# Evaluating the effect of reinforcing fibres on pervious concrete volumetric and mechanical properties according to different compaction energies

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## 1. Introduction

Pervious concrete is a cementitious material characterised by a network of interconnected voids allowing meteoric water to percolate within the concrete matrix. The optimal void content typically ranges from 15% up to 35% of the concrete total volume depending on the applications (ACI Committee 522, 2010; Delatte, Mrkajic, & Miller, 2009; Yang & Jiang, 2003). Gap-graded coarse aggregates and almost no fines are used in the mixes to preserve a high range of voids and therefore drainability features. A viscous cement paste (cement, water and admixtures) is then used to prevent segregation and to bond the aggregates. The water/cement ratio usually varies between .2 and .4, while cement content, generally measured with respect to the aggregate weight, ranges between .18 and .23 of cement/aggregate ratio (Tennis, Leming, & Akers, 2004). The finer portion of the aggregate (below 2 mm of nominal size) is typically omitted from

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pervious concrete mixtures since it increases the paste volume, which in turn decreases the interconnected void volume and drainability. Recently, a small portion of sand has been included in pervious concrete mixes for enhancing freeze-thawing durability, friction and resistance to ravelling when exposed to high traffic volumes (Wang, Schaefer, Kevern, & Suleiman, 2006) although voids and drainability have been reduced.

Moreover, compaction represents a crucial point to be assessed both in the laboratory and *in situ*. Preparing samples according to different compaction methods and energies results in a wide range of outcomes in terms of void content, drainability and resistance properties. In addition, lab compaction needs to be calibrated according to real *in situ* compaction in order to foresee material properties, once placed, and future performance. To date, several compaction methods are reported to be used on site depending on countries' best practices. As a consequence, a significant inconsistency is observed within the results gathered in the laboratory according to standard compaction methods (mainly rodding, vibrationing, impulsive and gyratory compaction). Too much compaction closes up the mix, thus resulting in poor drainability and generally high resistance, and vice versa.

The present study investigated on the improvements provided by reinforcing fibres in pervious concrete mixtures according to several compaction energies. The study was designed to balance resistance and, therefore, applicability on high-volume roads, with high void content and drainability to preserve the primary feature attributed to pervious concrete.

## 2. Background

Concrete pervious pavements have been acknowledged to provide the following benefits: reduce the superficial run-off resulting in an effective storm-water management system (Wang et al., 2006), increase the natural recharge of the groundwater and let the water evaporate from the subsoil (Nemirovsky, Welker, & Traver, 2011; United States Environmental Protection Agency, 2009), limit the needs for roadway drainage systems and reduce initial installation costs (United States Environmental Protection Agency, 2009), acoustic absorption (Neithalath, Weiss, & Olek, 2006), decrease of surface heating and urban heat island effect (Haselbach, Boyer, Kevern, & Schaefer, 2011) and also act as a filter for contaminants in water (Luck, Workman, Coyne, & Higgins, 2008).

Besides the "multi-attribute" properties and eco-efficiency, pervious concrete still needs further research for being used on high-volume roads. For instance, several problems have been acknowledged with ravelling when pervious concrete is exposed to heavy traffic loads or when water/cement ratios are particularly low (ACI Committee 522, 2010; Tennis et al., 2004). Freeze-thaw durability is commonly recognised as a weak point of pervious concrete pavements (Schaefer, Wang, Suleiman, & Kevern, 2006). Superficial properties such as friction and micro/macro texture still need to be clearly assessed (Schaefer, Kevern, & Wang, 2009). Reinforcing fibres have been recently added in pervious concrete mixtures (Schaefer et al., 2010; Schaefer, Kevern, Wang, & Wiegand, 2010) to improve bonding between aggregates and paste, and thus providing the mix with durability and enhanced strength and abrasion resistance (Dong Wu, Huang, Shu, & Wang, 2013).

In addition, construction practices vary among countries depending more on experience and trial-and-error approaches than technical guidelines that are generally accepted. In particular, compaction method highly affects the final product in terms of void content, drainability and mechanical performance (Chopra, Wanielista, Ballock, & Spence, 2007; Schaefer et al., 2006). Pervious concrete is not suitable for being consolidated by vibrators like ordinary concrete mixtures due to its high viscosity and void content (Putman & Neptune, 2011) which could in turn generate local cavities and low void areas during construction. Hand steel rollers are generally applied for compaction (Shu, Huang, Wu, Dong, & Burdette, 2011) rapidly after pouring within fixed forms since pervious concrete has a very low strength when initially placed; low compaction energy can consequently be instantly applied. However, these types of applications are limited to bikeways, parking lots and local roads with low traffic. Hardening of the mixture with time may potentially allow a higher compaction energy (i.e. using a steel drum light roller) but chemical links in concrete could be easily broken if the energy is too high or applied too late. Proper compaction has been proven to be essential for increasing the strength and durability of the pavement, but timing, weight of the roller and number of passes still have to be correctly assessed (Bonicelli, Crispino, Giustozzi, & Shink, 2013). Moreover, finding out an accurate correlation between *in situ* and lab compaction is crucial to provide useful information to contractors to obtain comparable results. Numerous studies have been conducted to understand how to manufacture pervious concrete specimens capable of replicating the properties of pervious concrete in the field. Several methods of sample preparation have been throughout considered including vibration, dropping, rodding, standard Proctor/Marshall hammer blowing or gyratory compactions. It was demonstrated that the impulsive compaction is suitable to reproduce *in situ* pervious concrete characteristics with a low standard deviations (Putman & Neptune, 2011; Rizvi, Tighe, Vimi, & Norris, 2009). For these reasons, the present study adopted the Marshall compactor device for compacting samples.

It has been also demonstrated (Huang, Wu, Xiang, & Burdette, 2010; Kevern, Schaefer, Wang, & Wiegand, 2010; Wang, Schaefer, Kevern, & Suleiman 2006) that adding a small amount of fibre to pervious concrete mixes leads to enhancements in strength, freeze-thaw resistance and porosity. In this study, four types of fibres were selected for a specific aggregate gradation while varying the compaction energy and modifying the mixture characteristics (water/cement ratio).

Indirect tensile strength (ITS), stiffness modulus, void content and permeability coefficient of pervious concrete specimens were evaluated.

## 3. Experimental plan

After defining the characteristics of the mix components (aggregate testing, paste evaluation and content optimisation of admixtures), pervious concrete specimens were prepared in the laboratory. The analysis was initially focused on three base-mixtures, which were characterised by three different mix proportions (water/cement ratio) without including reinforcing fibres. Since it does not exist a unique laying and compaction procedure for *in situ* applications, compaction energy was introduced as a further variable to be considered in the study. In particular, four levels of compaction energy were applied to specimens.

For each one of the base mixtures, four types of fibres were tested in order to measure the mechanical characteristics (strength and stiffness) and the functional properties (void content and drainability) of the mix. The main goal was to find a compromise between the strength of the material, which would be adequate to support medium-to-high traffic loading, and its ability to let the water percolate through the pavement structure and reach the soil beneath assuming the pavement structure made of a pervious concrete layer over a high void aggregate base material.

### 3.1. *Materials, mix design and compaction methodology*

#### 3.1.1. *Materials*

A standard CEM II 42.5R Portland limestone cement was selected for this study according to the standard EN 197-1 (2011). The aggregate size distribution, which is the same for all mixes, is shown in Figure 1.

Two gradations of coarse limestone aggregates were adopted: sieve size 3–6 mm and sieve size 6–10 mm and they were mixed together creating a consistent gradation curve, the same for all the mixes; no fine sand was added to the mixes. Aggregates, characterised in the laboratory according to ASTM C131-06 (2006), EN 933-3 (2004), and EN 933-4 (2008), showed a Los Angeles Index (LA) between 20 and 25%, Shape Index (S.I.) from 3.7 to 9.5% and Flattening Index (F.I.) between 8.5 and 12.5%.

High range water reducer (HRWR), air-entraining admixture (AEA) and viscosity-modifying admixture (VMA) were added in the mixes to improve the overall performance and to enhance workability. Types of selected fibres included: polypropylene fibres (PP), polyolefin fibres (PO) and polypropylene/polyethylene fibres of two different lengths (PE-12 mm and PE-18 mm). PPs were fibrillated fibres made by virgin polypropylene with no structural function (mainly used to reduce plastic shrinkage in concrete); the fibre length was 19 mm and the density was .91 kg/dm$^3$. POs were composed of a monofilament polyolefin polymer with a length of 19 mm and a density of .91 kg/dm$^3$. This type of fibre also provided a structural function. The latter type of fibre considered in this study (PE-12 mm and PE-18 mm) was short monofilament polypropylene/polyethylene fibre with no structural function; the density was equal to .91 kg/dm$^3$as well. Fibres were selected according to different geometrical, chemical and mechanical properties in order to conduct a wider and comprehensive investigation into the effect of fibres in pervious concrete.

#### 3.1.2. *Mix design*

As mentioned, three base mixes were designed (Mix A, Mix B and Mix C): cement/aggregate ratio (c/a) and water/cement ratio (w/c) are reported in Table 1. The quantity of admixtures was differently proportional to guarantee the same workability on the low-water mix (Mix C in Table 1). Fibre content was 1 kg/m$^3$. The following investigation matrix was developed (Table 1).

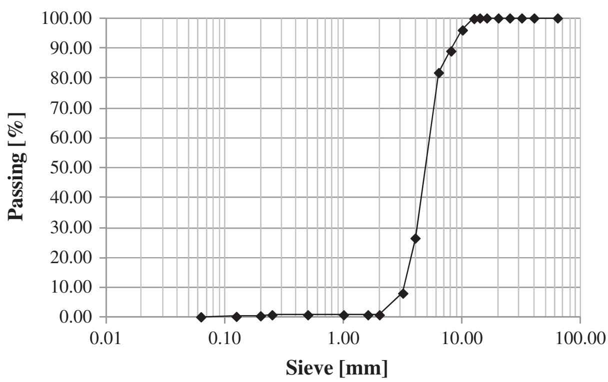


Figure 1. Aggregate size distribution curve.

Table 1. Mix proportions of mixtures analysed.

| MIX TYPE | w/c | c/a | HRWR [% cement weight] | AEA [% total mix weight] | VMA [% aggregate weight] | Fibre PP [kg/m$^3$] | Fibre PO [kg/m$^3$] | Fibre PE12 [kg/m$^3$] | Fibre PE18 [kg/m$^3$] |
|---|---|---|---|---|---|---|---|---|---|
| MIX A | .35 | .2 | 1.1 | .017 | .15 | – | – | – | – |
| MIX A PP | .35 | .2 | 1.1 | .017 | .15 | 1 | – | – | – |
| MIX A PO | .35 | .2 | 1.1 | .017 | .15 | – | 1 | – | – |
| MIX A PE12 | .35 | .2 | 1.1 | .017 | .15 | – | – | 1 | – |
| MIX A PE18 | .30 | .2 | 1.1 | .017 | .15 | – | – | – | 1 |
| MIX B | .30 | .2 | 1.1 | .017 | .15 | – | – | – | – |
| MIX B PP | .30 | .2 | 1.1 | .017 | .15 | 1 | – | – | – |
| MIX B PO | .30 | .2 | 1.1 | .017 | .15 | – | 1 | – | – |
| MIX B PE12 | .30 | .2 | 1.1 | .017 | .15 | – | – | 1 | – |
| MIX B PE18 | .30 | .2 | 1.1 | .017 | .15 | – | – | – | 1 |
| MIX C | .27 | .2 | 2 | .017 | .15 | – | – | – | – |
| MIX C PP | .27 | .2 | 2 | .017 | .15 | 1 | – | – | – |
| MIX C PO | .27 | .2 | 2 | .017 | .15 | – | 1 | – | – |
| MIX C PE12 | .27 | .2 | 2 | .017 | .15 | – | – | 1 | – |
| MIX C PE18 | .27 | .2 | 2 | .017 | .15 | – | – | – | 1 |

### *3.1.3. Compaction methodology*

A concrete drum mixer was used for mixing and a Marshall compactor was then adopted to prepare cylindrical specimens (100 mm in diameter, 50–60 mm in height) according to the standard EN 12697-30 (2012). Four levels of compaction energy were applied: 5, 10, 15 and 20 Marshall blows on one side of the specimen, in order to simulate different *in situ* compaction loads. The 5-blow compaction (very low compaction energy) was intended to represent the compaction energy applied by the light weight hand-roller. Increasing the blows simulated a drum roller compaction according to increased roller weights. However, the growth in compaction energy could be related to both the weight of the roller and the number of consecutive passes. More than 20 blows were not considered during this study since previous investigations demonstrated production of impermeable specimens (Bonicelli et al., 2013). Specimens were extracted from the mold after one day of hardening and were then cured in a moisture-curing chamber and the temperature was set at 20–22 °C and humidity at 80–90%.

Three specimens were prepared for each compaction energy step to guarantee the reproducibility of results.180 specimens were prepared.

## *3.2. Mechanical properties*

Mechanical properties were evaluated according to the ITS and stiffness to define the capability of the material to withstand traffic load stresses. ITS testing was conducted on cylindrical specimens according to the standard EN 12697-23 (2006). Stiffness, represented by the elastic modulus, was determined according to the standard EN 12697-26 (ANNEX-F) (2012) for the stiffness characterisation of bituminous mixtures since no specific standard for pervious concrete has yet been developed. Tests were conducted using the Nottingham Asphalt Tester machine (indirect tensile test configuration) and applying cyclic loads to cylindrical specimens. Samples were preliminary conditioned in a climatic chamber at 20 °C. A constant strain of 5 μm and 2 Hz frequency was set. The following formula was used to calculate the elastic modulus:

$$S_m = \frac{F \times (v + 0.27)}{(z \times h)}$$

where $S_m$: the measured elastic modulus, [MPa]; $F$: peak value, [N]; $z$: horizontal deformation obtained during the load cycle [mm]; $h$: average value of the specimen thickness, [mm] and $v$: Poisson coefficient.

The obtained values were corrected with the load area factor and the test was repeated for two diameters of each specimen.

The majority of the research about pervious concrete commonly agreed to attribute Poisson coefficients between .15 and .2 (Alam, Haselbach, & Cofer, 2012; Vancura, MacDonald, & Khazanovich, 2011) to the material, similar to the standard concrete Poisson coefficient. Elastic Modulus greatly depends on aggregate sieve size distribution, void content and water/cement ratio. However, stiffness should be univocally determined to assess correctly the stress and strain distribution within the pavement layers during the design phase. Afterwards, outcomes should be compared with the maximum admissible stresses and strains observed during lab investigations.

### 3.3. *Functional properties*

The functional properties considered during the present study were related to void content and drainability. Obvious differences between void content resulting from the preliminary investigation phase and the *in situ* sampling after construction were detected during several full-scale tests. This inhomogeneity is often due to the compaction energy applied; when higher than requested generally results in a non-compliance of the permeability requirements that are strictly related to the void content. Therefore, the influence of reinforcing fibres on the volumetric properties of the specimens was assessed. The effective void content test was conducted according to the standard test method for effective porosity and effective air voids of compacted bituminous paving mixture samples ASTM D 73063M – 11 (2011). Drainability was instead determined using a falling head permeameter according to the EN 12697-40 (2012) standard. The drainability capacity was calculated considering the flow time $t$, the cross-sections of specimen $a$ and tube $A$, the specimen length $L$ and the two heads of water $h_1$ and $h_2$ (Neithalath et al., 2010; Wang et al., 2006) applying to the formula:

$$K = \frac{L \times a}{A \times t} \times \ln \frac{h_1}{h_2}$$

### 3.4. *Analysis of results*

In this section, outcomes from the laboratory investigations are presented. Mechanical and functional characteristics of the three base mixes were evaluated, as were the effects of the addition of fibres to each base mix.

#### 3.4.1. *Mechanical property analysis*

Elastic Modulus and ITS tests were conducted to determine the strength and the stiffness of the base mixes and the influence of fibres and compaction energy on the material structural properties. Results in Figure 2 showed that for low compaction energies (1) adding these types of fibres did not enhance the strength of the material exception for PE18 fibres and (2) the stiffness did not significantly change if compared with the base mixes (MIXA, MIXB and MIXC). Even when low compaction energy was applied, PE18 fibres demonstrated to produce greater strength values while maintaining the elastic modulus similar to the referring mix.

PP contribution was not relevant; slight increases in stiffness and ITS were shown for low-water mixtures (MIXC) especially for very high compaction (20 Marshall blows). PP was not expected to provide significant improvements in strength and stiffness but was mainly adopted to avoid plastic shrinkage.

The enhancements due to PO were instead tangible in all the mixes (Mix A, B and Mix C), producing an effective increment in strength (10–15%). PO proved to work ideally with all water contents and compaction energies.

PE12 led to considerable decreases in strength and stiffness in all the mixes and for each compaction step. This was due to the physical characteristic of the fibre, it was indeed the shorter; however, chemical composition of PE12 was the same as PE18, which was the fibre providing the better results in terms of mechanical properties. For these reasons, it can be affirmed that the length of the fibre respect to the aggregate dimension is a main feature when selecting reinforcing fibres for pervious concrete mixtures. PE12 fibre also presented some flaws during mixing: it tended to retain the

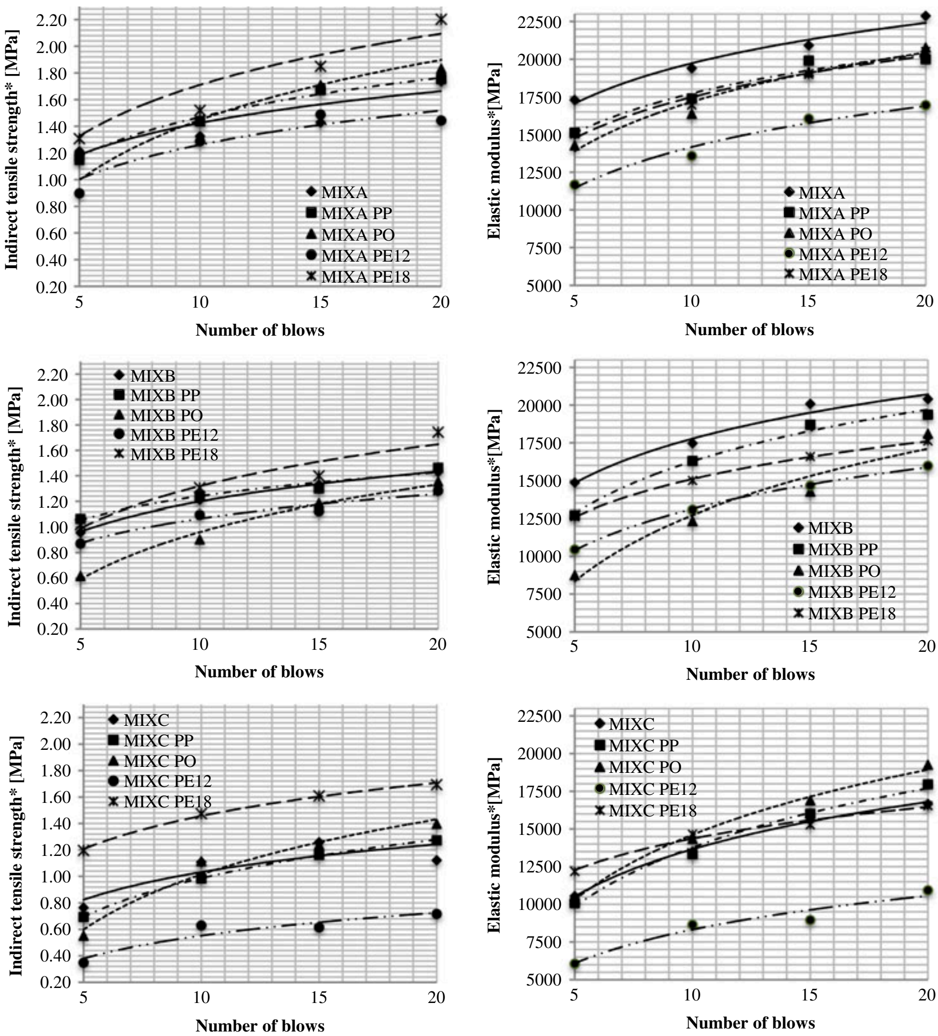


Figure 2. Mechanical and structural properties of pervious concrete mixtures with fibres.
*Each point in the graph represents the average results among three specimens.

Figure 3. Segregation due to polypropylene/polyethylene fibres during mixing.

Figure 4. Fibres in MIX A and C.

cement paste together with the finer aggregate, thus forming small, circular spheres (Figure 3). Lowering the cement paste resulted in a poor covering of the aggregates and segregation. Flow ability and self-compaction were consequently mediocre, and greater specimens were obtained for the same compaction energy (higher void content and permeability) as discussed in the following section.

Generally, whenever greater compaction energy was applied (more than 10 blows), fibres were able to increase strength and stiffness in most of the cases (except PE12) even if the positive contribution ranged from low to mid-high depending on the type. Instead, when compaction energy was low (5 Marshall blows), the percentage of effective voids remained significantly high (20% or greater). Fibres (exception made for PE18) could not therefore provide any significant reinforcing function to the material. Figure 4 shows how the specimens appeared for variations of water/cement ratio; MIX C (on the left) is considerably drier with respect to MIX A (on the right). As a consequence, the amount of cement paste and aggregate coating thickness varied significantly. The effectiveness of fibres changed accordingly. Several non-collaborating fibres can be seen for MIX C, while MIX A showed a better inclusion of fibres into the paste. Compaction energy and w/c ratio were proved to be the two fundamental parameters for evaluating the effect of fibres in pervious concrete pavement layers. Figure 5 highlights the different types of fibres and their spread into the mix using optical microscope imaging.

(a) (b) (c)

Figure 5. Optical microscopes imaging of different types of fibres: (a) polypropylene, (b) polyolefin and (c) polypropylene/polyethylene12 mm.

### 3.4.2. Functional property analysis

The volumetric properties and drainability characteristics of MIX A, B and Care illustrated in this section together with the influence of fibres on void content and permeability coefficient. Results are referred to the four steps of compaction previously discussed.

Different considerations should be made depending on the mixes when referring to the influence of fibres on functional properties of pervious concrete. As shown in Figure 6, adding fibres did not correspond to appreciable variations in void content and the permeability coefficient when high-water mixes were considered (MIX A), although PE12 resulted in segregation phenomena and consequently higher void contents, and PE18 produced a pervious concrete more pervious and generally higher void contents according to all the considered compaction levels.

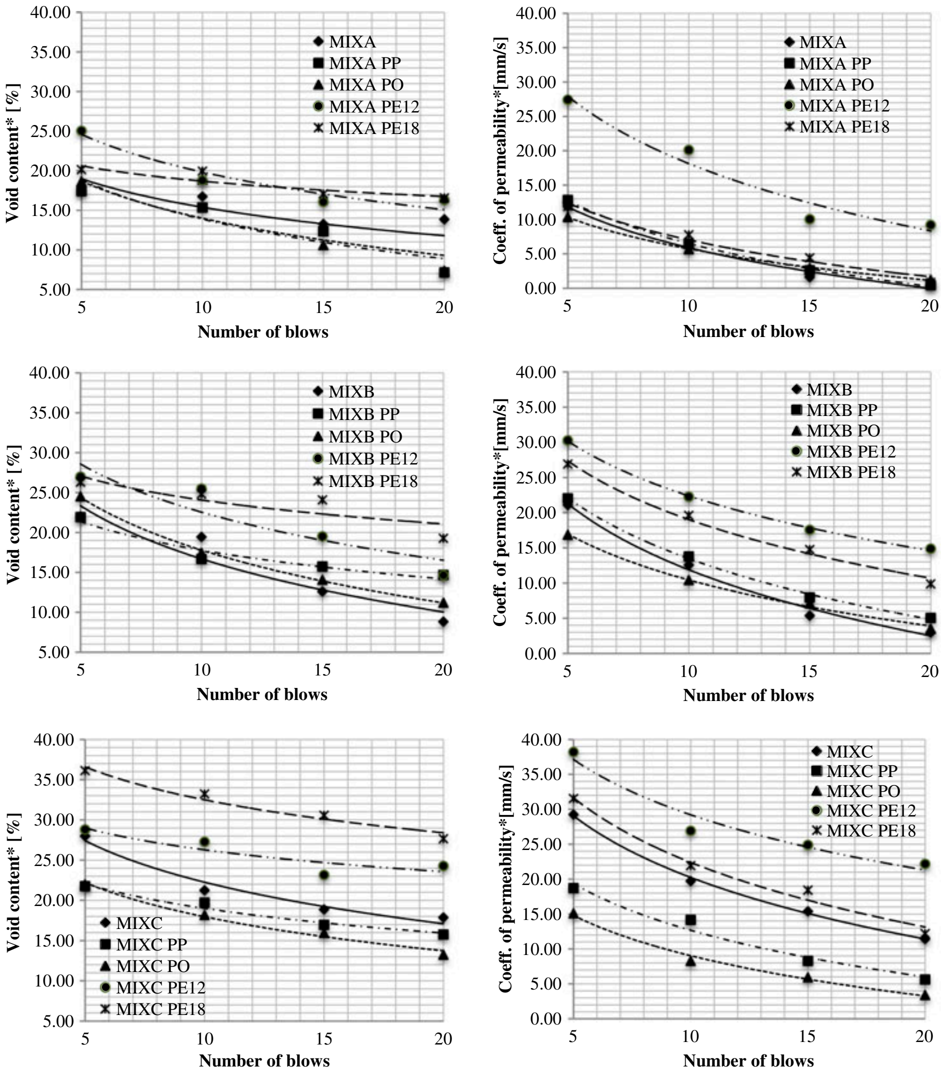


Figure 6. Functional properties of pervious concrete mixtures with fibres.
*Each point in the graph represents the average results among three specimens.

Whenever low-water mixes were considered (MIX C), the supplementing of fibres generally led to a consistent reduction in void content and drainability capacity. In particular, PP reduced the void content around 10% while PO produced an even greater reduction (i.e. around 20%). It can therefore be inferred that fibres tended to close up the mixes and reduced voids. This effect was almost steady for different compaction energies. However, PE12 and PE18 showed opposite effect sand increased both the effective voids and the permeability coefficient. The segregation of fines and cement paste that formed clots together with PE12 produced a drier mixture characterised by low workability and low coating of aggregates.

Bulk densities were calculated according to the standard EN 12697-6 (2012) to complete the analysis on volumetric properties of mixes. Good correlation was detected between void content and density results. Bulk density values of the mixes are summarised in Table 2.

The main objective of this study was to determine the proper balance between strength and permeability in order to assure the proper resistance to high traffic without losing the capacity to drain. Void content (or bulk density), ITS and the permeability coefficient were reported in Figure 7 for all the specimens tested during the present study.

The graphs showed a good correlation between the volumetric properties (void content and density) and the drainability capacity, expressed in terms of permeability coefficient, as expected. However, correlation between volumetric and mechanical properties (the ITS was considered in the analysis) was pretty good for low void content specimens (high density), but somehow very small for high void content specimens (low density) showing greater variability. Finally, this study also evidenced that the effects on volumetric and mechanical properties varied depending on the type of fibre adopted; in particular, fibres PE 18 led to greater strength materials maintaining low density levels and quite large void contents.

Table 2. Bulk densities of the mixes according to compaction energy.

| | 5 | | 10 | | 15 | | 20 | |
|---|---|---|---|---|---|---|---|---|
| Compaction energy [Number of blows] | [kg/m$^3$] | St. dev. | [kg/m$^3$] | St. dev. | [kg/m$^3$] | St. dev. | [kg/m$^3$] | St. dev. |
| MIXA | 1961 | 13.0 | 2024 | 32.6 | 2133 | 10.3 | 2175 | 5.4 |
| MIXAPP | 1944 | 20.9 | 2084 | 13.2 | 2092 | 5.4 | 2139 | 9.7 |
| MIXAPO | 1987 | .8 | 2087 | 11.3 | 2153 | 12.0 | 2196 | 10.4 |
| MIXAPE12 | 1807 | 25.6 | 1891 | 2.4 | 1964 | 35.0 | 1989 | 4.2 |
| MIXAPE18 | 1893 | 32.0 | 1983 | 14.9 | 2009 | 1.7 | 2134 | 31.1 |
| MIXB | 1866 | 30.3 | 2004 | 36.4 | 2121 | 44.3 | 2137 | 81.9 |
| MIXBPP | 1895 | 4.1 | 1979 | 9.7 | 2052 | 5.8 | 2094 | 6.6 |
| MIXBPO | 1879 | 6.1 | 1996 | 24.1 | 2063 | 9.1 | 2115 | 7.5 |
| MIXBPE12 | 1737 | 21.4 | 1797 | 31.0 | 1841 | 24.5 | 1863 | 21.3 |
| MIXBPE18 | 1817 | 51.4 | 1909 | 39.9 | 1974 | 34.9 | 1996 | 27.4 |
| MIXC | 1846 | 7.5 | 1932 | 9.4 | 1995 | 9.4 | 2037 | 15.0 |
| MIXCPP | 1888 | 6.4 | 1985 | 3.2 | 2048 | 17.5 | 2094 | 9.4 |
| MIXCPO | 1892 | 12.0 | 2004 | 13.3 | 2081 | 5.3 | 2132 | 20.5 |
| MIXCPE12 | 1775 | 15.4 | 1801 | 12.3 | 1902 | 14.8 | 1911 | 29.2 |
| MIXCPE18 | 1804 | 12.4 | 1880 | 31.3 | 1960 | 14.4 | 1989 | 12.4 |

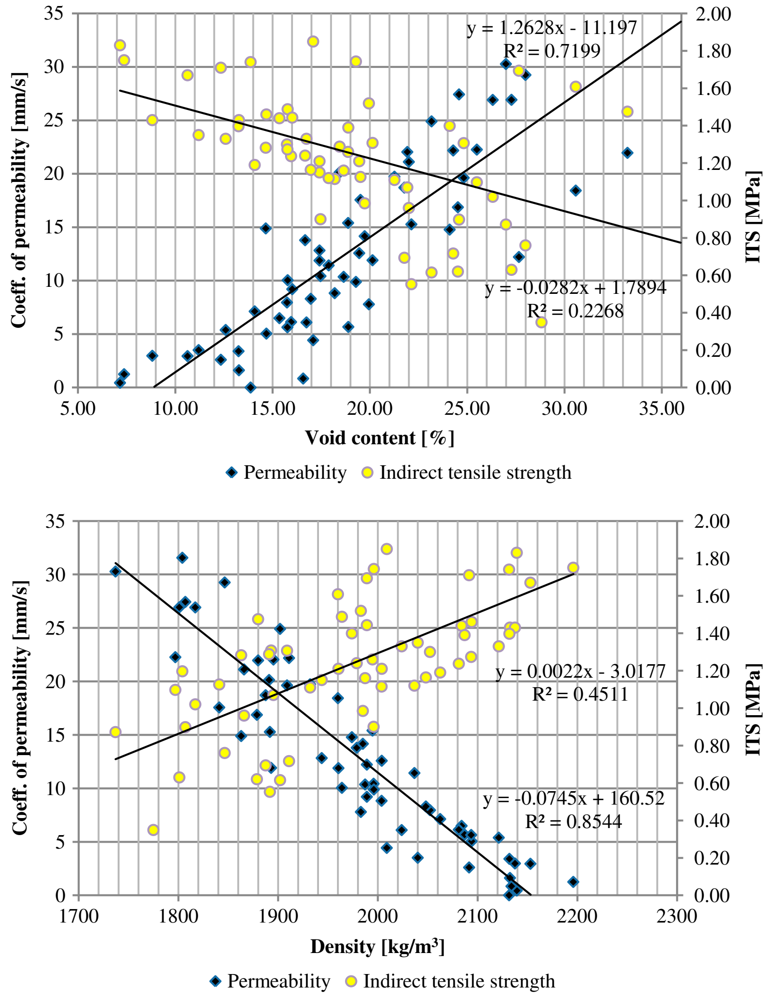


Figure 7. Mechanical and functional properties of pervious concrete mixtures with and without fibres.
*Each point in the graph represents the average results among three.

## 4. Discussion

This investigation, conducted on pervious concrete mix design and compaction, took into consideration several aspects. On one hand, high void content and great drainability did not correspond to the greatest strength, thus causing the pavement to be less consistent and rapidly fail during its service life. On the other hand, achieving high resistances by providing strong compactions significantly decreased the effective void content and the drainability of the material. For these reasons, it was useful to analyse the effect provided by reinforcing fibres with different physical and chemical properties on the mechanical and functional characteristics of pervious concrete mixes.

Results identified certain types of fibres that generally led to favourable improvements, by increasing resistance without limiting the drainability. However, other types of fibres could be detrimental and worsen both the objectives of strength and drainability. Furthermore, increasing the energy of compaction turned to enhance the effect of fibres. The amount of water in the mix was also proven to greatly affect fibre effectiveness, and fibres contributed less in low-water mixes.

The adopted methodology highlighted how compaction results to be fundamental for pervious concrete pavements. In fact, the same material can potentially produce different values of mechanical and functional parameters if the compaction energy changes.

## 5. Conclusion

The effect of reinforcing fibres in pervious concrete mixtures was investigated during this study. Several compaction levels were considered. Four types of fibres were added to base mixes characterised by different values of water/cement ratios. The resulting mixes were then analysed in terms of void content, permeability, stiffness and tensile strength.

Results showed how it is possible to provide mechanical benefits in pervious concrete mixtures by adding fibres while keeping almost unchanged the drainability properties. However, the correct type of fibre has to be selected since some types could be detrimental instead of beneficial. Quantifying the effect of fibre addition is also dependent upon the cement paste content.

Finally, it is recommended to study other fibre contents and other types of fibres and perform full-scale preliminary investigations to define the correct equivalence between laboratory and *in situ* compaction.

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