Evaluating the incidence of mix design parameters and compaction on the properties of pervious concrete mixtures for urban pavements: a statistical approach

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Abstract. Pervious concrete is an emerging pavement material that allows the percolation of water through its structure. This innovative material offers several environmental benefits, such as reducing water runoff volumes and peak flowrates, enabling the natural recharge of groundwater reservoirs and filtering contaminants in water, among others. Despite the promising environmental advantages of this material, some limitations remain in the fields of application due to its mechanical performance and the limited availability of mix-design guidelines. The current study aimed at investigating the effect of water proportion, cement content and compaction energy on volumetric and mechanical properties of pervious concrete mixtures. The influence of these variables were statistically analyzed and modeled through regressions in order to develop a primal procedure for proportioning. Outcomes from ANOVA showed that all the studied factors significantly contributed to both strength and porosity, being cement/aggregate ratio and compaction energy the most influential. The resulting regression models had fair-to-good coefficients of determination; models were used to generate contour graphs of the material properties that were plotted in order to develop user-friendly mix proportioning schemes.

1. Introduction
The worldwide phenomenon of urbanization, that has produced a rapid increase of the paved impervious areas, consequently determined a serious change in the natural course of water cycle. In response to this, the use of pervious concrete as paving material has emerged as an alternative that aims to mitigate the environmental damage derived from the speeded growth of impermeable surfaces.

Pervious concrete is an innovative cementitious material that allows water to percolate through its rigid matrix. This type of material presents several environmental benefits, mostly deriving from its perviousness. It has been shown that in-service pervious concrete pavements considerably reduce stormwater runoff volumes and decrease the peak flowrates [1]; therefore minimizing expenses for drainage systems [2]. Moreover, from an eco-friendly point of view, pervious concrete pavements facilitate the recharge of aquifers [2], allow the evaporation of water from the subgrade soil [3], and act as a filter for contaminants contained in the water (e.g. copper, lead, and zinc) by retaining them within its porous matrix [2, 4]. Additionally, pervious concrete offers some collateral benefits, such as alleviating the Urban Heat Island effect [5], reducing tire-pavement noise and splash-and-spray phenomenon, thus increasing comfortability in urban areas [6]. It helps in improving safety in roads by increasing skid resistance and reducing ponding that could cause car hydroplaning [2] and pedestrian slipping [7]. For
all of the above, Pervious Concrete Pavement is catalogued as a Best Management Practice for storm water management by the US Environmental Protection Agency (EPA).

The permeability of pervious concrete is consequence of an interconnected macroscopic pores network. This pores system is obtained by substantially reducing the finer aggregates content, and utilizing little water/cement ratios (typically between 0.20 and 0.42 [8]) besides relatively low cement/aggregate ratios (usually from 0.18 up to 0.23 [9]) in the mixtures, in order to decrease the cement paste volume.

Although, pervious concrete can be employed in several light-traffic applications; such as bike paths, driveways, highway shoulders, parking lots, patios, pedestrian areas, walkways, and low-volume roadways [7, 2], this technology is not largely widespread because of the lack of standardized and widely-accepted mix design guidelines and construction practices [5, 8].

The current study aims at systematically investigate the effect of water proportion, cement content and compaction energy on strength, stiffness and volumetric properties of pervious concrete mixtures. The influence of these variables was statistically analyzed and modeled through regressions techniques in order to develop a procedure to adequately proportion pervious concrete mixtures to reach an optimal balance between structural performance and volumetric characteristics for bearing different solicitations.

2. Materials and methods

2.1. Experimental plan

The current investigation was intended as a three-level full factorial experiment, assessing the effect of: water/cement ratio, cement/aggregate ratio and compaction energy, on the indirect tensile strength (ITS) and porosity. Thus, since three levels of three independent variables were evaluated, 27 treatments (nine mixtures subjected to three different compaction energies each one) were prepared and tested [10]. Additionally, the elastic modulus was briefer analyzed through a two-level experiment for a single compaction energy. The amounts of water and cement in the mixtures were expressed as ratios of masses to set them as intensive variables, that is, independent of the quantity of material. Three replicates per treatment were made.

2.2. Materials and mix proportions

CEM II 42.5R cement was used to produce the mixtures. A single distribution curve of aggregate sizes, determined according to the standard EN 933-1 [11], was employed to produce the pervious concrete mixtures; it is illustrated in Figure 1. Further information about materials used can be found in [10]. The different studied mixtures, with their respective mix proportions are presented in Table 1.

| w/c   | c/a = 0.17 | w/c = 0.20 | c/a = 0.23 |
|-------|------------|------------|------------|
| 0.30  | W30C17     | W30C20     | W30C23     |
| 0.35  | W35C17     | W35C20     | W35C23     |
| 0.40  | W40C17     | W40C20     | W40C23     |

2.3. Specimen preparation

Mixtures were prepared using a standard drum mixer, then poured into cylindrical Marshall molds and compacted using a Marshall compactor according to the standard EN 12697-30 [12]. Only one side of the specimen was compacted in order to better simulate the in-situ compaction conditions. Resulting specimens were 100 mm in diameter and 50-60 mm in height, and presented a mass of approximately 1050 g. Specimens were demolded after one day and then finally cured in a chamber having moist-controlled conditions.
Three levels of compaction energy were applied to simulate different in-situ compaction methods. The 3-blow compaction pretended to recreate the compaction energy of an in-situ lightweight hand-roller. On the other hand, the 25-blow compaction was intended to replicate the compaction energy of 3-4 passes of a small drum roller (approx. 1.53 tons); and the 50-blow compaction might replicate either the compaction of a medium weight drum roller or 4-6 passes of a small drum roller.

2.4. Test procedures

The procedure used to calculate the porosity of the specimens consisted in 1) estimating the maximum density of each mixture in accordance with the standard EN 12967-5, and 2) determining the bulk density of each specimen according to the standard EN 12697-6, procedure D [13]. Porosity was computed as follows (Eq. 1):

\[ \phi = 100 \cdot \left(1 - \frac{\rho_b}{\rho_m}\right) \]  

where \( \phi \) is total porosity in percentage, \( \rho_b \) is bulk density and \( \rho_m \) is maximum density.

Indirect tensile strength (ITS) tests were conducted in compliance with the standard EN 12697-23 [14], after seven days, following the usual time for curing in road applications.

Finally, the standard EN 12697-26 (ANNEX F) [15] was adopted for the determination of elastic modulus of the cylindrical specimens. A constant strain of 5 µm and 2 Hz frequency were imposed. In particular, the elastic modulus of the mixtures W30C17, W40C17, W30C23 and W40C23 was measured and evaluated according to different curing times.

3. Results and discussions

The main objective of the present study was to assess statistically the relationship between the input variables (mix-proportioning parameters and specifications for construction procedures) and the responses (fundamental properties of pervious concrete).

On one hand, ANOVA tests were carried out to determine if the variations in the composition of the mixtures and the applied compaction had a significant effect in the properties of the final product, and to estimate their relative contribution (it was computed as the ratio of the sum of squares of a particular input variable to the total sum of squares). The significance level considered was 0.05. Data were assumed to be normally distributed.
On the other hand, multiple regression models based on the least squares method were used to describe the relationship between dependent and independent variables. These models were developed from the set of data obtained from the laboratory tests. Once established, the models could be used to make predictions. The steps involved in building these models included performing ANOVA to determine the overall significance of the model and the suitability of its terms (variables involved).

Appropriate models were constructed through a forward-backwards elimination process that used the following criterion: if the p-value is greater than the significance level, the model terms are considered inadequate; hence, the model must be altered by adding or removing terms. The significant and non-significant components were identified by means of t-test. This was repeated iteratively until the p-value associated to each multiplier estimate was lower than the significance level. Accuracy criteria such as $R^2$ and $R^2$ adjusted were also computed. Finally, response surfaces and contour plots were generated from the regression models in order to graphically illustrate the studied behaviors. Contour plots could be used to define the proportioning of the mixture and to select a compaction level during design. Outcomes from the ITS and porosity tests are reported in Table 2.

| Mix ID | Indirect Tensile Strength [MPa] | Porosity [%] |
|--------|---------------------------------|--------------|
|        | 3 blows | 25 blows | 50 blows | Mean St. Dev. | Mean St. Dev. | Mean St. Dev. | Mean St. Dev. |
| W30C17 | 0.34     | 0.02     | 1.54     | 0.15  | 1.63     | 0.10  | 39.63     | 0.51  | 32.06     | 3.39  | 23.75     | 0.51  |
| W30C20 | 0.81     | 0.09     | 1.41     | 0.13  | 1.66     | 0.07  | 34.68     | 1.57  | 29.14     | 3.79  | 22.76     | 2.26  |
| W30C23 | 0.91     | 0.12     | 1.63     | 0.07  | 2.09     | 0.12  | 37.33     | 2.94  | 26.75     | 3.42  | 21.08     | 0.47  |
| W35C17 | 0.56     | 0.18     | 1.13     | 0.12  | 1.35     | 0.12  | 38.31     | 0.07  | 30.31     | 0.15  | 26.20     | 0.55  |
| W35C20 | 0.93     | 0.16     | 1.50     | 0.11  | 1.84     | 0.16  | 33.31     | 1.94  | 31.08     | 4.87  | 21.86     | 1.68  |
| W35C23 | 1.09     | 0.11     | 1.69     | 0.14  | 1.85     | 0.22  | 33.31     | 1.57  | 25.19     | 0.81  | 20.29     | 1.98  |
| W40C17 | 0.68     | 0.28     | 1.35     | 0.15  | 1.39     | 0.06  | 36.39     | 0.25  | 28.68     | 0.22  | 25.56     | 0.44  |
| W40C20 | 0.87     | 0.11     | 1.48     | 0.16  | 1.73     | 0.09  | 35.35     | 0.26  | 25.84     | 0.11  | 21.89     | 0.22  |
| W40C23 | 1.16     | 0.21     | 1.51     | 0.07  | 1.68     | 0.06  | 31.69     | 0.51  | 23.10     | 0.04  | 19.59     | 0.77  |

### 3.1. Porosity assessment

The ANOVA performed for the analysis of porosity measurement is shown in detail in Table 3.

| Source of variation | df | Sum of squares | Variance | F-stat | p-value | % of contribution |
|---------------------|----|----------------|----------|--------|---------|------------------|
| **Principal effects** |    |                |          |        |         |                  |
| Water/cement ratio  | 2  | 61.8610        | 30.9305  | 8.21   | 0.0007  | 2.07             |
| Cement/aggregate ratio | 2   | 305.168       | 152.584  | 40.52  | 3.33E-04| 10.22            |
| Number of blows     | 2  | 2301.94        | 1150.97  | 305.65 | 4.39E-04| 77.08            |
| **Interactions**    |    |                |          |        |         |                  |
| c/a × w/c           | 4  | 18.1187        | 4.52968  | 1.2    | 0.3186  | 0.61             |
| w/c × n_b           | 4  | 40.1517        | 10.0379  | 2.67   | 0.0405  | 1.34             |
| c/a × n_b           | 4  | 25.7298        | 6.43246  | 1.71   | 0.1595  | 0.86             |
| **Error**           | 62 | 233.472        | 3.76567  |        |         | 7.82             |
| **Total**           | 80 | 2986.44        |          |        |         | 100              |

*Degrees of freedom

First of all, since their p-values are far lower than 0.05, it can be stated with a 95% confidence that all the three principal factors, i.e. water/cement ratio, cement/aggregate ratio and compaction energy, have a significant contribution to the variability of the porosity in specimens. Additionally, interaction between water/cement ratio and number of blows is also significant; this could be explained by the effect
of water lubricating aggregates, hence slightly facilitating the rearrangement of particles when subjected to Marshall hammering.

Further, compaction is by far the most important input variable when defining porosity, since it provides the 77.08% of its variability; and it is followed by cement/aggregate ratio, with a 10.22% of contribution. On the other hand, the contribution of water/cement ratio, either by itself or through its interaction with the number of blows, is minuscule. The regression model for the porosity was defined as shown in Eq. 2

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \]  

where \( x_1 \) is the number of Marshall blows, \( x_2 \) is cement/aggregate ratio, \( x_3 \) is water/cement ratio, \( \beta_0 \) is the intercept value of the regression, and \( \beta_1, \beta_2 \) and \( \beta_3 \) are the multipliers of each variable.

The multiplier estimates for each factor and other relevant information concerning the regression model built to predict the porosity are presented in details in Table 4.

**Table 4. Porosity multiple regression model parameters**

| Factor | Multiplier estimate | Standard error | t-stat | p-value |
|--------|---------------------|----------------|--------|---------|
| \( \beta_0 \) | 59.06131 | 2.87126 | 20.56982 | 5.10754E-33 |
| \( \beta_1 \) | -0.27534 | 0.01251 | -22.01861 | 5.73916E-35 |
| \( \beta_2 \) | -78.84568 | 9.80231 | -8.04358 | 8.38396E-12 |
| \( \beta_3 \) | -21.21481 | 5.88139 | -3.60711 | 5.47896E-04 |

It can be noticed that, with the exception of the intercept, all the factors present negative coefficients, meaning that rising the value of any input variable would cause a reduction in porosity. This could be attributed to the fact that compaction reduces the void volume by rearranging the aggregates, whereas the increase of both water and cement implies the growing of cement paste volume, that would fill the empty spaces. Besides, \( R^2 \) and Adjusted \( R^2 \) values suggest that the model has a fairly good accuracy when calculating porosity.

The contour plots of porosity vs. cement/aggregate ratio and water/cement ratio for different compaction levels are shown in Figure 2. Response surface of porosity in percentage, at: (a) 3 blows, (b) 25 blows, and (c) 50 blows
For all the studied compaction levels, to keep constant a certain porosity value while increasing the cement/aggregate ratio, it would be necessary to reduce the water/cement ratio, with the purpose of avoiding the excessive variation of cement paste volume.

3.2. Indirect tensile strength analysis

The ANOVA test, made for the Indirect Tensile Strength presented p-values under 0.05, thus it can be asseverated with a 95% confidence that compaction energy and cement/aggregate ratio are significant at contributing to the variation of ITS in the pervious concrete specimens, having the number of blows the highest incidence, with a 71.29% contribution. In addition, the interactions of water/cement ratio with cement/aggregate content and number of blows are both significant. Their significance could be explained by two reasons: 1) water is essential for the cement hydration process, but also is fundamental for the workability of the material and strongly influences the strength of the cement paste; and 2) water also modifies the rheology of the paste, affecting its response when exposed to the compaction process carried out by the Marshall compactor. The ANOVA test made for the Indirect Tensile Strength is presented in Table 5.

Table 5. Analysis of Variance for the Indirect Tensile Strength

| Source of variation          | df* | Sum of squares | Variance | F-stat  | p-value | % of contribution |
|-----------------------------|-----|----------------|----------|---------|---------|-------------------|
| **Principal effects**       |     |                |          |         |         |                   |
| Water/cement ratio          | 2   | 0.00482        | 0.00241  | 0.11    | 0.8968  | 0.03              |
| Cement/aggregate ratio      | 2   | 2.25129        | 1.12564  | 50.96   | 9.16E-05| 14.37             |
| Number of blows             | 2   | 11.1722        | 5.58608  | 252.89  | 9.95E-05| 71.29             |
| **Interactions**            |     |                |          |         |         |                   |
| c/a × w/c                   | 4   | 0.24798        | 0.06199  | 2.81    | 0.0331  | 1.58              |
| w/c × n_b                   | 4   | 0.44351        | 0.11088  | 5.02    | 0.0014  | 2.83              |
| c/a × n_b                   | 4   | 0.18224        | 0.04556  | 2.06    | 0.0965  | 1.16              |
| **Error**                   | 62  | 1.36949        | 0.02209  |         |         | 8.74              |
| **Total**                   | 80  | 15.6715        |          |         |         |                   |

The regression model for the Indirect Tensile Strength was set as shown in Eq. 3

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_3 \]  

(Eq. 4)

where \( x_1 \) is the number of Marshall blows, \( x_2 \) is cement/aggregate ratio, \( x_3 \) is water/cement ratio, \( \beta_0 \) is the intercept value of the regression, and \( \beta_1, \beta_2 \) and \( \beta_3 \) are the multipliers of each variable.

The multiplier estimates associated to each factor and additional information regarding the regression model constructed for Indirect Tensile Strength are reported in Table 6. It is notable that the intercept has a negative value, i.e. there is no default ITS, suggesting that it is necessary to have certain minimum levels of cement content and compaction to develop strength, which is coherent with reality. As expected, as both number of blows and cement/aggregate ratio increases, the mechanical properties of the specimens also increase. Moreover, the values of the accuracy parameters \( R^2 \) and Adjusted \( R^2 \), indicate that the usefulness of the developed model for predicting the ITS values within the studied ranges of the input variables, is adequate.

Figure 3, presents the contour plots of Indirect Tensile Strength compared to cement/aggregate ratio and water/cement ratio for different compaction levels, derived from the regression model at issue. It can be observed that there present few ITS values in common, denoting well-defined strength ranges for each compaction levels. Besides, for all the studied compaction levels, to keep constant certain ITS value while increasing the cement/aggregate ratio, it would be necessary to increase the water/cement
ratio, in order to guarantee sufficient paste hydration. Moreover, contours become steeper as the compaction levels increases; this is produced by the interaction factor between water content and compaction, and indicates that strength of pervious concrete mixtures are more susceptible to changes in water content at higher compaction levels.

Table 6. Indirect Tensile Strength multiple regression model parameters

| R²    | Adjusted R² | Standard error | F-stat | F-critical |
|-------|-------------|----------------|--------|------------|
| 0.79600 | 0.78806     | 0.20376        | 100.152| 1.66618E-26|

| Factor | Multiplier estimate | Standard error | t-stat | p-value |
|--------|---------------------|----------------|--------|---------|
| β₀     | -0.49982            | 0.18874        | -2.64817| 0.00981 |
| β₁     | 0.03069             | 0.00612        | 5.01422| 3.32394E-06 |
| β₂     | 6.74074             | 0.92428        | 7.29297| 2.30683E-10 |
| β₃     | -0.03515            | 0.01716        | -2.04873| 0.04390 |

Figure 3. Response surface of Indirect Tensile Strength in MPa, at:
(a) 3 blows, (b) 25 blows, and (c) 50 blows

Figure 4 shows the relation ITS and porosity of all the studied mixtures.
Clearly, there exist a strong inverse correlation between Indirect Tensile Strength and porosity, which was expected. According to the equation, which describes the correlation at issue, when there is no porosity, mixtures have an average tensile strength of 3.24 MPa, which is within the usual ranges for traditional concrete. Moreover, concrete loses approximately 2% ($0.0666/3.2394 \approx 0.02$) of this theoretical strength for each 1% of porosity added. Due to the good $R^2$, one could assume that much of the variation of ITS in pervious concrete is controlled by porosity. Although, other factors such as matrix (cement-coated-aggregate skeleton) strength and porosity distribution along the dimensions of the specimens, which is highly influenced by compaction, could be important too.

### 3.3. Stiffness evaluation

The elastic modulus of different mixtures were evaluated after 7 and 28 days of curing, for fixed intermediate compaction energies (corresponding to 25 compaction blows). In general, elastic modulus after 28 days of curing is on average 16% higher than the 7-day value. Results of this analysis are presented in Figure 5.

![Figure 5. Elastic moduli after 7 and 28 days of curing](image)

Elastic modulus at 28 days were selected to be analyzed through an ANOVA test, which is reported in Table 7, in order to assess the long-term mechanical behavior of the pervious concrete mixtures.

### Table 7. Analysis of Variance for the Elastic Modulus

| Source of variation      | df | Sum of squares | Variance | F-stat   | p-value | % of contribution |
|--------------------------|----|----------------|----------|----------|---------|------------------|
| Water/cement ratio       | 1  | 13540500       | 13540500 | 31.9756  | 0.00048 | 19.85            |
| Cement/aggregate ratio   | 1  | 44386686       | 44386686 | 104.818  | 7.11879E-06 | 65.08         |
| Interactions             | 1  | 6890220        | 6890220  | 16.2711  | 0.00377 | 10.10            |
| Error                    | 8  | 3387706        | 423463   | 4.97     |          |                  |
| Total                    | 11 | 68205114       |          |          |         |                  |

Both water/cement ratio and cement/aggregate ratio have significant contribution to elastic modulus variation, as well as the interaction between them. Even if the usual time for curing, in road application, is 7 days, this study can help in defining how pervious concrete material develop the stiffness during the time. This information is interesting for design and for long-term evaluations.

### 4. Conclusions
In the current study, the effects of water proportion, cement amount and compaction energy on indirect tensile strength, total porosity and elastic modulus of pervious concrete mixtures were investigated from a statistical approach; as a conclusion of a previous laboratory investigation when 27 sets of specimens were prepared and tested [10]. The influence of these variables were analyzed, and modeled through regressions in order to develop a primal procedure to adequately proportioning pervious concrete mixtures for different solicitations. The main concluding remarks based on the findings mentioned above are summarized below:

- Compaction energy is the most influential input variable studied, for both strength and porosity, contributing respectively with the 77.08% and 71.29% of the property variability in the tested specimens.
- Cement/aggregate ratio is the mix-design parameter that contributes the most to the variation of indirect tensile strength, elastic modulus and porosity.
- Most of the strength variation is consequence of changes in porosity.

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