EXPERIMENTAL AND MICROMECHANICAL APPROACH TO ELASTIC PROPERTIES OF PERVIOUS CONCRETE

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Abstract. Pervious concrete refers to a material composed by Portland cement, coarse aggregate, little or none fine aggregate, water and, at times, additives and additions. The pervious concrete porosity affects its elastic properties, as pointed by available studies. In the perspective of a wide use, a comprehensive formulation of the corresponding behavior is necessary. In this context, the present study describes a micromechanical model for the macroscopic elastic properties of the pervious concrete. Reasoning on the representative elementary volume (REV) of such a composite, the overall elastic characteristics are determined from the knowledge of the elastic properties of its constituents (aggregate + cement paste + pores). Moreover, aiming the comprehension of the elastic and strength behaviors of pervious concrete produced with local supplies (Porto Alegre, RS), this work evaluates experimentally the following parameters: elastic modulus and uniaxial compressive strength. The results show how the elastic properties are related to the porosity of pervious concrete produced with local materials and confirm the possibility of estimating the elastic properties through the micromechanical approach.

Keywords: Pervious Concrete; Elastic Properties; Experiments, Micromechanics

1 Introduction

The great need for housing and the materials scarcity after the destruction caused by the World War II allied to the unprecedented demand for bricks and the subsequent inability of the industry to produce them, as well as the less cement use per unit volume in pervious concrete when compared to plain concrete, has led in the past, to the adoption of pervious concrete as a building material (Malhotra [1]). Currently, it is gaining prominence due to the benefits it presents to the environment, being widely recognized as a sustainable building material. Its benefits include the ability to store and transport water through its structure, thereby reducing problems associated with storm water runoff, ability to refill groundwater supplies with less pollutants (Haselbach et al. [2]), and the ability to reduce the effect of urban heat islands (Takebayashi and Moriyama [3]; Li et al. [4]).

In fact, this material has been used for a wide range of applications, which are: permeable pavements for parking spaces, drainage systems for outdoor areas of shopping centers, lighter structural walls and/or with better response to heat, pavements, walls or floors where better acoustic absorption is desired, base layer for streets, highways, roadways and airport runways, coastal and maritime structures, and storage of solar energy. However, pervious concrete use in many countries, especially emerging countries, is still not common, mainly because of the lack of knowledge of the production technique and construction experience (Chandrappa and Biligiri [5]). Since this kind of concrete has an interconnected pore structure, it usually has no structural reinforcement because the high risk of corrosion of the metallic reinforcement (ACI 522R-10 [6]).

Pervious concrete is a cementitious material that has interconnected pores, resulting in a structure with high permeability, allowing the easy water flow (ACI 522R-10 [6]). This is a zero slump concrete, which is made of Portland cement, coarse aggregate, little or none fine aggregate, water, mineral and chemical admixtures. The combination of these ingredients produces a hardened material with connected pores ranging from 2 to 8 mm. The porosity of a typical pervious concrete varies from 15 to 35%, with the minimum of 15% prescribed by the National Ready Mix Concrete Association (NRMCA). The uniaxial compressive strength may vary from 2.8 to 28 MPa. The water-cement ratio is low when compared to that used in conventional concretes, and its value varies between 0.25 and 0.45 with the main intention of providing the wrapping of the aggregate by a thin layer of paste (Malhotra [1], Chandrappa and Biligiri [5]). Concrete mixtures already employed range from a minimum of 1:3 to a maximum of 1:12 (cement:aggregate). Typically, the aggregate volume in pervious concrete ranges from 50 to 65% while in conventional concrete usually ranges from 60 to 75%. It is known that the density, strength (tensile and compression), elasticity modulus, infiltration rate, hydraulic conductivity, and structural performance of pervious concrete are all function of their porosity (Ghafoori and Dutta [7], Crouch et al. [8], Chindaprasirt et al. [9], Delatte et al. [10], Sumanasooriya and Neithalath [11], Deo and Neithalath [12], Neithalath et al. [13], Henderson et al. [14], Kevern et al. [15]). The Young modulus is an essential property for the evaluation of the mechanical response of materials and structures. Thus, it is important to understand the relationship between porosity and Young modulus to evaluate the mechanical response of pervious concrete systems.

There are a limited number of studies available in the literature that focus in the determination of the pervious concrete elastic properties. The Young modulus of the pervious concrete was estimated by the ultrasonic test by Onstenk et al. [16] and the porosities of their concrete samples ranged from 11 to 31%. In another study (Crouch et al. [8]), the effect of aggregate sizes and gradations on the Young modulus were evaluated. Moreover, the concrete moduli and respective porosities were correlated. Alam and Haselbach [17] also investigated the Young modulus of pervious concrete with different porosities, based on samples produced with a controlled porosity distribution. From a large number of samples, the influence of the porosity on Young modulus was evaluated, and a correlation between then was obtained.

The studies mentioned above used the traditional way to formulate constitutive models, which is based on empirical procedures experimentally established. An alternative method, based on micromechanical reasoning, allows the macroscopic mechanical behavior description of composite materials through the implementation of homogenization techniques. The objective is the substitution of a heterogeneous medium by an equivalent homogeneous medium, whose elastic constitutive equations result from the solution of a boundary problem on the representative elementary volume (REV) of the material.

Several micromechanical models have been developed to estimate the elastic properties of different composite materials. They are mostly based on the result established by Eshelby [18] related to ellipsoidal inclusions embedded within the infinite medium. Depending on the morphology of the microstructure, estimate schemes of composites elastic properties may refer to the diluted estimation (Gross and Seelig [19]), Mori-Tanaka (Mori and Tanaka [20], Benveniste [21]), self-consistent (Hashin [22]) or generalized self-consistent model (Christensen [23]). These micromechanical models are based on the behavior of the constituents of the heterogeneous medium and its microstructure configuration.

In this work, the fundamental elastic parameter for the characterization of the material elastic response, the Young modulus of the pervious concrete, is evaluated. Two different approaches are adopted: the phenomenological, with the execution of experiments to obtain the Young modulus, and the micromechanics, using the self-consistent model for their estimation.

2 Experimental Approach

2.1 Materials and Methods

In order to produce the pervious concrete, materials from Porto Alegre city, South of Brazil, were used. Moreover Portland Cement Type III (high level strength) and flat elongated basaltic aggregate, available and commonly found, were added to the mixture. The water-cement ratio was 0.3 and no mineral or chemical admixtures were used in the material production. The aggregate granulometric distribution can be seen in Table 1.

Test specimens of two different concrete mixtures (in weight), 1:4 and 1:5, were produced, resulting in twenty and eighteen specimens, respectively. The adopted proportion was based on the studies already developed by the pervious concrete research group of the Laboratory of Testings and Structural Models (LEME) (Höltz [24], Lamb [25], Schwetz et al. [26], Schwetz et al. [27]).

Table 1. Aggregate granulometric distribution

Sieve (mm)	Retained Mass (%)	Total Retained Mass (%)
9	0.0	0
12.5	0.4	0
9.5	10.4	11
6.3	38.9	50
4.8	19.5	69
2.4	19.3	88
1.2	5.3	94
0.6	2.5	96
0.3	2.0	98
0.15	1.7	100
0.075	0.1	100
Bottom	0.0	100

The pervious concrete specimens used in this study were produced in two different mixtures. They were molded using cylindrical metal molds with 100 mm of diameter and 200 mm height. The fresh concrete had his weigh controlled, was inserted in each specimen and was manually compacted into the molds in order to obtain different porosities, prioritizing a compaction that would provide hardened concretes with porosities ranging from 20 to 25%. After molding, the cylindrical molds were covered with plastic for 7 days. Curing occurred in uncontrolled temperature and humidity.

2.2 Performed Experiments

Different tests were performed with the produced specimens, including the porosity measurement and the uniaxial compressive test to obtain the elasticity modulus and the uniaxial compressive strength, which are described in the sequence.

Porosity. All samples were analyzed for porosity using ASTM C1754 (ASTM [28]) modified based on the study by Montes et al. [29]. The modification refers to the samples drying. In this study, air drying was adopted with the samples placed on a leaked surface in a laboratory environment for at least one day after the demolding of the specimens.

The porosity (ϕ) or void content influences all the properties of the pervious concrete, therefore its measurement is fundamental. ASTM C1754 (ASTM [28]) specifies the measuring methodology for pervious concrete porosity. The test consists of weighing the specimens when they are dried at room temperature and when immersed for at least 30 minutes, as well as verifying their dimensions for further calculation of ϕ by the expression $\phi(\%) = (1 - ((m_D - m_W) / (\rho_W V)))100$, where m_D and m_W are the dry and the submerged mass of the specimen (kg), respectively, ρ_W is the density of the liquid used in the immersion at temperature of the bath and V is the volume of the specimen.

Young Modulus. The Young modulus (E) and Poisson ratio (ν) are materials elastic properties. In the case of isotropic materials, these two properties completely characterize their behavior when strain and stress are small (elastic regime). Therefore, they are fundamental for characterization and behavior estimation of materials.

There is currently no specific standard to determine the Young modulus and Poisson ratio of pervious concrete. Thus, for this purpose, ASTM C469 (ASTM [30]) was utilized with adaptations for pervious concrete. Due to the available equipment and the configuration of the pervious concrete specimen, only the Young modulus was measured. The load was applied using a hydraulic press (Fig. 1). The standard (ASTM [30]) establishes the use of Linear Variable Differential Transformers (LVDTs) attached to the test body by a support. The application of the load should vary from a value of 5% of the rupture load (minimum load) and 30% of the rupture load (maximum load), repeating the procedure three times (three cycles).

Figure 1. Press and sensors for the measurement of dimension variations.

Due to the variability of the pervious concrete uniaxial compressive strength (porosity variability), a maximum load of 16.5 kN and a minimum load of 2.5 kN were used in all specimens, reaching the same stress level in all specimens. This choice was based on the strength limits found in the available literature (2 to 28 MPa), aiming to apply a load that produced stress and strains in the material elastic regime considering the analyzed porosities variation (from 15 to 28%).

The load level and length variation of the specimens during the compressive test are collected through an appropriated acquisition system. The first two data cycles were discarded and only data from the third cycle were utilized, as suggested by the standard. The load data and the length variation, converted respectively to stress and strain allow the Young modulus (E) determination.

Uniaxial Compressive Strength. The uniaxial compressive strength was obtained for all specimens whose elastic properties were measured. Without the geometry variation measuring equipment (supports and LVDTs), the load was gradually applied with hydraulic press (Fig. 1) until the concrete rupture and the maximum load was obtained.

2.3 Results

The results of the performed tests are presented in this section. Figure 2 shows the variation of the Young modulus with the porosity for the two concrete mixtures evaluated.

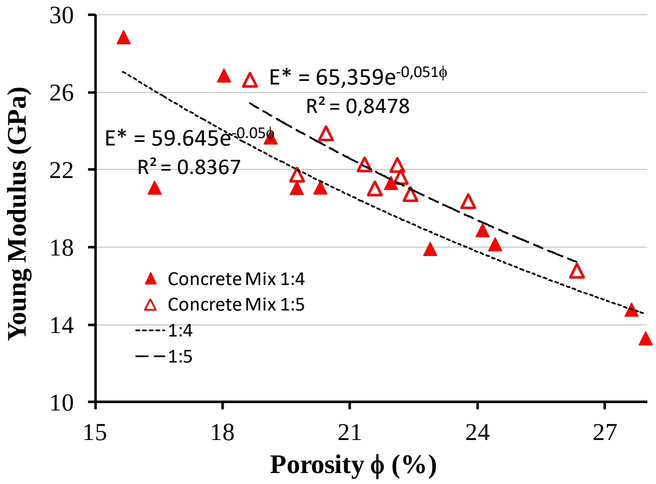

Figure 2. Young Modulus variation with the porosity of the studied mixtures.

The results showed strong dependence of elastic properties on porosity. Likewise, the equations that correlate the elastic properties with the porosity are also presented, which were obtained from least squares regressions. In this approach exponential regressions were chosen since they have presented higher determination coefficients (R^2) when compared to other regressions types (linear, logarithmic, polynomial, and power). These equations allow estimating the elastic properties and determining which porosity should be sought in the production of the pervious concrete to achieve the desired elastic properties for the specific type of cement, aggregate and mixtures employed. Regarding the analyzed mixes, this parameter seems to have little influence on elastic properties of pervious concrete. For a better understanding of the mix influence in the elastic response of the material, it is suggested the use of its limit values found in the literature (minimum of 1:3 to a maximum of 1:12) in future works

The obtained Young modulus results were also displayed with experimental data of other studies (Fig. 3) available in the literature (Alam and Haselbach [17], Crouch et al. [8]) which focus on elastic properties of different pervious concretes. Crouch et al. [8] evaluated the effects of aggregate gradation, amount, and size on pervious Portland cement concrete Young modulus. A standard mix and three variable mixes using a uniform gradation of limestone, increased aggregate amount, and increased aggregate size were used. For the standard mix, referred to as Mix A, and for the Mix B, which the gradation was more uniform, the aggregate content remained the same. The Mix C, was given the same gradation as Mix B, whereas the aggregate content was raised from 58.7 to 61.7% of the total volume. The Mix D, also contained an aggregate content level of 61.7% of the total material volume and a uniform gradation, while the maximum size aggregate was increased. Portland cement and fly ash were used as binder materials. The aggregate to binder ratio for the Mixes A and B were 4.5 and for the Mixes C and D were 5.6. All four mixes had water to binder materials ratio (w/b) of 0.39.

Alam and Haselbach [17] investigated the Young modulus of pervious concrete for a range of porosities based on specimens made with a less variable porosity distribution along their depths. They used a large number of specimens to evaluate Young modulus variability based on porosity, and to develop a correlation between the porosity and the elastic modulus of pervious concrete. The pervious concrete specimens used in this study were prepared with uniformly graded 69.5mm (#8) coarse basalt aggregate and no sand. Type I ordinary Portland cement was used as binder. The cement to aggregate ratio for all the batches was 0.25. Four batches of pervious concrete cylindrical specimens were prepared on different days, all 100mm in diameter and approximately 200mm in length. The mix designs varied slightly due to water content and additional water being sprayed over the concrete mix to maintain workability during the preparation of the specimens. Batch 1 had a w/c ratio of 0.28 and batch 2, 3, and 4 had a w/c ratio of 0.3. The batches were prepared with lifts, each lift being compacted to an approximately equal wet density. The lifts were used in order to maintain a more equal vertical porosity distribution in each specimen than would have been obtained if the specimens were made with a single lift with only top surface compaction.

Figure 3 indicates that the elastic modulus results show the same tendency identified in the few available studies on the subject. Moreover, it is important to note that no studies were found on the Poisson ratio of pervious concrete and its dependence on the influent variables (aggregate granulometry, cement type, porosity, and cement quantity).

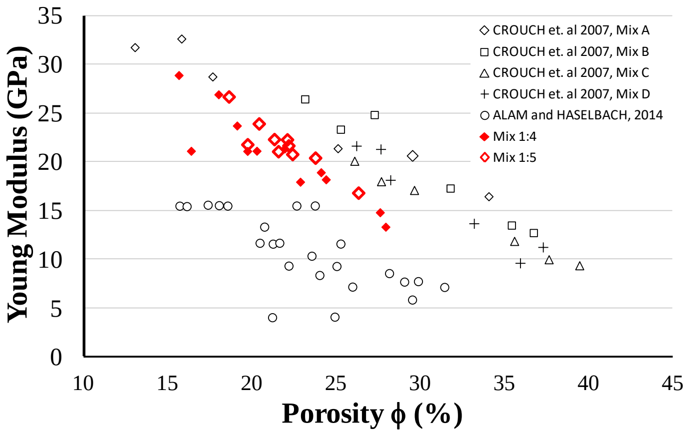

Figure 3. Young Modulus results of this study with those of Alam and Haselbach [17] and Crouch et al. [8].

Furthermore, Fig. 4a also displays the variation of the uniaxial compressive strength with porosity (ϕ) for the two concrete mixtures evaluated. Again exponential regressions presented higher determination coefficients (R^2) and so, are more adequate for the estimation of the strength of the pervious concrete produced with materials from Porto Alegre city. Finally, Fig. 4b display of the strength results of the present study and the results from Crouch et al. [8]. Alam and Haselbach [17] did not present strength results.

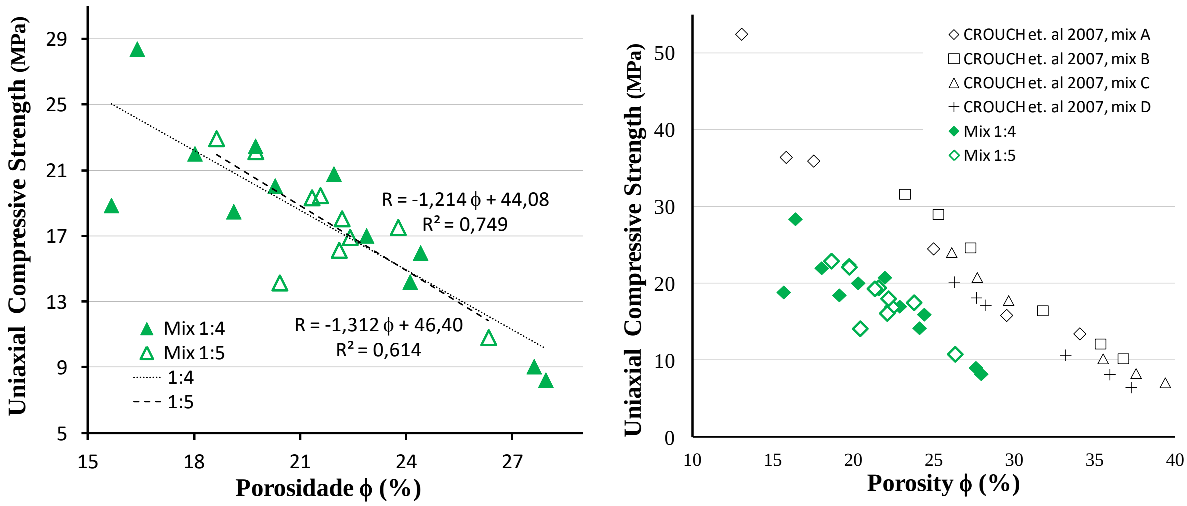

Figure 4. Uniaxial Compressive Strength versus Porosity (a) analyzed mixes and (b) this study and Crouch et al. [8] results.

3 Micromechanical Approach

3.1 Fundamentals of continuum micromechanics

This section provides a very brief introduction to micromechanics and homogenization in linear elasticity. The interested reader may refer for instance to Dormieux et al. [31], Torquato [32], Nemat-Nasser and Hori [33] for a more detailed presentation.

Basic concepts. The homogenization theory aims at estimating the effective behavior of composite materials. The main interest of the approach lies on the possibility to use the obtained effective behavior to perform computations at the scale of the homogeneous structure by reasoning on the so-defined homogenized structure instead over the original heterogeneous one (Fig. 5).

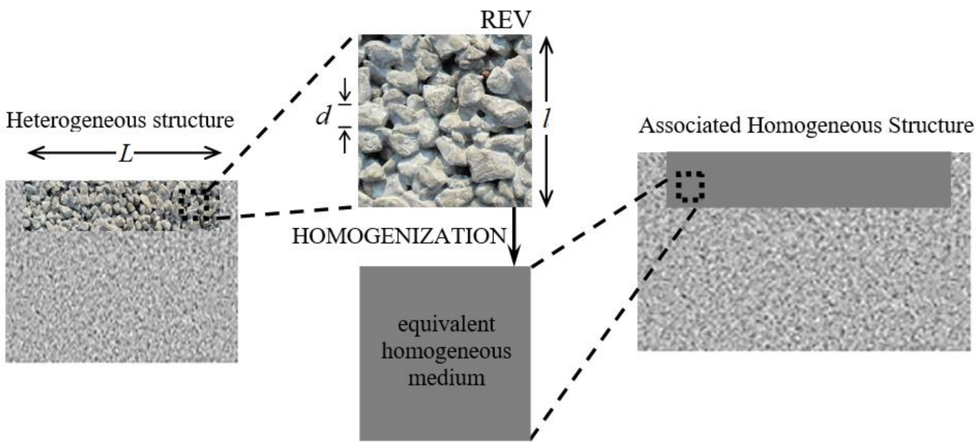

Figure 5. Schematic description of the homogenization process.

In continuum micromechanics, the material is understood as a macro-homogeneous but heterogeneous body at the scale adopted for material description. A central concept of the homogenization procedure is the existence of a representative elementary volume (REV) of characteristic size l which must comply with two conditions:

- to be elementary, which means that it is small enough compared to the size L of the structure;

- to be representative, that is to be large enough compared to the size d characterizing the heterogeneity of the microstructure.

The above conditions represent the so-called condition for scale separation $d << l << L$, necessary for the concept of REV to be valid (Zaoui [34]).

In general, the microstructure within each REV is so complicated that it cannot be described in detail. Therefore, quasi-homogeneous sub-domains with known physical quantities (such as volume fraction, elastic or strength properties) are reasonably defined within the REV. They are referred to as material phases. The central objective of continuum micromechanics is to estimate the mechanical properties of the material defined on the REV from the aforementioned phase properties.

The loading of the REV is defined by means of uniform strain boundary conditions $\underline{u}(x) = \underline{\underline{E}} \cdot \underline{x} \;\; on \;\; \partial\Omega$ (Fig. 6), where $\underline{\underline{E}}$ denotes the macroscopic strain tensor and $\underline{x}$ is the position vector labeling points within the REV Ω or located along its boundary $\partial\Omega$.

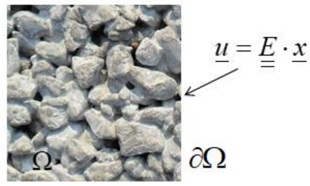

Figure 6. Loading mode of the REV: uniform strain boundary conditions.

Homogenization in elasticity. In the framework of homogenization of random composite media applied to linear elasticity, each phase (r) is characterized by its four-order stiffness tensor $\underset{\sim}{c}^{r}$ relating the stress tensor to strain tensor.

The formulation of the macroscopic elastic behavior stems from the resolution of the following concentration problem (Suquet [35]):

$$\begin{cases} \operatorname{div} \underline{\underline{\sigma}} = 0 & \text{on} \;\; \Omega \\ \underline{\underline{\sigma}} = \underset{\sim}{c}(\underline{x}) : \underline{\underline{\varepsilon}} & \text{on} \;\; \Omega \\ \underline{u} = \underline{\underline{E}} \cdot \underline{x} & \text{on} \;\; \partial\Omega \end{cases} . \tag{1}$$

From linearity arguments, it appears that the local strain $\underline{\underline{\varepsilon}}(\underline{x})$ is proportional to the macroscopic strain $\underline{\underline{E}}$ through strain concentration tensor $\underset{\sim}{A}\;\underline{x}$, i.e. $\underline{\underline{\varepsilon}}(\underline{x}) = \underset{\sim}{A}\;\underline{x} : \underline{\underline{E}}$. Averaging the local elastic constitutive equation over the REV yields the expression of the homogenized stiffness tensor:

$$\underset{\sim}{C}^{\mathrm{hom}} = \left\langle \underset{\sim}{c} : \underset{\sim}{A} \right\rangle = \sum_{r} f^{r} \; \underset{\sim}{c}^{r} : \left\langle \underset{\sim}{A} \right\rangle_{r} . \tag{2}$$

In the above relationship, f^{r} stands for the volume fraction of phase (r), $\underset{\sim}{c}^{r}$ is the stiffness tensor of phase (r) and $\langle a \rangle$ (resp. $\langle a \rangle_{r}$) refers to the volume average of field a over the REV (resp. over the domain occupied by phase (r)). Interestingly noting, a kinematically compatible strain field complies with the average rule $\langle \underline{\underline{\varepsilon}} \rangle = \underline{\underline{E}}$.

As emphasized by Eq. (2), the determination of the overall elasticity tensor requires being able to compute estimates of the average of strain concentration tensor over each phase (r). The latter estimates are in practice obtained by resorting to an appropriate homogenization scheme integrating some information on the morphology. In the Eshelby-based approach (Eshelby [18]), the average strain concentration tensor $\langle \underset{\sim}{A} \rangle_{r}$ is estimated from the uniform strain that establishes in an ellipsoidal inclusion embedded into an infinite medium (reference medium) with stiffness $\underset{\sim}{c}^{0}$ subjected to uniform strain boundary conditions at infinity of the form $\underline{u}\;\underline{x} = \underline{\underline{E}}^{\infty} \cdot \underline{x}$ for $\left|\underline{x}\right| \rightarrow +\infty$. This reference strain $\underline{\underline{E}}^{\infty}$ is related to the macroscopic strain $\underline{\underline{E}}$ applied at the boundary of the REV according to the average strain rule $\langle \underline{\underline{\varepsilon}} \rangle = \underline{\underline{E}}$. The shape of the ellipsoid representing a given phase and the stiffness $\underset{\sim}{c}^{0}$ both depend on the morphology of the microstructure. In the framework of Eshelby-based approach, the estimate of $\langle \underset{\sim}{A} \rangle_{r}$ reads

$$\left\langle \underset{\sim}{A} \right\rangle_r^{\text{est}} = \left[\underset{\sim}{1} + \underset{\sim}{P}^{0,r} : \ \underset{\sim}{c}^r - \underset{\sim}{c}^0 \ \right]^{-1} : \left\langle \left[\underset{\sim}{1} + \underset{\sim}{P}^0 : \ \underset{\sim}{c} - \underset{\sim}{c}^0 \ \right]^{-1} \right\rangle^{-1}. \tag{3}$$

where $\underset{\sim}{P}^{0,r}$ is the fourth-order Hill tensor. It depends on the stiffness $\underset{\sim}{c}^0$ of the reference matrix as well as on the shape and orientation of the considered inclusion. Closed-form analytical expressions of Hill tensor $\underset{\sim}{P}^{0,r}$, or equivalently of the so-called Eshelby tensor $\underset{\sim}{S}^{0,r} = \underset{\sim}{P}^{0,r} : \underset{\sim}{c}^0$, are available for particular configurations of material symmetry and inclusion shape (see for instance Laws [36], Mura [37]).

Substitution of Eq. (3) into Eq. (2) yields the sought estimate for the homogenized (macroscopic) elasticity tensor:

$$\underset{\sim}{C}^{\text{ est}} = \left\langle \underset{\sim}{c} : \left[\underset{\sim}{1} + \underset{\sim}{P} : \ \underset{\sim}{c} - \underset{\sim}{c}^0 \ \right]^{-1} : \left\langle \left[\underset{\sim}{1} + \underset{\sim}{P}^0 : \ \underset{\sim}{c} - \underset{\sim}{c}^0 \ \right]^{-1} \right\rangle^{-1} \right\rangle. \tag{4}$$

When a particular continuous phase (m) surrounding all the other phases can be clearly identified, the Mori-Tanaka scheme (Mori and Tanaka [20], Benveniste [22]) considers it as the reference medium: $\underset{\sim}{c}^0 = \underset{\sim}{c}^m$. On the other hand, the self-consistent scheme (Hill [38], Budiansky [39]) adopts the searched homogenized material as the reference medium: $\underset{\sim}{c}^0 = \underset{\sim}{C}^{\text{hom}}$. The self-consistent scheme is classically used to model perfectly disordered materials such as polycristal-like microstructures.

Elastic properties of Pervious Concrete. In order to determine the elastic properties of the pervious concrete, the linear homogenization method is applied. The self-consistent scheme is chosen to analytically evaluate the pervious concrete elastic modulus. This model refers to a morphology in which no phase can be regarded as matrix (perfect disorder). Equivalently, each phase is considered embedded in the homogenized medium to be determined, i.e., the homogenized medium is considered as the reference medium. The microstructure of the pervious concrete is modeled, in this study, as three-phase composite material: aggregate + paste + pores, whose elasticity is characterized respectively by $\underset{\sim}{c}_G$, $\underset{\sim}{c}_{PT}$ and $\underset{\sim}{c}_P \to 0$. All the constituents are modeled with spherical shape (Fig. 7).

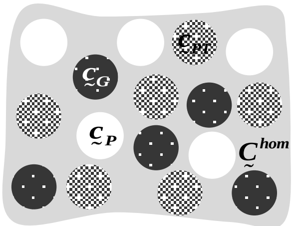

Figure 7. Self-consistent model.

Assumption of elastic isotropy for the constituents implies the elastic isotropy of pervious concrete at the macroscopic level. The homogenized elasticity tensor $\underset{\sim}{C}^{\text{hom}}$ can therefore be completely defined by means of the homogenized bulk modulus K^{kom} and shear modulus G^{hom}. These coefficients depend on the elastic modulus of the aggregate (k^G and g^G), cement paste (k^{PT} and g^{PT}) and pores ($k^P = 0$ and $g^P = 0$), as well on the volume fraction of them, respectively, f^G, f^{PT} and $f^P = \phi$. The estimates of K^{kom} and G^{hom} are computed from the Eshelby tensor $\underset{\sim}{S}$ which is a function of the geometry of the inclusion and Poisson's ratio of the reference medium (see Appendix A).

Equation (4) is employed with $\underset{\sim}{c}^0 = \underset{\sim}{C}^{\text{hom}}$. In this way, the homogenized bulk and shear moduli K^{kom} and G^{hom} of the composite, are implicitly defined. Actually, it is not possible to express analytically K^{kom} and G^{hom} as a function of k^G, g^G, k^{PT}, g^{PT}, f^G, f^{PT} and ϕ. Their computation requires the numerical resolution of a sixth-order polynomial equation, which can be achieved making use of a formal software, such as the MAPLE software.

The results obtained from the homogenization theories are compared in this section with the experimental results performed on pervious concrete.

As the elastic properties of the basalt aggregated and the cement paste were not known, usual boundary values of these properties were employed (Vallejo [40], Mehta and Monteiro [41], Silveira [42]). Table 2 shows the used values.

Table 2. Basalt aggregate and cement paste elastic properties utilized in the pervious concrete elastic properties estimation

Constituents properties	E (MPa)	ν
Superior Aggregate Elastic Properties (SAEP)	75000	0.38
Inferior Aggregate Elastic Properties (IAEP)	20000	0.19
Superior Paste Elastic Properties (SPEP)	25000	0.25
Inferior Paste Elastic Properties (IPEP)	10000	0.18

To compute the components (aggregate and paste) volume fraction, the specific gravity of cement grains and the basalt rock, respectively, 3.15 (Mehta and Monteiro [41]) and 3.0 (Silveira [42]), were used. Moreover, an important issue to be addressed is the evaluation of the volume of hydrated cement from the knowledge of anhydrous cement content in the mixture.

The simplest way (Maghous et al. [43]) to address the above issue is the Powers hydration model (Powers and Brownyard [44]), which proves to be still relevant and remains widely used because of the easiness of its implementation. It provides the volume fraction of hydration products, including the volume fraction of hydrates that is of interest herein. The required information is the volume of hydrates ϑ_h created when a unit volume of anhydrous cement is hydrated. Denoting by φ^h the volume fraction of hydrates formed at a given degree of hydration ξ, we have $\varphi^h = \vartheta_h\, \xi\, \varphi_0^a$ where φ_0^a is the volume fraction of anhydrous cement initially mixed with coarse aggregate, that is at before the hydration reaction starts ($\xi = 0$). This quantity is computed from the knowledge of the cement mass content.

In the case of pervious concrete, there is enough water than needed for complete hydration, and the reaction stops when all available anhydrous is consumed, i.e. when $\xi = 1$. This means that the volume fraction of hydrated cement after the process of curing is $\varphi^h = \vartheta_h\, \varphi_0^a$. In the context of Powers model, we adopt $\vartheta_h = 2.13$.

Figure 8 shows the experimental data and the micromechanical estimates obtained with the Self-consistent scheme.

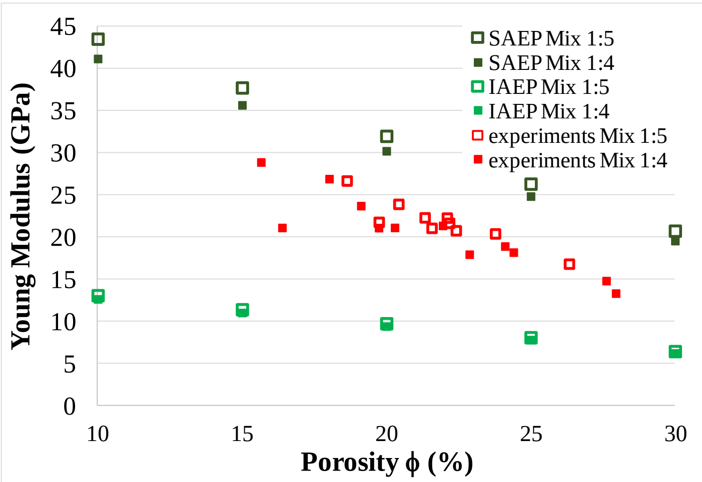

Figure 8. Experimental data and Self-consistent scheme estimations.

As observed in the experimental approach, typical values of pervious concrete porosity have great influence on the elastic properties of this material. Despite the high variability experimentally obtained for the elastic modulus (Fig. 2 and Fig. 3), it was found that the increase of the pervious concrete porosity causes a considerable reduction in this property. The results obtained by the micromechanical approach employing homogenization scheme based on Eshelby results, were able to capture this behavior and are in agreement with the results of literature studies.

Besides the porosity influence, Figures 8 also carry an indication of the influence of the elastic properties and volume fraction of the constituents (aggregate and paste) on the elastic properties of the pervious concrete.

A good agreement is obtained and consistency with the experimental data can be considered reasonable. For a better assessment of the proposed model potential, it is necessary the knowledge of all influential parameters, which were not available. Experimental data of pervious concrete elastic modulus and Poisson coefficient concrete along with the paste and aggregate elastic properties as well as the aggregate shape could allow better evaluations.

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Appendix

The Eshelby tensor $\underset{\sim}{S}$ for sphere inclusion is listed below:

$$\begin{gathered} S_{1111} = S_{2222} = S_{3333} = \frac{7-5\nu^0}{15(1-\nu^0)} \\ S_{1122} = S_{2233} = S_{3311} = S_{2211} = S_{3322} = S_{1133} = \frac{5\nu^0 - 1}{15(1-\nu^0)}. \\ S_{1212} = S_{1313} = S_{2323} = \frac{4-5\nu^0}{15(1-\nu^0)} \end{gathered} \tag{A.1}$$

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