T-add (adm)**	**Actual RE (kΩ-cm)**	**Estimated RE (kΩ-cm)**	**% reproducibility**	**% error**
28	1.00	14.90	8.98	60%	39.7%
90	1.00	27.72	23.22	84%	16.2%
120	1.00	26.05	29.78	86%	14.3%
180	1.00	20.23	26.44	69%	30.7%
14	2.00	14.23	13.41	94%	5.7%
28	2.00	17.17	26.20	47%	52.6%
90	2.00	21.76	19.47	89%	10.5%
120	2.00	29.01	21.91	76%	24.5%
180	2.00	25.30	27.43	92%	8.4%
14	3.00	15.90	21.30	66%	34.0%
28	3.00	15.07	11.92	79%	20.9%
90	3.00	22.37	17.66	79%	21.0%
120	3.00	23.31	31.35	66%	34.5%
180	3.00	24.42	18.36	75%	24.8%

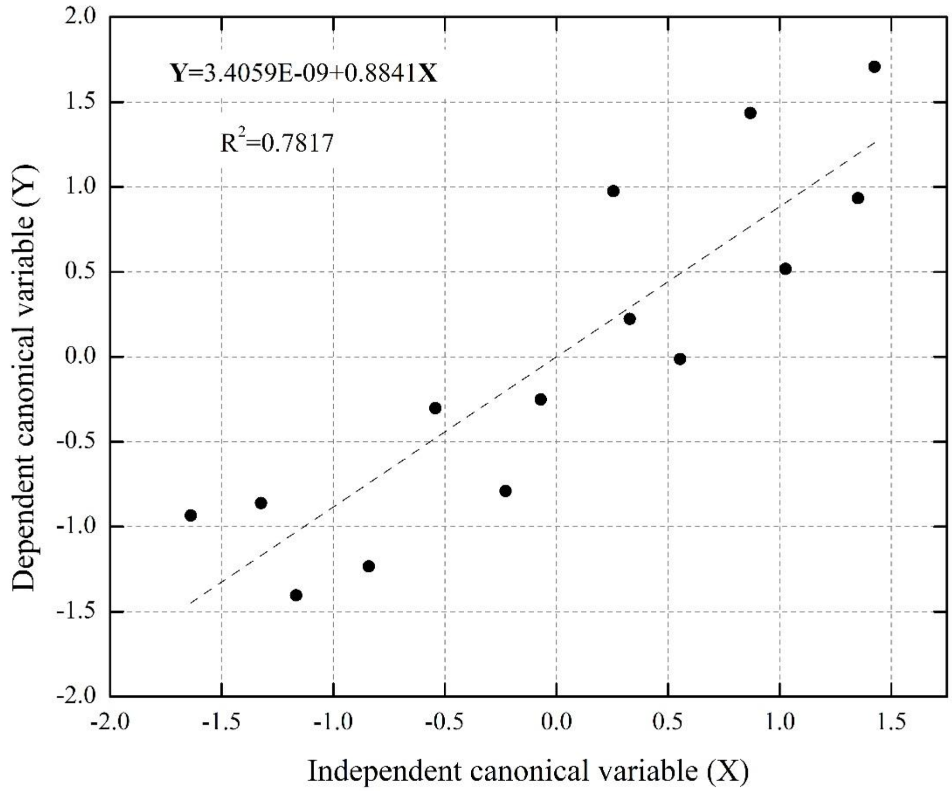


Figure 4. Scatter plot created with canonical variables X and Y considering λ_1=0.781691.

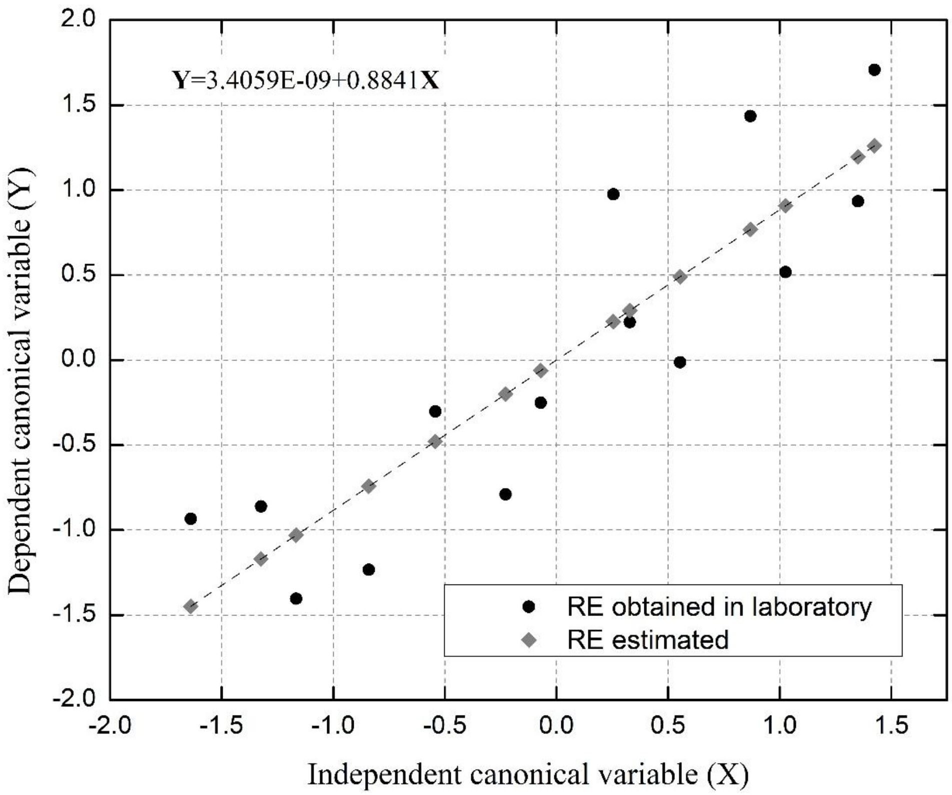


Figure 5. Scatter plot comparing estimated electrical resistivity (RE) values against RE values obtained in the laboratory.

The reproducibility obtained for the electrical resistivity property in the pervious concrete analyzed, based on the linear correlation equation obtained with ACC, is above 50%. Finally, in Figure 5, the series containing the estimated RE values was added to the original graph with the two canonical variables, clearly showing the uniformity of the data in the latter series, since they were calculated using the trend line equation of the original data. Studies using ACC in the study of pervious concrete are rare in the literature. However, they allow us to explore how the properties of pervious concrete, such as its composition, physical characteristics, and behavior under different conditions, are correlated with properties such as permeability, water resistance, and particularly filtration capacity. This allows us to establish the long-term behavior trend with respect to mechanical properties, supporting the design of the mixture, considering the composition and particle size distribution of the aggregates, the water/cement ratio, the density, and the incorporation of fibers, PET, or other materials.

4. CONCLUSIONS

The addition of fibers to pervious concrete increased its response to the application of point compressive loads. This is evidenced by the increase in compressive strength shown by the two mixtures with additives, both with microfiber and PET, compared to the mixture without additives. With the lower results of the dynamic modulus of elasticity, it was possible to verify that the durability of pervious concrete is lower than that of conventional hydraulic concrete; because this modulus is a measure of the stiffness of the material and its elastic recovery capacity, contributing to its stability and durability. As the values obtained for the manufactured material are lower than the typical values for conventional concrete, it can be concluded that its durability will be lower. The data obtained on the breaking modulus follow the same trend as the dynamic elasticity. The TP6-M and TP6-PET mixtures showed better behavior under tensile stress than the TP6 control mixture. There is a direct relationship between the compressive strength and tensile strength of pervious concrete. The indirect tensile strength in the concrete mixture with PET is 16%-35% of the compressive strength. For the TP6 and TP6-M mixtures, the indirect tensile strength is in the range of 15% to 30% of their compressive strength. The application of the Canonical Correlation Analysis technique to the material analyzed in this work was relevant for its analysis, as it was easier to interpret the results of the mechanical tests on the material produced, as well as to identify the relationship between the seven variables examined. The use of alternative methodologies to conventional ones to carry out mechanical behavior analysis presents a great opportunity in the field of materials; the canonical correlation technique, in particular, allows associations to be identified in the linear correlation of multiple variables, making it possible to define a specific mechanical property (previously defined as a variable in the analysis) from the linear correlation equation generated by the technique. This last idea can be extended to a durability property in hydraulic concrete or in any material where there is a relationship between certain properties. If a durability analysis is carried out indirectly at an early age using the ACC technique, it opens up the opportunity to estimate the durability of the material at a later age in studies where, as in this one, it is not possible to carry out a direct measurement of the durability of the material and it is only possible to perform some physical tests with which the durability of the material can be estimated indirectly.

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