*sustainability*

MDPI

*Article*

# Using Natural Pozzolans to Partially Replace Cement in Pervious Concretes: A Sustainable Alternative?

**Ignacio Oviedo [1], Mauricio Pradena [1,*], Óscar Link [1] and José T. Balbo [2]**

[1] Departamento de Ingeniería Civil, Universidad de Concepción, Edmundo Larenas 219, Casilla 160-C Correo3, Concepción 4030000, Chile
[2] Escola Politécnica, Departamento de Engenharia de Transportes, Universidade de São Paulo, Cidade Universitária, São Paulo 05508-010, SP, Brazil
* Correspondence: mpradena@udec.cl

**Abstract:** Concrete is one of the most widely used construction materials all around the globe. Associated with urban expansion, concrete pavements increase the impermeable surfaces that affect the hydrological cycle and generate urban heat islands. Cement is one of the main components of concrete, and its production is one of the main sources of worldwide $CO_2$ emissions. Pervious concrete with partial cement replacement represents a more sustainable alternative. In this paper, the use of natural pozzolans zeolite and pumicite, as partial cement replacement materials in pervious concrete mixtures, is analyzed. The mechanical and hydraulic properties of pervious concretes using different percentages of pumicite and zeolite to replace cement (0% to 20%) were evaluated by a series of tests on compressive strength, flexural strength, permeability, porosity, and a microanalysis by SEM for the samples. Additionally, experiments with a plasticizer additive were conducted. The results show that mixtures with 0.35 W/C ratio present better mechanical and hydraulic properties; pumicite shows a better performance than zeolite, with the better properties achieved at 10% cement replacement; and the addition of plasticizer increased the final strengths. It is recommended to partially replace cement by adding 10% pumicite and to consider using 0.7% of plasticizer.

**Keywords:** compressive strength; flexural strength; natural pozzolans; permeability; pervious concretes; plasticizer; porosity; pumicite; zeolite

check for updates

**Citation:** Oviedo, I.; Pradena, M.; Link, Ó.; Balbo, J.T. Using Natural Pozzolans to Partially Replace Cement in Pervious Concretes: A Sustainable Alternative? *Sustainability* **2022**, *14*, 14122. https://doi.org/10.3390/su142114122

Academic Editor: Rajesh Kumar Jyothi

Received: 4 October 2022
Accepted: 17 October 2022
Published: 29 October 2022



## 1. Introduction

Currently, concrete is one of the most widely used construction materials all around the globe due to its affordable price, mechanical properties, and durability [1–3]. Associated with urban expansion, the use of concrete increases impermeable surfaces that affect the hydrological cycle, especially by increasing surface runoff, and generates urban heat islands in the surrounding environment [4–6].

Pervious concretes have been used instead of standard concretes to reduce the negative effects of urbanization on hydrology and the thermal behavior of cities [7]. They consist of concrete with the absence of or little presence of fine aggregates that generates an interconnected network of pores, allowing rainwater to infiltrate its structure and eventually reach the ground [8–10]. In addition to the classical mechanical properties evaluated for the characterization of standard concretes, hydraulic properties, such as infiltration capacity and porosity are also evaluated in pervious concretes and are considered in its design methods [11–14]. Due to the inverse relationship between mechanical and hydraulic properties, one open question is: how can the strength of the concrete be maximized without significantly reducing its infiltration capacity? [15,16].

At the same time, one of the main components of concrete is cement, with an increasing worldwide demand [17,18]. Unfortunately, the cement industry emits greenhouse gases into the atmosphere and consumes large amounts of energy, reaching between 8% and 9%

of the global anthropogenic $CO_2$ emissions [19]. Therefore, there is a need to find materials that can replace cement to reduce environmental impacts.

Throughout the history of concrete, the addition of minerals has been used for different purposes, mainly related to economy, ecology, and technology. In particular, natural pozzolans represent a favorable alternative to partially replace cement in concretes [20]. Natural pozzolans, such as zeolite and pumicite, do not have binding properties by themselves but when combined with lime and milled at room temperature in the presence of water, they react with calcium hydroxide, forming insoluble and stable compounds with binding properties [21]. Particularly, zeolite is part of a group of microporous aluminosilicate minerals, with some 50 natural and 150 synthetic types of zeolites currently known [22], while pumicite is a mineral of volcanic origin that is created after the magma solidifies and the silicon dioxide and aluminum trioxide in its chemical composition prevail.

There are several investigations showing that it is possible to replace some of the cement with zeolite [1,20–24] or pumicite [25,26] to achieve similar concrete mechanical properties in standard concretes and there are fewer studies on pervious concrete mixes with zeolite [27–29] or pumicite [30] that replace up to 40% of the cement in both types of concretes.

There are investigations with other supplementary cementitious materials; the most used correspond to blast furnace slag, fly ash, and natural pozzolans [31]. There are other materials also used to replace cement, such as biomass ash, steel slag, limestone, waste glass, and others, where the properties, performance, and methods of obtaining them are different from each other [31–34]. The focus on natural pozzolans, such as zeolite and pumicite, is mainly due to the fact that they do not come from the residues of industrial processes; they are present in nature and are locally abundant in Chile.

The use of plasticizing additives as water reducers has been implemented in concrete in order to obtain higher strengths; however, their behavior is influenced by the type of cement, the type of additive, the dose used, and the type of supplementary cementitious materials utilized [35–40]. In addition, in pervious concretes it is necessary to take care that the hydraulic properties are not greatly affected by the use of high doses of additives [41].

It is important to evaluate the behavior of these minerals in pervious concretes since there are fewer investigations on it. The mixture, both in design and behavior, is different from standard concretes and the mechanical and hydraulic properties of the resulting concretes are dependent on the chemical composition of both the pozzolana and the cement, with the main objective being to obtain pervious concretes with similar properties to those of a reference sample while using less cement.

The aim of this paper was to explore the use of zeolite and pumicite to partially replace cement in pervious concrete for its use in urbanization, contributing to a more sustainable worldwide urban expansion. Section 2 presents the materials and methods, describing the concrete components, experimentation, and experimental series. Section 3 presents the results of the water–cement ratio, the effects of pumicite and zeolite on pervious concrete properties, and the effects of a plasticizer additive.

## 2. Materials and Methods

### *2.1. Materials*

#### 2.1.1. Water

The water used was from the public water supply that complied with NCh 1498:2012 and was not contaminated prior to use [42].

#### 2.1.2. Cement

Cement typically used by the construction industry in Chile was considered in this research. According to the standard NCh 148, based on ASTM C150/C150M-20, this cement is classified as standard-grade pozzolanic cement [43]. The properties of the cement are indicated in Table 1.

**Table 1.** Cement characteristics.

| Properties | | Cement | Requirements NCh 148 |
|---|---|---|---|
| Specific gravity (g/cm$^3$) | | 2.8 | - |
| Autoclave expansion (%) | | 0.1 | <1.0 |
| Initial setting (h:m) | | 02:40 | >1.00 |
| Final setting (h:m) | | 03:40 | <12:00 |
| Compressive strength (kg/cm$^2$) | 7 days | 320 | >180 |
| | 28 days | 410 | >250 |

### 2.1.3. Water–Cement Ratio

The water-to-cementitious-materials ratios used in this investigation are 0.35 and 0.39, according to the typical range of values used in pervious concretes [11]. Higher values are not recommended because if the W/C ratio of the mixture is higher, mechanical properties could be lower and the cement paste could settle to the bottom of the molds or the field, compromising permeability by generating an impermeable layer [44,45].

### 2.1.4. Fine Aggregate

Sand consists of a stone material composed of hard particles with a stable shape and size that pass through the 4.75 mm aperture sieve and it is retained on the 0.075 mm sieve [46]. In this research, Bío Bío sand was utilized because it is the typical fine aggregate for making concrete in the local market. The sand properties according to the standards NCh 1239:2009 [47], based on ASTM C128-07a, and the granulometric distribution of this sand according to NCh 165:2009 [48], based on ASTM C136:2006, are indicated in Table 2 and Figure 1, respectively.

**Table 2.** Properties of fine aggregate and coarse aggregate.

| Physical Properties | Fine Aggregate | Coarse Aggregate |
|---|---|---|
| Relative Density (kg/m$^3$) | 2682 | 2643 |
| Relative Density SSD (kg/m$^3$) | 2729 | 2683 |
| Apparent Relative Density (kg/m$^3$) | 2814 | 2752 |
| Compacted Bulk Density (kg/m$^3$) | 1635 | 1500 |
| Water Absorption (%) | 1.75 | 1.49 |
| Materials finer than #200 sieve (%) | 0.59 | 0.05 |
| Fineness Modulus | 2.53 | 8.89 |

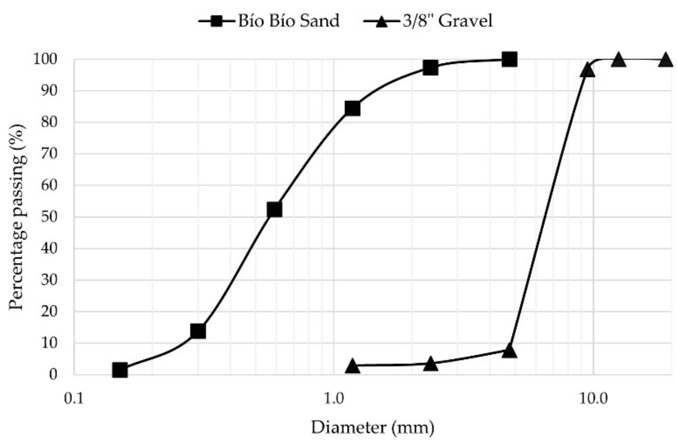



**Figure 1.** Granulometric distribution of fine aggregate and coarse aggregate.

### 2.1.5. Coarse Aggregate

Gravel consists of a stone material composed of hard particles with a stable shape and size that is retained on the 4.75 mm aperture sieve with established tolerances [46]. The coarse aggregate used in this research corresponds to 3/8″ gravel obtained in the local market near Concepción, Chile and it was extracted from the bank of the Ñuble river. The gravel properties according to the standards NCh 1117:2010 [49], based on ASTM C127-07, and the granulometric distribution of this gravel according to NCh 165:2009 [48], based on ASTM C136:2006, are indicated in Table 2 and Figure 1, respectively.

#### 2.1.6. Zeolite

The zeolite used in this research corresponds to the clinoptilolite-mordenite type, obtained in local deposits of the Maule region, Chile. It complies with the ASTM C618-19 standard as a class N natural pozzolan [50].

#### 2.1.7. Pumicite

The pumicite used was obtained from a deposit in the metropolitan region of Santiago de Chile and, like the zeolite, it complies with the ASTM C618-19 standard as a class N natural pozzolan [50].

#### 2.1.8. Additive

The additive used is classified as type D according to the NCh 2128:1995 standard [51], based on ASTM C494. It is a setting-retarding plasticizer additive and was used here as a water reducer.

### *2.2. Variables to Characterize Pervious Concrete*

#### 2.2.1. Compressive Strength

The compressive strength was evaluated according to the NCh 1037 standard [52], based on the ASTM C-39:2005, using cylindrical molds with a diameter of 15 cm and a height of 30 cm. It was evaluated at 7, 14 and 28 days to register the evolution of concrete strength over time, according to [9,21,24–29]. The results consist of the simple average of 5 repetitions of tested specimens.

#### 2.2.2. Flexural Strength

The flexural strength was evaluated according to the NCh 1038 standard [53], based on the ASTM C-78:2018, using 55 cm × 15 cm × 15 cm prismatic molds. Five repetitions of each experiment were tested. The flexural strength was measured after 28 days for all experiments according to [5,15]. Additionally, it was measured at 7 days in the reference pervious concretes, i.e., without pumicite or zeolite, and in the concretes with additive.

#### 2.2.3. Permeability

For the permeability measurement, a falling head permeameter specified by the ACI 522R-10 committee [11] was used. To carry out this test, a single specimen was considered and it was repeated three times with said specimen to determine the time it takes for the water to descend between known heights. Equation (1) indicates how to calculate the permeability coefficient according to this method.

$$k\left(\frac{cm}{s}\right) = \frac{a \times L}{A \times t} \times \ln\left(\frac{h_1}{h_2}\right) \tag{1}$$

where "a" is the cross-sectional area of the standpipe in $cm^2$, "L" is the length of the sample in cm, "A" is the cross-sectional area of the sample in $cm^2$, "t" is the recorded time from $h_1$ to $h_2$ in s, "$h_1$" is the initial water level equal to 40 cm, and "$h_2$" is the final water level equal to 20 cm.

2.2.4. Porosity

The porosity test was carried out according to the ASTM C1754:2012 standard [54] and Equation (2) indicates how to calculate the percentage of voids in the selected specimen. For this test, the simple average between 3 samples was considered.

$$\text{Porosity }(\%) = \left[1 - \left(\frac{M_d - M_s}{\rho_w \times V}\right)\right] \times 100 \quad (2)$$

where "$M_d$" is the dry mass of the specimen in kg, "$M_s$" is the submerged mass of the specimen in kg, "$\rho_w$" is the density of water in kg/m$^3$, and "V" is the volume of the specimen in m$^3$.

2.2.5. Microanalysis

In addition to the macro-characterization of the samples, such as their mechanical properties in a hardened state, a micro-level analysis of the behavior of natural pozzolans was carried out, by means of SEM (scanning electron microscopy) image analysis, comparing a reference sample (without minerals) with samples with zeolite or pumicite replacing 20% of cement. The aim of this approach was to achieve a deeper understanding of the macro-level behavior of the pervious concrete samples with and without zeolite or pumicite.

*2.3. Experimental Series*

Series 1 aimed at determining the best pervious concrete reference sample and consisted of two experiments with water–cement ratios of 0.35 and 0.39 with 15% and 20% of fine or coarse aggregate, respectively.

Series 2 aimed at evaluating the effect of pumicite and zeolite content on the pervious concrete properties. Two experiments with 10% and 20% of pumicite and two experiments with 10% and 20% of zeolite, each partially replacing cement, were conducted.

Series 3 aimed at evaluating the effects of an additive on the pervious concrete mixtures without and with pumicite. It consisted of two experiments with 0.7% of the plasticizer additive added as a percentage of the cement weight.

Table 3 shows the experimental series. "W/C" is the water–cementitious-material ratio, "FA/CA" is the percentage of fine aggregate with respect to coarse aggregate, "Z" is the percentage of zeolite to replace cement, "P" is the percentage of pumicite to replace cement, and "A" is the dose of additive to be used. "P1" corresponds to compressive strength, "P2" to flexural strength, "P3" to permeability, and "P4" to porosity. Table 3 indicates the evaluation ages (days) of each property for each experiment.

**Table 3.** Experimental series.

| Series | Experiment | W/C | FA/CA | Z | P | A [1] | P1 | P2 | P3 | P4 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.39 | 15% | 0 | 0 | 0 | 7-14-28 | 7-28 | 28 | 28 |
| | 2 | 0.35 | 20% | 0 | 0 | 0 | 7-14-28 | 7-28 | 28 | 28 |
| 2 | 1 | 0.35 | 20% | 10% | 0 | 0 | 7-14-28 | 28 | 28 | 28 |
| | 2 | 0.35 | 20% | 20% | 0 | 0 | 7-14-28 | 28 | 28 | 28 |
| | 3 | 0.35 | 20% | 0 | 10% | 0 | 7-14-28 | 28 | 28 | 28 |
| | 4 | 0.35 | 20% | 0 | 20% | 0 | 7-14-28 | 28 | 28 | 28 |
| 3 | 1 | 0.35 | 20% | 0 | 0 | 0.7% | 7-14-28 | 7-28 | 28 | 28 |
| | 2 | 0.35 | 20% | 0 | 10% | 0.7% | 7-14-28 | 7-28 | 28 | 28 |

[1] Plasticizer is indicated as a percentage of cement weight.

*2.4. Experimentation*

2.4.1. Pervious Concrete Mix Dosage

The method proposed by Nguyen [12] for the mix's dosage of pervious concrete was used because it presents a more detailed theoretical or mathematical basis than the

ACI 522R-10 [11], ICPA [13] (Argentinean Portland Cement Institute), and NRMCA [14] (National Ready Mixed Concrete Association) methods. The target porosity was set to 15% and the W/C ratio was set between 0.35 and 0.39. The amount of fine aggregate between coarse aggregate was considered in the range of 15% and 20% according to [55].

The amount of coarse aggregate was considered between 1325 kg/m$^3$ and 1365 kg/m$^3$ due to an indication of the ICPA method [13] for the specific size of the coarse aggregate used in this research and to keep the amount of fine aggregate within the desired ranges.

The design dosages for each mixture are presented in Table 4, in the order of the series and the experiments: the selection of the control or reference sample, the partial replacements of the cement by natural pozzolans, and the combination process with additive.

The nomenclature used in Series 1 correspond to "PC-XX-YY", where "PC" is pervious concrete, "XX" is the W/C ratio of the mixture, and "YY" is the percentage of fine/or coarse aggregate. The nomenclature used in Series 2 correspond to "PC-II-JJ", where "PC" is pervious concrete, "II" indicates if the replacement corresponds to zeolite or pumicite, and "JJ" is the percentage of cement replacement. In Series 3, "PL" indicates the use of the plasticizer additive.

**Table 4.** Mix dosages for experimental plan in kg/m$^3$.

| Series | Exp. | Mixture ID | Gravel | Sand | Cement | Water | Zeolite | Pumicite | Additive [1] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | PC-0.39-15 | 1345.7 | 201.9 | 345.3 | 134.7 | - | - | - |
| | 2 | PC-0.35-20 | 1325.5 | 265.2 | 341.8 | 119.6 | - | - | - |
| 2 | 1 | PC-Z-10 | 1325.5 | 265.2 | 310.7 | 119.6 | 31.1 | - | - |
| | 2 | PC-Z-20 | 1325.5 | 265.2 | 284.8 | 119.6 | 57.0 | - | - |
| | 3 | PC-P-10 | 1325.5 | 265.2 | 310.7 | 119.6 | - | 31.1 | - |
| | 4 | PC-P-20 | 1325.5 | 265.2 | 284.8 | 119.6 | - | 57.0 | - |
| 3 | 1 | PC-0.35-20-PL | 1325.5 | 265.2 | 341.8 | 101.7 | - | - | 0.7 |
| | 2 | PC-P-10-PL | 1325.5 | 265.2 | 310.7 | 101.7 | - | 31.1 | 0.7 |

[1] Plasticizer is indicated as a percentage of cement weight.

2.4.2. Preparation, Compaction, and Curing

The preparation and curing of specimens proceeded according to the NCh 1017 standard [56], based on ASTM C-31:2009. The demolding of the cylindrical specimens was carried out after 24 h and after 48 h for the prismatic specimens according to the same regulation. In the case of the mixtures in which the additive was used, they were granted an additional 24 h for demolding.

Compaction proceeded according to the NCh 1017 standard [56], based on ASTM C-31:2009. For the cylindrical molds, this consisted of three layers of equal volume, twenty-five blows distributed with a rod, and five lateral blows to the mold for each layer of concrete. For the prismatic molds, it consisted of two layers of equal volume with eight blows for every 100 cm$^2$ of surface, and five blows at the ends of the mold, for each layer.

After demolding, the specimens were placed in a curing chamber with humidity above 95% and a temperature of 23 °C. The specimens were kept in the chamber until their corresponding test age.

## 3. Results

### *3.1. Best Reference Sample*

The results of the mechanical and hydraulic properties for the reference samples without additive are presented in Figure 2. The error bars correspond to the standard deviation of the repetitions tested for each test age of the samples.

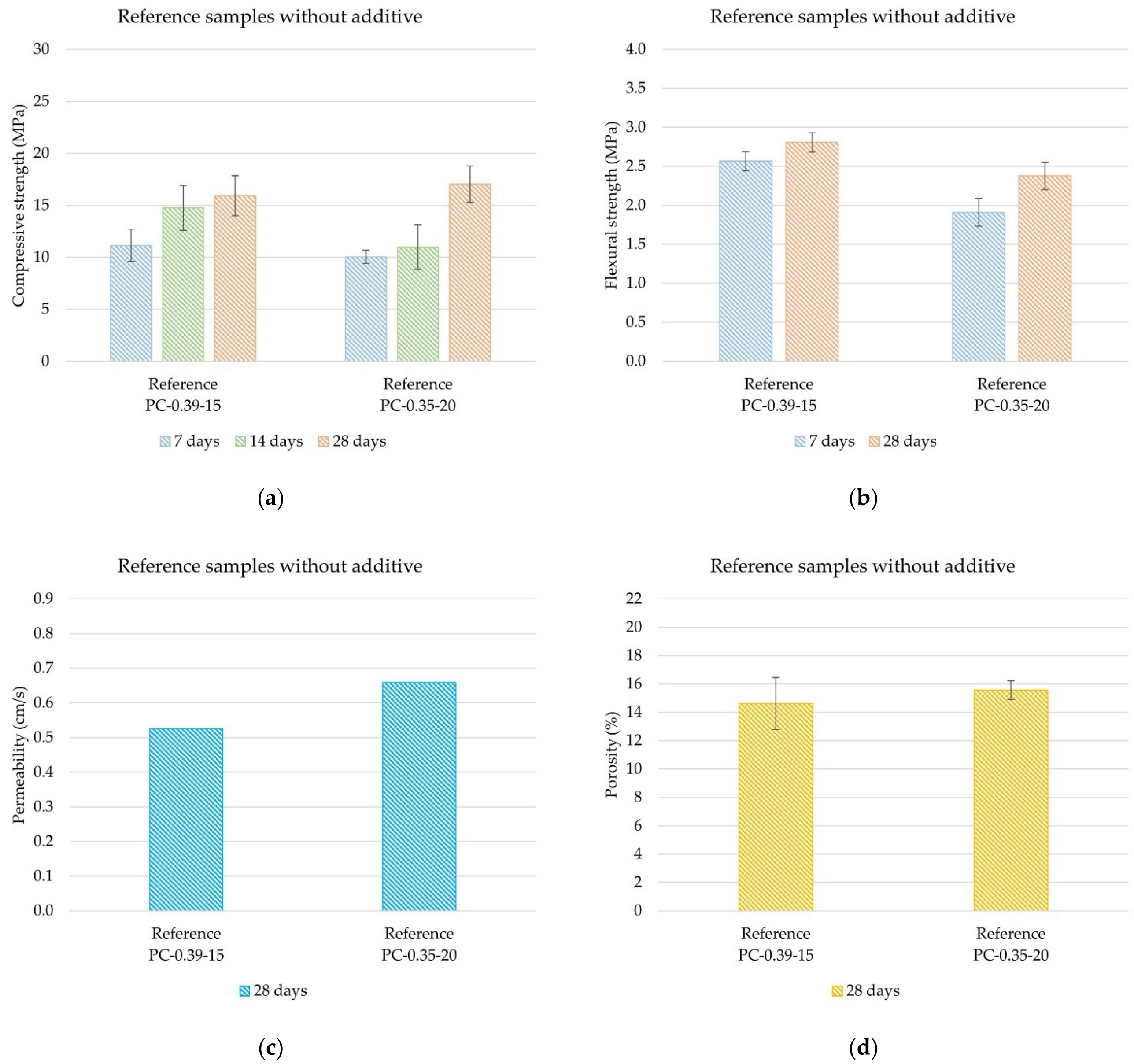



**Figure 2.** Mechanical and hydraulic properties of pervious concrete reference samples without additive: (**a**) compressive strength at 7, 14 and 28 days; (**b**) flexural strength at 7 and 28 days; (**c**) permeability at 28 days; (**d**) porosity at 28 days.

In compressive strength (Figure 2a), although the strengths at 7 and 14 days are higher in the PC-0.39-15 sample, the compressive strength of the PC-0.35-20 sample at 28 days is 7% higher. However, the results are within the standard deviation range. The flexural strength of the PC-0.39-15 sample is greater than the PC-0.35-20 sample at 7 and 28 days, at 35% and 18%, respectively (Figure 2b). However, at 28 days, the results are comparable between them and are within the standard deviation. It was observed that the permeability of all reference samples is in the range established by the ACI 522R-10 (Figure 2c), which corresponds to 0.135 cm/s [9], allowing their use for paving purposes. On the other hand, the porosities obtained are between 14% and 16% (Figure 2d), while the design porosity is 15%. There is an inherent variation due to the compaction of each specimen for permeability analysis, while for porosity analysis, the test provides the total porosity (interconnected pores and cavities that do not contribute to permeability). There is a direct relationship between porosity and permeability, and the PC-0.35-20 reference sample is 27% more permeable than the PC-0.39-15 sample. This may be because for sample

PC-0.39-15, having a higher W/C ratio, excess cement paste may contribute to the clogging of the interconnected pores as concrete strength develops.

Considering the previous results, acceptable results in compressive and flexural strength and mainly given that its permeability is higher, it was determined that sample PC-0.35-20 is suitable to be used as the reference sample for Series 2.

### 3.2. Effects of Pumicite and Zeolite on Pervious Concrete Properties

The results of the mechanical and hydraulic properties of the samples with zeolite in comparison with the reference sample are presented in Figure 3.

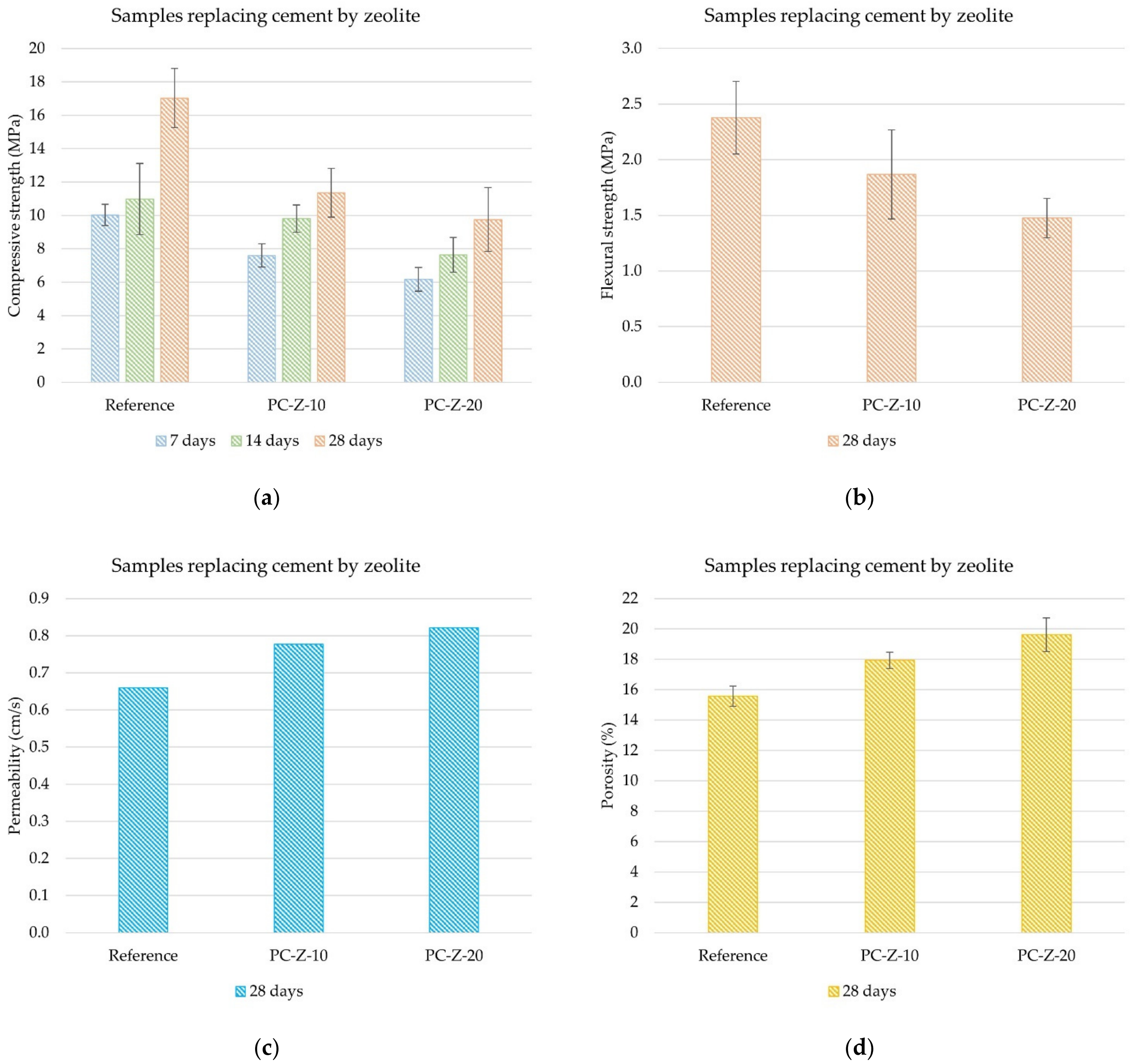



**Figure 3.** Mechanical and hydraulic properties of pervious concrete samples replacing cement with zeolite: (**a**) compressive strength at 7, 14, and 28 days; (**b**) flexural strength at 28 days; (**c**) permeability at 28 days; (**d**) porosity at 28 days.

With respect to the reference sample, the compressive strength of the PC-Z-10 sample (Figure 3a) decreased by 22%, 11%, and 33% at 7, 14, and 28 days, respectively. In the case of the PC-Z-20 sample, the differences are greater; the compressive strength decreased by 38%, 30%, and 43% at 7, 14, and 28 days, respectively. The flexural strength of the PC-Z-10 sample at 28 days (Figure 3b) decreased by 21%, with respect to the reference sample, while for the PC-Z-20 sample, it decreased by 38%. It was observed that the permeability of all the samples (Figure 3c) is in the range established by the ACI 522R-10 [9], allowing their use for paving purposes. On the other hand, the porosities obtained are between 14% and 20% (Figure 3d), while the design porosity is 15%. It was observed that when replacing cement with zeolite, the porosity increased, which caused the permeability to increase in the same way.

There are investigations in which the use of zeolite increases the mechanical properties up to 10% replacement [22–24]; however, in these investigations, pure Portland cement and other types of zeolite are used and they are focused on standard concretes, not on pervious concretes. There are other cases in which the incorporation of zeolite decreases or maintains the stability of the mechanical properties [1,20,21,28–30], similar to the results obtained in this research.

The results of the mechanical and hydraulic properties of the samples with pumicite in comparison with the reference sample are presented in Figure 4.

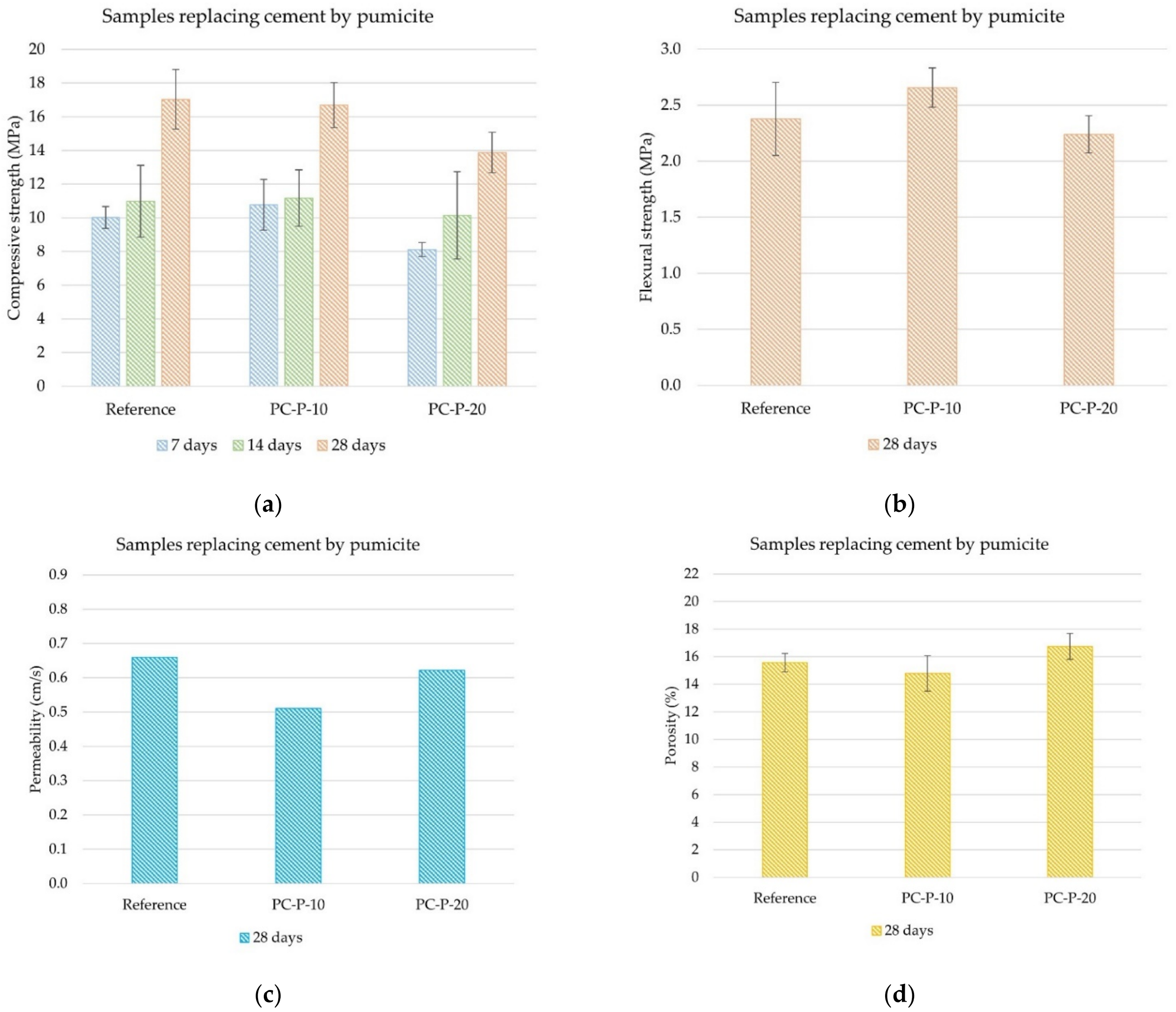



**Figure 4.** Mechanical and hydraulic properties of pervious concrete samples replacing cement with pumicite: (**a**) compressive strength at 7, 14, and 28 days; (**b**) flexural strength at 28 days; (**c**) permeability at 28 days; (**d**) porosity at 28 days.

With respect to the reference sample, the compressive strength of the PC-P-10 sample (Figure 4a) increased at 7 and 14 days by 7% and 2%, respectively, while at 28 days it decreased by 2%. In the case of the PC-P-20 sample, the compressive strength decreased by 19%, 8%, and 21% at 7, 14, and 28 days, respectively. It was observed that the samples with pumicite present results comparable to the reference sample since they are in the established range of the standard deviation. The flexural strength of the PC-P-10 sample at 28 days (Figure 4b) increased by 12%, with respect to the reference sample, while for the PC-P-20 sample, it decreased by 6%. It was observed that the results with pumicite are comparable to the reference sample, and even when replacing 10% of the cement, higher strengths were obtained. It was observed that the permeability of all the samples (Figure 4c) is in the range established by the ACI 522R-10 [9], allowing their use for paving purposes. On the other hand, the porosities obtained are between 14% and 18% (Figure 4d), while the design porosity is 15%.

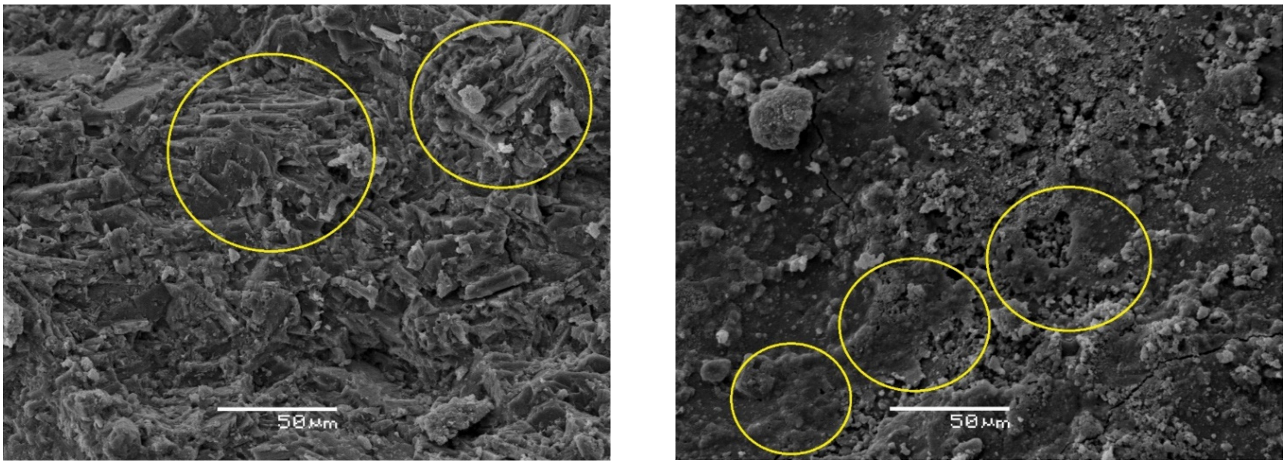
There are investigations in which the use of pumicite decreases the mechanical properties up to 20% replacement [25,26]; however, in these investigations, pure Portland cement is used and they are focused on standard concrete, lightweight concrete, or mortar and not on pervious concrete. There are few investigations in porous concrete where the incorporation of pumicite increases the mechanical properties of the concrete up to 10% replacement [30], similar to the results obtained in this research.

It was observed that when replacing cement with zeolite, the porosity increased, which caused the permeability to increase in the same way. In the case of pumicite, when replacing 10% of the cement, the permeability and porosity decreased, and when replacing 20% of the cement, the results are similar to the reference sample.

Considering the previous results, the pozzolanic mineral that obtained the best performance was pumicite, which is possible to obtain strengths similar to the reference sample with up to 20% replacement; however, the best percentage of cement replacement with pumicite is 10%, which even increased the strength without significantly affecting the permeability.

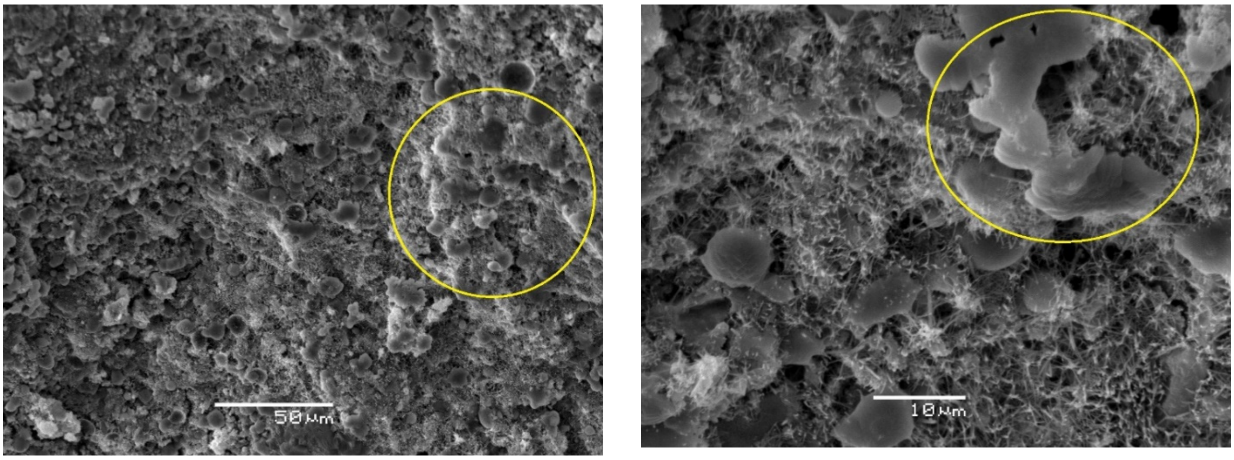
### *3.3. SEM Microscopy Analysis*

Figure 5 shows the microstructure of the reference sample, while the microstructure of samples with zeolite or pumicite (replacing cement by 20%) are shown in Figures 6 and 7, respectively. The samples were analyzed at around 70 days to ensure that the pozzolanic reaction with the cement stabilized and to be able to make comparisons between them.



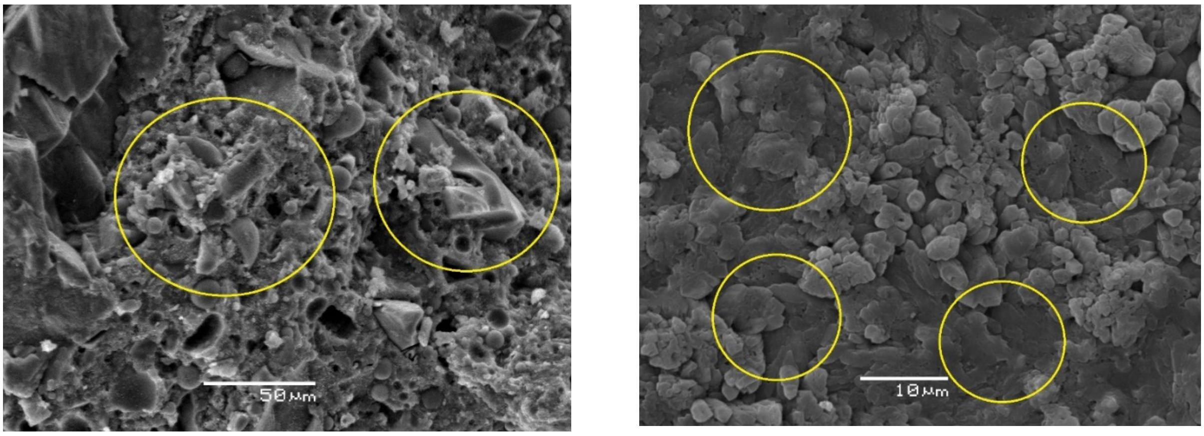

(**a**) (**b**)

**Figure 5.** SEM images of the microstructure of the reference sample: (**a**) view of the C-H crystals in cement matrix; (**b**) C-S-H gel in cement matrix.




(**a**) (**b**)

**Figure 6.** SEM images of the microstructure of the samples with 20% zeolite replacing cement: (**a**) view of the cement matrix and C-H surfaces; (**b**) view of C-H surfaces and ettringite crystals.




(**a**) (**b**)

**Figure 7.** SEM images of the microstructure of the samples with 20% pumicite replacing cement: (**a**) view of the cement matrix and C-H crystals; (**b**) C-S-H gel in cement matrix.

The main components that could be identified in the images are:

- Calcium silicate hydrate (or C-S-H gel): the main product of the hydration of Portland cement.
- Calcium hydroxide: C-H crystals are large prismatic crystals of calcium hydroxide and C-H surfaces.
- Ettringite: a result of the reaction of calcium aluminate ($C_3A$) with calcium sulfate.

It was noticed that the reference sample presents a high amount of C-H hexagonal crystals (Figure 5a) and the C-S-H gel matrix is denser than the sample with zeolite. Moreover, it presents large C-H surfaces (Figure 5b). The sample with zeolite shows a reduction in the amount of C-H hexagonal crystals, unlike the reference sample, and it presents some small C-H surfaces (Figure 6a). Additionally, it is observed that (Figure 6b) there is a high presence of ettringite crystals. The sample with pumicite shows a strong presence of C-H hexagonal crystals (Figure 7a) and a denser microporous matrix with large surfaces of C-S-H gel (Figure 7b). Finally, a replace of cement with this type of zeolite led to a reduction in the amount of C-H crystals and it reduces the size of C-H surfaces, as is concordant with the results of other authors [57].

It is important to note that, since the sample with zeolite has a large number of short ettringite crystals, has fewer calcium hydroxide crystals, and the cement matrix is more porous, it is possible that the samples tend to crack early; therefore, lower mechanical strengths and higher hydraulic properties were obtained [58].

In the case of pumicite, it is noted that the presence of the C-S-H gel in the cement matrix is denser than the reference sample, and this could be the reason that the higher mechanical properties and lower hydraulic properties were obtained, since the C-S-H gel is the main hydration product of the cement and its main source of strength [59].

### 3.4. Effects of Additive on Pervious Concrete Properties

The mechanical and hydraulic properties of the combination sample with 10% pumicite and additive in comparison with their respective reference samples are presented in Figure 8.

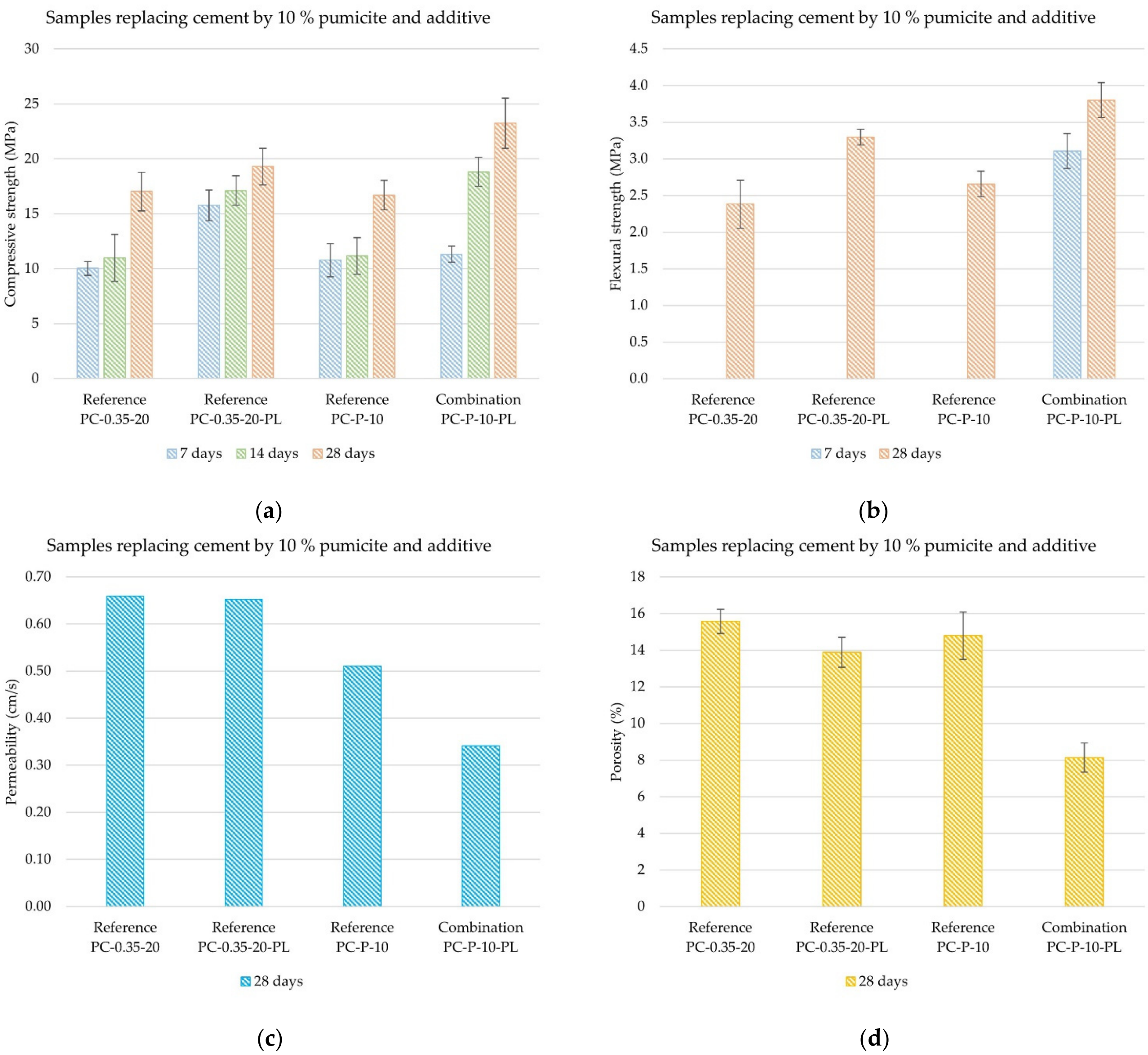



**Figure 8.** Mechanical and hydraulic properties of pervious concrete combination sample replacing cement with 10% pumicite and additive in comparison with their respective reference samples: (**a**) compressive strength at 7, 14, and 28 days; (**b**) flexural strength at 7 and 28 days; (**c**) permeability at 28 days; (**d**) porosity at 28 days.

For the sample PC-0.35-20, the incorporation of plasticizer increased the average strength at 7, 14, and 28 days by 57%, 56%, and 13%, respectively, with respect to the sample without additive. This increase in resistance is due to the innate effect of the additive, which repels the cement grains, so, being used as a water reducer, it allows for a decrease in the W/C ratio of the mixture for the same workability. At 7 days, the compressive strength of the combination sample (PC-P-10-PL) increased by 12% and 5%, with respect to the reference samples PC-0.35-20 and PC-P-10, respectively (Figure 8a); however, at this age, the compressive strength of the reference sample with additive (PC-0.35-20-PL) is higher by 39%. At 14 days, while the difference in compressive strength between the reference samples without additive increased, the results are greater, with respect to the reference sample with additive. Specifically, the compressive strength of the combination sample increased by 71%, 10%, and 68%, with respect to the reference samples PC-0.35-20, PC-0.35-20-PL, and PC-P-10, respectively. At 28 days, the results of the combination sample were notably higher than all reference samples. Specifically, the compressive strength increased by 36%, 20%, and 39%, with respect to the reference samples PC-0.35-20, PC-0.35-20-PL, and PC-P-10, respectively, which validates the simultaneous use of pumicite with additive.

The flexural strength of the combination sample (Figure 8b) at 7 days exceeded the strength of the reference samples at 28 days, except in the case of the sample PC-0.35-20-PL. At 28 days, the flexural strength of the combination sample increased by 59%, 15%, and 43% in comparison with reference samples PC-0.35-20, PC-0.35-20-PL, and PC-P-10, respectively. The simultaneous incorporation of additive with pumicite considerably improved the flexural strength, with better results obtained compared to all reference samples.

It was observed that the permeability of all samples (Figure 8c) is in the range established by the ACI 522R-10 [9], allowing their use for paving purposes; however, the permeability of the combination sample decreased by 91%, 90%, and 49% compared to the reference samples PC-0.35-20, PC-0.35-20-PL, and PC-P-10, respectively.

On the other hand, the porosities obtained for the combination sample are between 7% and 9% (Figure 8d), while the design porosity is 15%, and it is lower than the reference samples. This is expected due to the high mechanical properties obtained and due to the decrease in porosity that is inherent to the use of pumicite that was investigated in the previous series.

## 4. Discussion

It is possible to reduce the amount of cement by partially replacing it with a mineral to obtain comparable or better results in terms of strength and adequate results in terms of permeability for pervious concrete mixtures.

The present study focused on the mechanical and hydraulic properties of pervious concretes with zeolite or pumicite as a partial cement replacement, specifically in terms of the evaluation of compressive strength, flexural strength, permeability, and porosity.

The results indicate that there is an optimal percentage of cement replacement by a pozzolanic mineral (10% pumicite) that can obtain comparable or better mechanical properties than traditional pervious concrete without significantly affecting its hydraulic properties.

Although other reports indicate that the incorporation of zeolite or pumicite could cause an increase in the strength of the concrete [23,24,26–28], this is not the case in this study when it comes to the zeolite. The explanation behind this phenomenon is related to the fact that the results obtained by other authors mostly correspond to traditional concrete mixtures [23–26,29], so the effect of using pozzolanic minerals in pervious concrete mixtures, added to the other variables, was part of this research and the effect of the different design methods and the balance between resistance and permeability must be considered.

Another important consideration is that concrete and minerals are geo-dependent, that is, their characteristics and properties depend on a series of environmental and geographical factors that influence the properties of the materials. For instance, there are different types of zeolites with different chemical and mineralogical compositions; therefore, some minerals could be more reactive with cement depending on their chemical structure. Another factor is the type of cement used. In Chile, the most common cement is the pozzolanic type, the same used in this research, so this effect must be considered in investigations where pure Portland cement is used.

Therefore, the results of this investigation are useful for cases where the zeolite, pumicite, and/or the cement utilized are similar to those used in this study.

The viability of using the mineral depends on technical and economic aspects. In the case of both minerals, their performance in concrete pavements and their economic viability should be evaluated, considering that both zeolite and pumicite are cheaper than cement [60].

The promising results obtained in this research can contribute to reducing up to 20% of the cement used in pervious concretes and replacing it with pozzolanic minerals, contributing to a reduction in the size of the carbon footprint generated by the cement industry and allowing the use of locally available minerals for use on permeable pavements.

This is important because, given the high strengths obtained, normally, between the range of 1.0 MPa to 3.8 MPa in flexural strength [61], the use of permeable pavements can be extended to bikeways, parking lots, pedestrian walkways, or places where the stresses above the pavement are not so high.

The present investigation focused on the evaluation of the main and fundamental properties of pervious concretes; however, considering the different benefits of replacing cement with pumicite, it is recommended to evaluate different characteristics, such as strength to abrasion or wear, indirect tensile strength, durability, and strength during freezing and thawing cycles, in future research.

Finally, although zeolite or pumicite can be incorporated in different percentages of cement replacement, it is important to highlight the significance of this research phase since it has been shown that there is an optimal percentage of replacement with one of the two alternative materials (10% pumicite) that does not significantly reduce the properties of the concrete and, on the contrary, improves them, being comparable to the properties of the reference concrete.

## 5. Conclusions

- Considering the incorporation of zeolite as a replacement for cement, it was found that, at any percentage of replacement, the compressive strength and flexural strength decrease. On the other hand, as the percentage of replacement increases, both the permeability and the porosity of the samples increase.
- Considering the incorporation of pumicite as a replacement for cement, the most important findings are those related to compressive and flexural strength. It was observed that with a 10% cement replacement with pumicite, greater compressive and flexural strength were obtained compared to the reference sample, while permeability decreases but not significantly. At 20%, the strengths decrease but are still comparable to the reference sample since they are within the standard deviation range, and the permeability is similar to the reference sample at this percentage.
- The incorporation of a plasticizer additive as a water reducer enables the improvement of the compressive and flexural strength, in all cases, without significantly affecting the permeability or porosity of the samples. However, it is necessary to consider that in the case of pervious concretes, the type of additive to be used and its dosage must be previously investigated in a laboratory to avoid the sedimentation of the cement paste mixture and prevent the generation of an impermeable layer at the bottom of the molds of the samples.
- The difference between the strengths obtained by replacing cement with zeolite or pumicite is explained by interpreting SEM images, which indicate that there are several differences with respect to the reference sample. The samples with zeolite present fewer C-H hexagonal crystals, the C-H surfaces are smaller, there is a greater presence of ettringite, and the C-S-H matrix is less dense than the reference sample. The samples with pumicite, on the other hand, show a dense microporous matrix similar to the

reference sample, the C-S-H matrix is denser than the reference sample, and a large number of C-H hexagonal crystals are present.

- The promising results obtained in flexural strength and permeability by replacing the cement with 10% pumicite and incorporating an additive make this technique ideal for use in permeable pavements since a fundamental requirement for its design is flexural strength.
- Finally, being able to replace either 10% or 20% of the cement with locally obtained pozzolanic minerals, from a sustainable point of view, contributes to a reduction in the size of the carbon footprint of the cement industry and promotes the use of supplementary cementitious materials in countries where their use has not yet become widespread.
- The work presented in this article attempted to contribute to a reduction in the use of cement in permeable pavement structures, seeking alternatives to traditional pavements that have less environmental impact, such as natural pozzolans (zeolite and pumicite).

**Author Contributions:** Conceptualization, M.P. and I.O.; methodology, M.P., Ó.L. and I.O.; formal analysis, I.O., M.P., Ó.L. and J.T.B.; investigation, I.O.; writing—review and editing I.O., M.P., Ó.L. and J.T.B.; supervision, M.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by ANID PCI 2019/13269-4.

**Acknowledgments:** The following organizations are acknowledged for their contribution to the work presented in this article: Institute for Applied Economic Geology GEA, University of Concepción, Chile and the Spectroscopy and Microscopy Center CESMI, University of Concepción, Chile.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Najimi, M.; Sobhani, J.; Ahmadi, B.; Shekarchi, M. An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan. *Constr. Build. Mater.* **2012**, *35*, 1023–1033. [CrossRef]
2. Divyah, N.; Prakash, R.; Srividhya, S.; Sivakumar, A. Parametric study on lightweight concrete-encased short columns under axial compression-Comparison of design codes. *Struct. Eng. Mech.* **2022**, *83*, 387–400. [CrossRef]
3. Prakash, R.; Divyah, N.; Srividhya, S.; Avudaiappan, S.; Amran, M.; Naidu Raman, S.; Guindos, P.; Vatin, N.I.; Fediuk, R. Effect of Steel Fiber on the Strength and Flexural Characteristics of Coconut Shell Concrete Partially Blended with Fly Ash. *Materials* **2022**, *15*, 4272. [CrossRef] [PubMed]
4. Andrés-Valeri, V.C.; Marchioni, M.; Sañudo-Fontaneda, L.A.; Giustozzi, F.; Becciu, G. Laboratory Assessment of the Infiltration Capacity Reduction in Clogged Porous Mixture Surfaces. *Sustainability* **2016**, *8*, 751. [CrossRef]
5. Yang, J.; Jiang, G. Experimental study on properties of pervious concrete pavement materials. *Cem. Concr. Res.* **2003**, *33*, 381–386. [CrossRef]
6. Takebayashi, H.; Moriyama, M. Study on surface heat budget of various pavements for urban heat island mitigation. *Adv. Mater. Sci. Eng.* **2012**, *2012*, 523051. [CrossRef]
7. Bonicelli, A.; Giustozzi, F.; Crispino, M. Experimental study on the effects of fine sand addition on differentially compacted pervious concrete. *Constr. Build. Mater.* **2015**, *91*, 102–110. [CrossRef]
8. Chandrappa, A.K.; Biligiri, K.P. Pervious concrete as a sustainable pavement material–Research findings and future prospects: A state-of-the-art review. *Constr. Build. Mater.* **2016**, *111*, 262–274. [CrossRef]
9. Nazeer, M.; Kapoor, K.; Singh, S.P. Pervious concrete: A state-of-the-art review. *J. Mater. Eng. Struct.* **2020**, *7*, 417–437.
10. Costa, F.B.P.D.; Lorenzi, A.; Haselbach, L.; Silva Filho, L.C.P.D. Best practices for pervious concrete mix design and laboratory tests. *Rev. IBRACON De Estrut. E Mater.* **2018**, *11*, 1151–1159. [CrossRef]
11. ACI Committe 522. *522R-10: Report on Pervious Concrete*; Technical Documents; American Concrete Institute: Farmington Hills, MI, USA, 2010.
12. Nguyen, D.H.; Sebaibi, N.; Boutouil, M.; Leleyter, L.; Baraud, F. A modified method for the design of pervious concrete mix. *Constr. Build. Mater.* **2014**, *73*, 271–282. [CrossRef]
13. Fernández, L.; Vitola, L.; Salminci, P. *Estado del arte en el uso de Hormigones Porosos, XII congreso de Vialidad y Tránsito*; Instituto del Cemento Portland Argentino: Buenos Aires, Argentina, 1998; pp. 761–784.
14. NRMCA. *Pervious Concrete: Guideline to Mixture Proportioning and Research Report*; National Ready Mixed Concrete Association: Silver Spring, MD, USA, 2009.
15. Sahdeo, S.K.; Ransinchung, G.D.; Rahul, K.L.; Debbarma, S. Effect of mix proportion on the structural and functional properties of pervious concrete paving mixtures. *Constr. Build. Mater.* **2020**, *255*, 119260. [CrossRef]

16. Huang, J.; Luo, Z.; Khan, M.B.E. Impact of aggregate type and size and mineral admixtures on the properties of pervious concrete: An experimental investigation. *Constr. Build. Mater.* **2020**, *265*, 120759. [CrossRef]
17. FICEM; ICH. *Hoja de Ruta de la Industria del Cemento en Chile: Hacia una Economía Baja en Carbono*; Federación Interamericana del Cemento; Instituto del Cemento y del Hormigón de Chile: Santiago, Chile, 2019.
18. Federación Interamericana del Cemento. *El Cemento, el Concreto y su Contribución en el Desarrollo de Ciudades Sostenibles y Resilientes*, 7th ed.; Cemento & Concreto de Iberoamérica y El Caribe: Bogotá, Colombia, 2020.
19. Monteiro, P.J.; Miller, S.A.; Horvath, A. Towards sustainable concrete. *Nat. Mater.* **2017**, *16*, 698–699. [CrossRef]
20. Raggiot, B.B.; Positieri, M.J.; Locati, F.; Murra, J.; Marfil, S. Zeolite, study of aptitude as a natural pozzolan applied to structural concrete. *Rev. Constr. J. Constr.* **2015**, *14*, 14–20. [CrossRef]
21. Raggiotti, B.B.; Positieri, M.J.; Oshiro, Á. Natural zeolite, a pozzolan for structural concrete. *Procedia Struct. Integr.* **2018**, *11*, 36–43. [CrossRef]
22. Ahmadi, B.; Shekarchi, M. Use of natural zeolite as a supplementary cementitious material. *Cem. Concr. Compos.* **2010**, *32*, 134–141. [CrossRef]
23. Tran, Y.T.; Lee, J.; Kumar, P.; Kim, K.H.; Lee, S.S. Natural zeolite and its application in concrete composite production. *Compos. Part B Eng.* **2019**, *165*, 354–364. [CrossRef]
24. Emam, E.; Yehia, S. Performance of concrete containing zeolite as a supplementary cementitious material. *Int. Res. J. Eng. Technol.* **2017**, *4*, 1619–1625.
25. Kabay, N.; Tufekci, M.M.; Kizilkanat, A.B.; Oktay, D. Properties of concrete with pumice powder and fly ash as cement replacement materials. *Constr. Build. Mater.* **2015**, *85*, 1–8. [CrossRef]
26. Hossain, K.M.A. Properties of volcanic pumice based cement and lightweight concrete. *Cem. Concr. Res.* **2004**, *34*, 283–291. [CrossRef]
27. Pachideh, G.; Gholhaki, M.; Moshtagh, A. Experimental study on mechanical strength of porous concrete pavement containing pozzolans. *Adv. Civ. Eng. Mater.* **2020**, *9*, 38–52. [CrossRef]
28. Pachideh, G.; Gholhaki, M.; Moshtagh, A. Performance of porous pavement containing different types of pozzolans. *Int. J. Eng.* **2019**, *32*, 1277–1283. [CrossRef]
29. Joshaghani, A. The Effects of Zeolite as Supplementary Cement Material on Pervious Concrete. In Proceedings of the 2016 International Concrete Sustainability Conference, Washington, DC, USA, 15–18 May 2016.
30. Azad, A.; Saeedian, A.; Mousavi, S.F.; Karami, H.; Farzin, S.; Singh, V.P. Effect of zeolite and pumice powders on the environmental and physical characteristics of green concrete filters. *Constr. Build. Mater.* **2020**, *240*, 117931. [CrossRef]
31. Juenger, M.C.; Snellings, R.; Bernal, S.A. Supplementary cementitious materials: New sources, characterization, and performance insights. *Cem. Concr. Res.* **2019**, *122*, 257–273. [CrossRef]
32. Suraneni, P.; Hajibabaee, A.; Ramanathan, S.; Wang, Y.; Weiss, J. New insights from reactivity testing of supplementary cementitious materials. *Cem. Concr. Compos.* **2019**, *103*, 331–338. [CrossRef]
33. Carsana, M.; Frassoni, M.; Bertolini, L. Comparison of ground waste glass with other supplementary cementitious materials. *Cem. Concr. Compos.* **2014**, *45*, 39–45. [CrossRef]
34. Jiang, P.; Chen, Y.; Wang, W.; Yang, J.; Wang, H.; Li, N.; Wang, W. Flexural behavior evaluation and energy dissipation mechanisms of modified iron tailings powder incorporating cement and fibers subjected to freeze-thaw cycles. *J. Clean. Prod.* **2022**, *351*, 131527. [CrossRef]
35. Mishra, S.; Tamrakar, R. Experimental Studies on Properties of Concrete due to different ingredient based Super Plasticizers. *Int. J. Sci. Eng. Technol. Res.* **2013**, *2*, 1036–1040.
36. Khan, M.; Ali, M. Effect of super plasticizer on the properties of medium strength concrete prepared with coconut fiber. *Constr. Build. Mater.* **2018**, *182*, 703–715. [CrossRef]
37. Malagavelli, V.; Paturu, N.R. Strength and Workability Characteristics of Concrete by using Different super plasticizers. *Int. J. Mater. Eng.* **2012**, *2*, 7–11. [CrossRef]
38. Elkady, H.; Serag, M.I.; Elfeky, M.S. Effect of nano silica de-agglomeration, and methods of adding super-plasticizer on the compressive strength, and workability of nano silica concrete. *Civ. Environ. Res.* **2013**, *3*, 21–34.
39. Topçu, İ.B.; Ateşin, Ö. Effect of high dosage lignosulphonate and naphthalene sulphonate based plasticizer usage on micro concrete properties. *Constr. Build. Mater.* **2016**, *120*, 189–197. [CrossRef]
40. Nagrockiene, D.; Pundienė, I.; Kicaite, A. The effect of cement type and plasticizer addition on concrete properties. *Constr. Build. Mater.* **2013**, *45*, 324–331. [CrossRef]
41. Elizondo-Martínez, E.-J.; Andrés-Valeri, V.-C.; Rodríguez-Hernández, J.; Sangiorgi, C. Selection of Additives and Fibers for Improving the Mechanical and Safety Properties of Porous Concrete Pavements through Multi-Criteria Decision-Making Analysis. *Sustainability* **2020**, *12*, 2392. [CrossRef]
42. INN. *Hormigón y Mortero—Agua de Amasado—Clasificación y Requisitos*; NCh1498.2012; Instituto Nacional de Normalización: Santiago, Chile, 2012.
43. INN. *Cemento—Terminología, Clasificación y Especificaciones Generales*; NCh148.1968; Instituto Nacional de Normalización: Santiago, Chile, 1968.
44. Kováč, M.; Sičáková, A. Pervious Concrete as an Environmental Solution for Pavements: Focus on Key Properties. *Environments* **2018**, *5*, 11. [CrossRef]

45. Deo, O.; Neithalath, N. Compressive response of pervious concretes proportioned for desired porosities. *Constr. Build. Mater.* **2011**, *25*, 4181–4189. [CrossRef]
46. INN. *Áridos para Morteros y Hormigones—Requisitos Generales*; NCh163.1979; Instituto Nacional de Normalización: Santiago, Chile, 1979.
47. INN. *Áridos para Morteros y Hormigones—Determinación de las Densidades reales y neta y de la Absorción de agua de las Arenas*; NCh1239.2009; Instituto Nacional de Normalización: Santiago, Chile, 2009.
48. INN. *Áridos para Morteros y Hormigones—Tamizado y Determinación de la Granulometría*; NCh165.2009; Instituto Nacional de Normalización: Santiago, Chile, 2009.
49. INN. *Áridos para Morteros y Hormigones—Determinación de las Densidades Reales y neta y de la Absorción de agua de las Gravas*; NCh1117.2010; Instituto Nacional de Normalización: Santiago, Chile, 2010.
50. *ASTM C618-19*; Standard Specification for Coal Fly Ash and Raw or Calcinated Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2019.
51. INN. *Hormigón y Mortero—Aditivos—Clasificación y Requisitos*; NCh2182.1995; Instituto Nacional de Normalización: Santiago, Chile, 1995.
52. INN. *Hormigón—Ensayo de Compresión de Probetas Cúbicas y Cilíndricas*; NCh1037.2009; Instituto Nacional de Normalización: Santiago, Chile, 2009.
53. INN. *Hormigón—Ensayo de Tracción por Flexión*; NCh1038.2009; Instituto Nacional de Normalización: Santiago, Chile, 2009.
54. *ASTM C1754/C1754M-12*; Standard Test Method for Density and Void Content of Hardened Pervious Concrete. ASTM International: West Conshohocken, PA, USA, 2012.
55. Cires, F.A. Propuesta de Método de Diseño de Mezclas de Hormigón Poroso para Pavimentos Permeables. Bachelor's Thesis, University of Concepción, Concepción, Chile, 2021.
56. INN. *Hormigón—Confección en obra y Curado de Probetas para Ensayos de Compresión, Tracción por Flexión y por Hendimiento*; NCh1017.2009; Instituto Nacional de Normalización: Santiago, Chile, 2009.
57. Ramezanianpour, A.A.; Mousavi, R.; Kalhori, M.; Sobhani, J.; Najimi, M. Micro and macro level properties of natural zeolite contained concretes. *Constr. Build. Mater.* **2015**, *101*, 347–358. [CrossRef]
58. Collepardi, M. A state-of-the-art review on delayed ettringite attack on concrete. *Cem. Concr. Compos.* **2003**, *25*, 401–407. [CrossRef]
59. Kunther, W.; Ferreiro, S.; Skibsted, J. Influence of the Ca/Si ratio on the compressive strength of cementitious calcium–silicate–hydrate binders. *J. Mater. Chem. A* **2017**, *5*, 17401–17412. [CrossRef]
60. U.S. Geological Survey. *Mineral Commodity Summaries 2021*; U.S. Geological Survey: Reston, VA, USA, 2021. [CrossRef]
61. Tennis, P.D.; Leming, M.L.; Akers, D.J. *Pervious Concrete Pavements*; Portland Cement Association: Skokie, IL, USA; National Ready Mixed Concrete Association: Silver Spring, MD, USA, 2004.