ANALYSIS OF PERVIOUS CONCRETE PROPERTIES FOR MIXTURES OF DIFFERENT W/C RATIOS

Júlia Nantes Hisatomi¹
Sergio Tunis Martins Filho²
Daniel Tescaro Cobo ³

RESUMO

Objectives: The influences of the different constituent materials of pervious concrete were analyzed through their physical, mechanical and hydraulic properties, aiming to propose acceptable mixtures for application.

Theoretical Reference: The mixes were prepared with the aid of a dosage curve obtained from the literature. For hydraulic behavior, the Forchheimer’s equation was used.

Method: Five mixes were produced, with a uniform particle size range of 4.8 – 6.3 mm, varying their water/cement ratios. Density, porosity, ultrasound, permeameter and compressive strength tests were carried out for all mixes.

Results and conclusion: The hydraulic characterization (d/√k) was satisfactory using non-linear equations. The relationship between total porosity and other properties, such as, compressive strength, ultrasonic pulse velocity and density in the hardened state, remained inversely proportional. The mixtures developed presented characteristics within those expected for practical applications.

Research implications: Despite many studies, methodologies to produce and analyze pervious concrete have not yet been standardized, with Darcy's law being widely used to describe the flow. This research seeks to contribute to the development of these methodologies, in addition to proposing mixtures with acceptable properties for application and non-linear analysis.

Originality and value: Pervious concrete is considered a sustainable alternative for low-traffic paving and allows reducing surface runoff. The study also aims to raise awareness and propagate sustainable systems that can help with urban drainage, reducing the socio-environmental impact caused by floods.

Keywords: Pervious Concrete, Physical Properties, Hydraulics, Compressive Strength.

ANÁLISE DAS PROPRIEDADES DO CONCRETO PERMEÁVEL PARA TRAÇOS DE DIFERENTES RELAÇÕES A/C

RESUMO

Objetivo: Foram analisadas as influências dos diferentes materiais constituintes do concreto permeável através de suas propriedades físicas, mecânicas e hidráulicas, com objetivo de propor traços aceitáveis para aplicação.

Referencial teórico: Os traços foram elaborados com o auxílio de uma curva de dosagem obtida na literatura. Para o comportamento hidráulico foi utilizada a equação de Forchheimer.

1 Universidade Tecnológica Federal do Paraná, Apucarana, Parana, Brazil. E-mail: juhisatomi@gmail.com
Orcid: https://orcid.org/0009-0001-2547-4777

2 Universidade Tecnológica Federal do Paraná, Apucarana, Parana, Brazil. E-mail: sergiotunis@hotmail.com
Orcid: https://orcid.org/0000-0002-4334-399X

3 Universidade Tecnológica Federal do Paraná, Apucarana, Parana, Brazil. E-mail: danieltobo97@gmail.com
Orcid: https://orcid.org/0000-0003-0855-3374
Método: Foram produzidos cinco traços, com faixa granulométrica uniforme de 4,8 – 6,3 mm, variando suas relações água/cimento. Os ensaios de densidade, porosidade, ultrassom, permeâmetro e resistência à compressão foram realizados para todos os traços.

Resultados e conclusão: A caracterização hidráulica ($d/\sqrt{k}$) foi satisfatória utilizando-se de equacionamento não linear. A relação entre a porosidade total e as demais propriedades, como, resistência à compressão, velocidade do pulso ultrassônico e densidade no estado endurecido, mantiveram-se inversamente proporcionais. Os traços, elaborados apresentaram características dentro do esperado para aplicações práticas.

Implicações da pesquisa: Apesar de muitos estudos, ainda não foram normatizadas metodologias para confecção e análise do concreto permeável, sendo muito utilizado a lei de Darcy para descrever o escoamento. Essa pesquisa busca contribuir com o desenvolvimento dessas metodologias, além de propor traços com propriedades aceitáveis para aplicação e análise de caráter não linear.

Originalidade e valor: O concreto permeável é considerado uma alternativa sustentável para pavimentação em áreas de baixo tráfego e que permite reduzir o escoamento superficial. O estudo também visa a conscientização e propagação de sistemas sustentáveis que possam auxiliar na drenagem urbana, reduzindo o impacto socioambiental das enchentes.

Palavras-chave: Concreto Permeável, Propriedades Físicas, Hidráulica, Resistência à Compressão.

RGSA adota a Licença de Atribuição CC BY do Creative Commons (https://creativecommons.org/licenses/by/4.0/).

1 INTRODUCTION

Pervious concrete is used in the construction of pavements in the most diverse urban areas, being a way to minimize the impacts caused by impermeable paving that intensifies the flow of surface water, causing sudden floods (TENNIS, LEMING, & AKERS, 2004; KIA, WONG, & CHEESEMAN, 2017). This material contains reduced or non-existent amounts of fine aggregates and just enough volume of paste to surround its coarse aggregates, which enhances its permeable capacity (KIA, WONG, & CHEESEMAN, 2017; ACI 522R-10, 2010; MARTINS FILHO, PIERALISI, & LOFRANO, 2022).

It is significant that there is still no consolidated and universally accepted dosage methodology that relates the constituent materials of pervious concrete with their properties (ACI 522R-10, 2010; LIAN & ZHUNGE, 2010; TORRES, HU, & RAMOS, 2015; CHANDRAPPA & BILIGIRI, 2016). The increase in paste volume enhances the connection between the aggregates and generates a reinforcement in compressive strength. However, this increase reduces its porosity and, consequently, its permeable capacity (MARTINS FILHO, PIERALISI, & LOFRANO, 2022; YANG, MA, SHEN, & ZHOU, 2008; PIERALISI, CAVALARO, & AGUADO, 2017).

Therefore, in order to seek greater understanding about the influence of constituent materials and direct the formulation of mixes for pervious concrete, Martins Filho (2021) prepared a dosage study based on the paste consistency results, obtained from of the methodology adapted from Nguyen et al. (2014). The approach used guarantees standardization of the consistency of the mixtures studied, so that there is no shortage or excess of paste.

The importance of studying the dosage of pervious concrete is directly related to the possibility of efficient mixes (MARTINS FILHO S. T., 2021). Normally, pervious concrete is not used for pavements with high traffic loads, since its high porosity reduces its mechanical performance (SANDOVAL, JUSSIANI, MOURA, ANDRELLO, & TORALLES, 2022; FERGUSON, 2005; HAGER, 2009; SABNIS, 2012; MARTINS FILHO, BOSQUESI,
Analysis of Pervious Concrete Properties for Mixtures of Different W/C Ratios

FABRO, & PIERALISI, 2020). The correct production and use of pervious concrete as pavement for low traffic loads can partially replace some local microdrainage works, ensuring better use of the land (GHAFOORI & DUTTA, 1995).

The hydraulic property of pervious concrete is normally evaluated using Darcy's law, which assumes linearity between flow and hydraulic gradient. However, the resulting flows appear predominantly non-Darcian. A dimensionless permeability parameter \( d/\sqrt{k} \), generated by the aforementioned approach, was able to adequately grade the flow resistance offered by each specimen, and yielded rich interpretations of how heterogeneity in pervious concrete influences flow behavior (MARTINS FILHO, PIERALISI, & LOFRANO, 2022).

Based on current considerations, this article aims to evaluate a mixture reference, based on a dosage curve elaborated by Martins Filho (2021), and its derivations. For this evaluation, the properties of pervious concrete will be investigated focusing on physical, mechanical and hydraulic characterization tests.

2 MATERIALS AND METHODS

2.1 Materials

The coarse aggregates used of basaltic origin were purchased from a quarry located in the Apucarana/PR region. The particle size range used, 4.8 to 6.3 mm, was the result of the sieving process based on the recommendations of ABNT NBR NM 248 (2003). Portland Cement CP II-Z regulated by ABNT NBR 16697 (2014) was used.

The particle size fraction obtained has already been characterized by the following tests: Unit weight, ABNT NBR NM 45 (2006a); Shape Index (SI), ABNT NBR 7809 (2006b); and Zingg Method (ZINGG, 1935). Table 1 shows the physical characteristics of the aggregates.

<table>
<thead>
<tr>
<th>Granulometric Classes (mm)</th>
<th>Length (L)</th>
<th>Width (W)</th>
<th>Thickness (T)</th>
<th>Shape Index (Standard Deviation)</th>
<th>Sphericity (Standard Deviation)</th>
<th>Unit weight (kg/m³) (Standard Deviation)</th>
<th>Void index</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8 – 6.3</td>
<td>13.48</td>
<td>7.08</td>
<td>3.76</td>
<td>3.89</td>
<td>0.53</td>
<td>1333.54</td>
<td>0.558</td>
</tr>
</tbody>
</table>

Source: Adapted from Martins Filho (2021).

The compositions used were defined based on the study prepared by Martins Filho (2021), and these are commonly found in the literature for applications in pervious concrete. In Figure 1, the w/c and P/Ag ratio for different particle size ranges can be seen, and the highlighted (red circle) is the point used in this experimental campaign.
Table 2 shows the mixes produced. It is noted that four concrete mixes were produced with a constant P/Ag ratio of 0.45, varying the water/cement ratio from 0.34 to 0.40, assigning the nomenclature to the four mixes of CP4534, CP4536, CP4538 and CP4540. In addition to these, one more mix as a form of comparison for different P/Ag ratios (0.45 and 0.55), keeping the reference w/c ratio of 0.36 constant (CP5536).

The pervious concrete molding process followed the recommendations of Schaefer et al. (2006). After making the concrete, a visual inspection was carried out and it was observed that the w/c ratio chosen covered the aggregates entirely with paste, and during the molding process the paste did not segregate, following the recommendations of Tennis, Leming and Akers (2004). The molding was carried out by placing the concrete inside the cylindrical mold in three layers, compacting each layer with 25 blows using a metal rod, following the regulations of ABNT NM 45 (2006a). To carry out the tests, a total of 43 cylindrical specimen were produced (100 mm in diameter and 200 mm in height).

When molding pervious concrete specimens, there is an important particularity: after compaction, there is a space no larger than 2 cm left at the top of the specimen. This space is filled with a “trowel” launched vertically and subsequent pressure, also vertically on the surface, without exerting the usual shearing effect used in the molding of conventional concrete. This procedure was carried out to ensure that the cement paste did not obstruct the upper pores when the spoon slide over the sample, obtaining the necessary finish, as suggested in Martins Filho (2021).
2.2 Methods

The tests carried out to characterize the pervious concrete were: density and total porosity in the hardened state; evaluation of flow in constant head permeameter; compressive strength; and determination of ultrasonic pulse velocity (UPV) using the Ultrasound Method. The Table 3 shows the number of specimens for each test and mixture.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Density in fresh/hardened state</th>
<th>Total porosity</th>
<th>UPV</th>
<th>Permeameter</th>
<th>Compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP4534</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>CP4536</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>CP4538</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>CP4540</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>CP5536</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
</tbody>
</table>

The density and total porosity of the pervious concrete in the fresh state and in the hardened state were obtained using the procedure described by ASTM C1688 (2014) and ASTM C1754 (2012), respectively. The compressive strength was obtained through the rupture of the specimen as established by ABNT NBR 5739 (1994), allowing the surface to be regularized.

The test to determine UPV was carried out using the methodology listed in Martins Filho et al. (2020) for each specimen, the ultrasonic pulse propagation time was determined using the PROCEQ/Pundit Lab brand ultrasound device, following the guidelines of ASTM C597 (1989). The reading of the CPs was carried out by direct longitudinal transmission, with an ultrasonic wave vibration frequency of 24 kHz and with an adjustment in the receiver of an amplification factor of 500 (corresponding to 54 dB). As the surface of the pervious concrete sample is normally irregular, a thick layer of gel was applied between the surfaces of the samples and the transducers.

The hydraulic property mentioned for pervious concrete was obtained through the constant head permeameter, which is commonly used by some researchers (MARTINS FILHO, PIERALISI, & LOFRANO, 2022; PIERALISI, CAVALARO, & AGUADO, 2017; ZAETANG, WONGSA, SATA, & CHINDAPRASIRT, 2013; SATA, WONGSA, & CHINDAPRASIRT, 2013; BHUTTA, et al., 2013; KUO, LIU, & SU, 2013; THO-IN, SATA, CHINDAPRASIRT, & JATURAPITAKKUL, 2012). Figure 2 shows an example of the constant head permeameter developed to carry out the test. The permeability results presented in this study were calculated with three hydraulic loads of 10, 20 and 30 cm, with respective static pressures of 1.96, 2.94 and 3.92 kPa for water at 20 °C.
The permeameter presented is composed of three parts, being an upper tube (1), used to control the water level (therefore, \( \Delta H \)); the specimen (2), which was wrapped in PVC film (Figure 2b) and sealing tape (Figure 2c) to reduce the flow of water on the side of the specimen; and a lower tube to control the water flow (3). To assemble the equipment, upper (1) and lower (3) tubes were fixed to the specimen (2) with tube sleeves. Afterwards, the equipment was fixed with three adjustable clamps attached to a wall to guarantee verticality (see Figure 2c).

After assembling the equipment, the water was released into the upper tube. The hydraulic load (water level - \( \Delta H \)) was kept constant and the volume of water (\( \Delta V \)) that passed through the specimen during 60 seconds (\( \Delta t \)) was measured. The hydraulic gradient (i) and the average body velocity (q) were estimated with Equations 1 and 2, respectively. In these equations, \( L \) represents the height of the specimen, \( Q \) represents the flow rate (accessed by \( Q = \frac{\Delta V}{\Delta t} \)) and \( A \) represents the cross-sectional area of the specimen.

\[
\begin{align*}
    i &= \frac{\Delta H}{L} \\
    q &= \frac{Q}{A}
\end{align*}
\]  

2.2.1 Determination of permeability parameters

Considering that the flow in pervious concrete is non-laminar, the Forchheimer equation \((i = aq + bq^2)\) was used. Where “a” is the linear coefficient and “b” is a quadratic coefficient (MARTINS FILHO, PIERALISI, & LOFRANO, 2022). Therefore, graphically, Forchheimer’s law better describes the non-linear flow, as can be seen in Figure 3.
Figure 3. Comparison between Darcy’s Law and Forchheimer’s Law
Source: Adapted from Martins Filho, Pieralisi and Lofrano (2022).

As can be seen in the graph, and through the research of Martins Filho (2021), Darcy’s Law is useful when it comes to adjustments at a single point, and its results are only useful in situations with the same flow rate/gradient. Using Forchheimer’s Law, it is possible to evaluate the behavior of the porous medium under all flow/gradient conditions.

Based on the methodological development listed by Martins Filho, Pieralisi and Lofrano (2022), it is notable that Ahmed and Sunada (1969) determined that the coefficients of Forchheimer’s law were $a = \frac{\mu}{\rho g k}$ and $b = \frac{1}{gcd}$, with "c" being a constant described by $c = \frac{k}{d^2}$, equation 3:

$$i = \frac{\mu}{\rho g k} \cdot q + \frac{1}{gcd} \cdot q^2$$

(3)

The parameter $d/\sqrt{k}$ is like a signature of the porous medium, and it is recommended to find a value for each specimen produced, regardless of whether they are of the same mix. And it represents the resistance of the porous media to flow in relation to its geometric conformation (MARTINS FILHO, PIERALISI, & LOFRANO, 2022).

3 RESULTS AND DISCUSSION

Table 4 presents the average properties tested for the different mixtures produced by varying the P/Ag and w/c ratios: density in the fresh and hardened state, total porosity, permeability, UPV and compressive strength. The respective standard deviations were shown in parentheses, below the mean.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Density in fresh state (kg/m³) (σ)</th>
<th>Density in hardened state (kg/m³) (σ)</th>
<th>Total porosity (%) (σ)</th>
<th>UPV (m/s) (σ)</th>
<th>Flow rate (l/s)</th>
<th>Compressive strength (MPa) (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1847.47 (44.39)</td>
<td>1799.67 (42.50)</td>
<td>32.42 (1.92)</td>
<td>3559.00 (131.74)</td>
<td>0.18 (0.03)</td>
<td>0.20 (0.04)</td>
</tr>
<tr>
<td>CP 45 34</td>
<td>1894.58 (47.91)</td>
<td>1872.18 (45.00)</td>
<td>28.17 (2.25)</td>
<td>3781.00 (139.92)</td>
<td>0.15 (0.04)</td>
<td>0.17 (0.05)</td>
</tr>
<tr>
<td>CP 45 36</td>
<td>1990.71 (41.69)</td>
<td>1928.75 (39.79)</td>
<td>25.02 (2.22)</td>
<td>3799.00 (58.17)</td>
<td>0.10 (0.04)</td>
<td>0.12 (0.05)</td>
</tr>
<tr>
<td>CP 45 38</td>
<td>1962.06 (41.69)</td>
<td>1915.76 (39.79)</td>
<td>23.39 (2.22)</td>
<td>3687.00 (58.17)</td>
<td>0.11 (0.04)</td>
<td>0.12 (0.05)</td>
</tr>
</tbody>
</table>
In order to corroborate the analysis of the results, Figure 4 presents a sample of each mix for visual analysis. A greater number of surface pores contributes to better hydraulic performance.

**Figure 4.** Visual analysis

In order to understand the behavior of pervious concrete, graphs were produced to present some correlations between the data obtained in the different tests.

In Figure 5 it is possible to observe the relationship between the densities after molding (in the fresh state) and after 7 days (in the hardened state). This difference can be related to the curing process of pervious concrete, resulting in lower density in the hardened state.

**Figure 5.** Relationship between Density in fresh state and in the hardened state

Figure 6a and Figure 6b show the influence of the w/c ratio on density in the hardened state and total porosity, respectively. While Figure 6c relates the density in the hardened state and the total porosity. It is evident that the increase in the w/c ratio results in a paste with a more fluid consistency, contributing to greater consolidation when molding and an increase in density, however it reduces the porosity of the pervious concrete.

<table>
<thead>
<tr>
<th>Reference mix</th>
<th>Density in fresh state (kg/m³)</th>
<th>Density in hardened state (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP 55 36</td>
<td>(47.77)</td>
<td>21.72</td>
</tr>
<tr>
<td>CP 4534</td>
<td>(45.05)</td>
<td>2024.45</td>
</tr>
<tr>
<td>CP 4536</td>
<td>(2.67)</td>
<td>1970.23</td>
</tr>
<tr>
<td>CP 4538</td>
<td>(57.40)</td>
<td>4032.00</td>
</tr>
<tr>
<td>CP 4540</td>
<td>(0.03)</td>
<td>0.06</td>
</tr>
<tr>
<td>CP 5536</td>
<td>(2.57)</td>
<td>0.08</td>
</tr>
<tr>
<td>CP 4534</td>
<td>(41.77)</td>
<td>102.12</td>
</tr>
<tr>
<td>CP 4536</td>
<td>(39.00)</td>
<td>0.04</td>
</tr>
<tr>
<td>CP 4538</td>
<td>(2.81)</td>
<td>0.04</td>
</tr>
<tr>
<td>CP 4540</td>
<td>(102.12)</td>
<td>0.05</td>
</tr>
<tr>
<td>CP 5536</td>
<td>(1.70)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

\[
D_e = 1.0069 \cdot D_f - 48.705
\]

\[R^2 = 0.8998\]
The standard deviation of each mixture also results from the pervious concrete molding process. The randomness of the formation of the porous medium in pervious concrete results in PCs with different porosities even though they belong to the same mix. Thus, although experimental inaccuracies may be evident, it is important to highlight that each porous medium is unique (MARTINS FILHO S. T., 2021).

In order to exemplify the approach to the hydraulic characterization of pervious concrete, a graph was created relating the flow speed and hydraulic gradient for each sample tested, as can be seen in Figure 7.

**Figure 6.** Relationship between w/c factor and density in hardened state (a), total porosity (b) and relationship between density in hardened state and total porosity (c).
Figure 7. b

From this graph, it was possible to observe that this relationship is non-linear, therefore it is valid to state that the Forchheimer equation describes the behavior more precisely (MARTINS FILHO, PIERALISI, & LOFRANO, 2022). From the constants of the non-linear equation “a” and “b”, it is possible to obtain the hydraulic parameters of the flow: $d$, $\sqrt{k}$ and $d/\sqrt{k}$ (MARTINS FILHO, PIERALISI, & LOFRANO, 2022). Table 5 presents the total porosity and hydraulic data of all samples tested in the constant head permeameter.

Table 5. Hydraulic Data.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Specimen</th>
<th>Pt (%)</th>
<th>a (s/m)</th>
<th>b $(10^3 s^2/m^2)$</th>
<th>$\sqrt{k}$ $(10E-5)$</th>
<th>d $(10E-5)$</th>
<th>d/\sqrt{k}</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP 45 34</td>
<td>1</td>
<td>28.43</td>
<td>27.29</td>
<td>4.59</td>
<td>6.11</td>
<td>16.81</td>
<td>2.75</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30.72</td>
<td>22.90</td>
<td>2.79</td>
<td>6.67</td>
<td>12.20</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>32.42</td>
<td>64.43</td>
<td>0.56</td>
<td>3.98</td>
<td>0.87</td>
<td>0.22</td>
</tr>
<tr>
<td>CP 45 36¹</td>
<td>5</td>
<td>28.17</td>
<td>41.40</td>
<td>3.06</td>
<td>4.96</td>
<td>7.39</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>31.00</td>
<td>20.02</td>
<td>2.54</td>
<td>7.14</td>
<td>12.68</td>
<td>1.78</td>
</tr>
<tr>
<td>CP 45 38</td>
<td>6</td>
<td>25.65</td>
<td>72.16</td>
<td>7.18</td>
<td>3.76</td>
<td>9.95</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>29.17</td>
<td>35.45</td>
<td>3.86</td>
<td>5.36</td>
<td>10.88</td>
<td>2.03</td>
</tr>
<tr>
<td>CP 45 40</td>
<td>2</td>
<td>17.54</td>
<td>98.98</td>
<td>23.14</td>
<td>3.21</td>
<td>23.38</td>
<td>7.29</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>23.40</td>
<td>42.10</td>
<td>6.90</td>
<td>4.92</td>
<td>16.39</td>
<td>3.33</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>27.09</td>
<td>16.61</td>
<td>5.06</td>
<td>7.83</td>
<td>30.49</td>
<td>3.89</td>
</tr>
<tr>
<td>CP 55 36</td>
<td>6</td>
<td>21.72</td>
<td>155.31</td>
<td>21.16</td>
<td>2.56</td>
<td>13.62</td>
<td>5.32</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>24.84</td>
<td>77.75</td>
<td>7.92</td>
<td>3.62</td>
<td>10.19</td>
<td>2.81</td>
</tr>
</tbody>
</table>

¹Reference mix

Figure 8 shows the relationship between total porosity and $d/\sqrt{k}$. As mentioned, the parameter $d/\sqrt{k}$ represents the flow resistance and is unique for each specimen.
The increase in porosity results in a decline in the resistance of the porous medium to the water flow. Although there is a trend, there is a dispersion of results mainly for the specimen with lower porosity, as expected, since there are greater non-occurrences of possible flow paths, that is, greater flow interference attributed by tortuosity. This reported dispersion is not necessarily linked to any discussion about the reliability of using \(d/\sqrt{k}\), but rather to its correlation with total porosity, which would possibly not be the only variable that affects hydraulic behavior, but there is no doubt that it has high correlation with its flow (MARTINS FILHO, PIERALISI, & LOFRANO, 2022).

Figure 9a and Figure 9b correlate the UPV with the density in hardened state and total porosity, respectively. As expected, the UPV is higher when the density is higher and the porosity is lower. This behavior can be explained by the better propagation of the ultrasonic pulse velocity in the matter, but attenuated when the presence of voids is high (MARTINS FILHO, BOSQUESI, FABRO, & PIERALISI, 2020).

It can also be observed that UPV increases when the P/Ag ratio is higher, since there is a greater possibility of finding shorter paths (MARTINS FILHO, BOSQUESI, FABRO, & PIERALISI, 2020). Furthermore, it promotes a reduction in the dispersion of results.

**Figure 8.** Relationship between Total Porosity and \(d/\sqrt{k}\).

**Figure 9.** Relationship between ultrasonic pulse speed and density in the hardened state (a) and total porosity (b).
Figure 10 shows the relationship between the w/c factor and compressive strength. In this correlation, only mixtures with the same P/Ag ratio were considered. The increase in the w/c factor promotes greater fluidity of the paste, resulting in better coverage and union between aggregates. When increasing the P/Ag ratio, an increase in compressive strength is noted for the mixture with the same constant w/c ratio, as expected.

![Graph showing the relationship between Compressive Strength and w/c Ratio](image)

Figure 10. Relationship between Compressive Strength and w/c Ratio

Figure 11 shows a correlation between compressive strength and total porosity. The reduction in porosity promotes an increase in compressive strength, but reduces its drainage capacity. The general equation, by analyzing a wider range of porosity, showed a higher correlation, regardless of the different P/Ag ratios.

![Graph showing the relationship between Compressive Strength and Total Porosity](image)

Figure 11. Relationship between Compressive Strength and Total Porosity.

As expected, the relationship between UPV and compressive strength presented in Figure 12 shows that these properties are directly proportional. In addition, this analysis shows that the Ultrasound Method can be used, with certain considerations, to interpret the properties of pervious concrete in a non-destructive way (MARTINS FILHO, BOSQUESI, FABRO, & PIERALISI, 2020).

\[
\sigma = 77.49 \cdot (w/c) - 19.23 \\
R^2 = 0.7788
\]

\[
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16
\]

\[
\sigma = 48.399e^{0.062x} \\
R^2 = 0.82
\]

\[
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16 \\
18 \\
20
\]

\[
y = 43.95e^{-0.058x} \\
R^2 = 0.7122
\]
4 CONCLUSION

This work sought to evaluate one of the points of the dosage curve prepared by Martins Filho (2021), thus a reference mix was chosen, and by varying the w/c ratio and a P/Ag ratio, 5 mixes were stated. The conclusions derived from this study:

- The UPV decreases with increasing total porosity, as the ultrasonic wave suffers attenuation caused by the presence of voids. Furthermore, UPV is directly related to density and compressive strength, contributing to the interpretation of the properties of pervious concrete.
- Despite the low hydraulic load, the flow is considered non-Darcian and can be characterized by the parameter $d/\sqrt{k}$, which is considered a signature of hydraulic behavior, as verified by Martins Filho, Perialisi and Lofrano (2022). Lower porosities, higher flow restrictions, resulting in greater $d/\sqrt{k}$.
- The reference mix and its variations were in accordance to the literature, as proposed. Therefore, the dosage curve used to define the mixes is considered viable for the point studied here and can serve in a valuable way as guidance for the production of pervious concrete.

ACKNOWLEDGEMENTS

We would like to acknowledge the Federal University of Technology of Parana (UTFPR).
REFERENCES


ZAETANG, Y., WONGSA, A., SATA, V., & CHINDAPRASIRT, P. (2013). Use of