Experimental study on the effects of fine sand addition on differentially compacted pervious concrete

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1. Introduction and background

The Environmental Protection Agency (EPA) listed Pervious Concrete Pavement (PCP) as one of the Best Management Practices for storm water management. The small amount of cement paste and the gap-graded aggregate distribution provide high porosity and the interconnected void system allows the water to percolate through the material. The void content typically ranges from 15% up to 35% of the concrete total volume [1–3] and a viscous cement paste (water/cement ratio – w/c – between 0.2 and 0.4 and cement/aggregate ratio – c/a – between 0.18 and 0.23) is adopted to achieve greater strength [4]. Several studies demonstrated PCP to provide the following benefits: reduce water run-off [5], allow the natural recharge of the groundwater and the

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evaporation of water from the soil beneath [6,7], limit the costs for roadway drainage systems [6], acoustic absorption [8], reduction of the urban heat island effect [9], and filter for contaminants in water [10].

The research on PCP progressed in recent years studying mix pro-portioning, construction logistics, material testing, and maintenance activities: some methodologies are available for mix proportioning [3,11] and the National Ready Mixed Concrete Association tried to standardize the construction practices [12]. The ASTM Committee C09.49 recently completed four standards about fresh and hardened unit weight determination, measurement of in-situ infiltration rate, and resistance to degradation *(*ASTM C1688/C1688M-2013, ASTM C1754/C1754M-2012, ASTM C1701/C1701M-2009, and ASTM C1747/C1747M-2013*)*. However, several other fundamental issues occurring during placement and testing procedures are still far to be definitive and broadly accepted.

The fine aggregate size (i.e., below 3 mm) is typically not included in the mix [4] to guarantee the proper drainability feature (void content) of pervious concrete mixes. Even though, including a small portion of fine sand (up to 7% of sand introduced as replacement of the coarse aggregates) has been proposed for enhancing freeze–thawing durability [13], surface friction, and resistance to raveling when exposed to high traffic volumes [5]. The role of the added-sand content on strength and drainability needs to be further observed [14]. Previous applications in Europe and Japan adopted small-size aggregates (i.e., passing at 2.36 mm or No. 8 ASTM sieve) as addition to standard PCP mixes providing a durable surface layer for roadway applications [15,16]. Other studies incorporated up to 15% of fine sand (mass ratio of fine aggregate to coarse aggregate); however, 5–10% was found to be an optimal amount for balancing strength [5,14,17,18] and drainability. Previous research showed that a *w*/*c* ratio lower than 0.27 is not suitable for mixes containing sand because the paste would be not sufficiently hydrated and will develop poor strength and durability. A *w*/*c* above 0.33 and addition of sand can otherwise produce drainability limitations due to excessive paste volume [14]. Greater percentage of fine aggregate in the mix generally produce an increase in the mortar thickness surrounding the aggregate and at the same time, porosity decreased and compressive strength significantly increased [14]. Fly ashes, latex emulsion, and other polymers have been also included to improve the PCP strength and durability, as well as a small amount of fibers [5,19–23].

For pervious concrete to achieve specific characteristics mix design is as responsible as a clear definition of construction best practices. Methodology of compaction (hand-roller, drum roller, vibratory plate roller, etc.), number of passes, and timing of compaction are only few of the numerous variables to take into account when dealing with pervious concrete applications. The same material could behave very differently and exhibits very different performance according to the compaction energy provided on the construction site. In situ and laboratory compaction methods and timing of proper compaction are, in fact, still not standardized. The compaction energy applied to the material has been proven to be fundamental for the mechanical and drainability properties of the mix [24–26]. To date, several compaction methods are reported to be used on site depending on countries' best practices and technical specifications [19,27–29]. The use of spud vibrators is not generally recommended for PCP construction operations because of the possibility to provide low-voids areas and cavities [27]. A common practice is to compact the fresh pervious concrete placed within fixed forms by using hand-steel rollers [3]; however, adjusting the mix-design and the timing of compaction can allow the adoption of steel drum light rollers. The proper compaction energy and timing should be calibrated so not to break the chemical links during the hardening process of the pervious concrete. The following methods can be acknowledged as the most adopted laboratory compaction methods: vibration, dropping, rodding, standard Proctor/Marshall hammer blowing, and gyratory compactor. Previous studies proved the suitability of impulsive compaction to reproduce in-situ pervious concrete characteristics with a low standard deviation [27,30].

2. Research objectives

The main goal of the present study was to look for a balance between the strength of the material, which would be adequate to support medium-to-high traffic loadings, and its ability to allow the water to percolate through the pavement structure and easily reach the soil beneath. Two main aspects were thus evaluated: the effect on mixture properties caused by the addition of small percentage of sand depending on the *w*/*c* ratios, and the consequence of different compaction energies. A statistical analysis of results was finally conducted to find relationships and correlations among the several variables.

3. Laboratory investigation

Three base mixes were identified according to three *w*/*c* ratios and two different percentages of sand were added into each one of them; a total of 9 mixes and 360 cylindrical specimens were tested and 9 slabs were built. Compaction energy was also evalu-ated according to four steps provided by means of the Marshall compactor: 5, 10, 15 and 20 compaction blows, respectively. The base mixes (the reference mixes: MIX A, MIXB and MIXC) and the mixes with fine sand added (sand mixes) were tested to mea-sure the mechanical characteristics (strength, stiffness, and particle loss resistance, respectively), the volumetric properties (bulk den-sity and void content), and the functional properties (drainability and skid resistance). The repeatability in each test was equal to five.

4. Materials, mix design, and specimen preparation

4.1. Materials

The materials used for the mix design of the mixes and the selected mix proportions derived from previous works that took into consideration several different compaction energies and mix proportions [26,31]. Based on previous results, the base mixes that better achieved a balance between mechanical and drainability properties were selected for this study. A CEM II 42.5R A-LL Portland limestone cement was selected for this study according to EN 197-1, the European standard for composition, specifications and conformity criteria for common cements. The aggregate size distribution is shown in Fig. 1. The three reference mixes had the same aggregate distribution curve but different *w*/*c* ratios; namely, 0.27, 0.30,

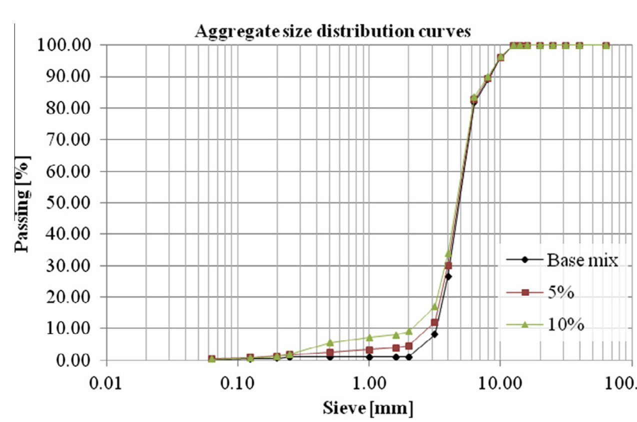

Fig. 1. Aggregate size distribution curves of base mixes without sand and mixes containing 5% and 10% of sand.

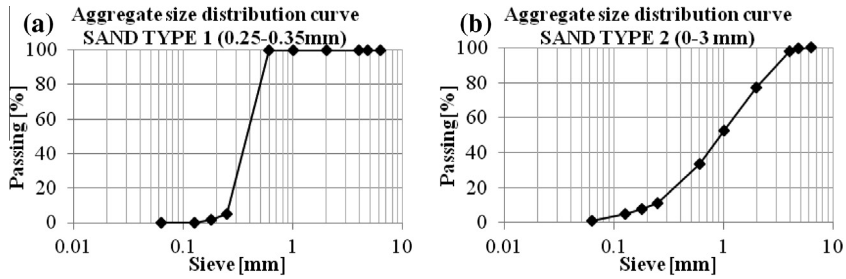

Fig. 2. Aggregate size distribution curves (a) type 1 sand (uniform in the 0.25–0.35 mm) and (b) type 2 sand (graded in the 0–3 mm).

Table 1
Mix proportions of the mixtures.

MIX type	w/c	c/a	HRWR [% cement weight]	AEA [% total mix weight]	VMA [% aggregate weight]	Fine sand [% aggregate weight]
MIX A	0.35	0.2	1.1	0.017	0.15	–
MIX A s5	0.35	0.2	1.1	0.017	0.15	5%
MIX A s10	0.35	0.2	1.1	0.017	0.15	10%
MIX B	0.30	0.2	1.1	0.017	0.15	–
MIX B s5	0.30	0.2	1.1	0.017	0.15	5%
MIX B s10	0.30	0.2	1.1	0.017	0.15	10%
MIX C	0.27	0.2	2	0.017	0.15	–
MIX C s5	0.27	0.2	2	0.017	0.15	5%
MIX C s10	0.27	0.2	2	0.017	0.15	10%

and 0.35. Three sand mixes were proportioned to have 5% of the aggregates substituted with fine sand and the latter three sand mixes so that 10% of the aggregates was replaced by the fine sand.

Two gradations of coarse limestone aggregates were proportioned for the reference mixes: 3–6 mm and 6–10 mm; 80% of the total aggregate weight was in the 3–6 mm interval while 20% in the 6–10 mm. Aggregates were preliminary characterized according to UNI EN 1097-2, EN 933-3, and EN 933-4 resulting in a Los Angeles Index (L.A.) between 20% and 25%, Shape Index (S.I.) from 3.7% to 9.5% and Flakiness Index (F.I.) between 8.5% and 12.5%. These indices have to settle in the required ranges to avoid abrasion or failure phenomena due to aggregate weakness.

Two gradations of sand were further mixed for the sand addition: "Type 1" was homogenous sieve size gradation sand (0.25–0.35 mm) with a finesses modulus (FM) of 1.9; "Type 2" sand had instead a well-graded distribution in the 0–3 mm sieve interval and FM of 3.17. The aggregate distribution curves of the two types of sands are reported in Fig. 2.

Recent studies [5,24] suggested introducing fine sand characterized by FM value of 2.9 according to ASTM C136; sand was thus proportioned at 80% (Type 1) and 20% (Type 2) rate to achieve the FM specifications [14].

High Range Water Reducer (HRWR), Air-Entraining Admixture (AEA), and Viscosity-Modifying Admixture (VMA) were added into the mixes to improve the overall performance and enhance workability. The specific quantities are reported in Table 1. It should be noted that a major content of HRWR was adopted in the mixes named MIX_C, MIX C_s5, and MIX C_s10 due to the poor water content and potential difficulties occurred during mixing and compaction.

4.2. Mix design

Three reference mixes, namely Mix A, Mix B, and MIX C, were prepared adopting a 0.2 c/a ratio. The investigation matrix is reported in Table 1.

4.3. Specimen preparation

Pervious concrete mixtures were mixed using a standard concrete drum mixer; cylindrical Marshall specimens (almost 101 mm in diameter and 55–65 mm thick) were prepared with a Marshall compactor according to the standard EN 12697-30 but applying four levels of compaction energy: 5, 10, 15, and 20 Marshall blows on one side of the specimen to simulate different in-situ compaction efforts. The increase in the number of blows simulated the greater compaction energy; this could be eventually related either to the weight of the roller (i.e., a light weight hand-roller or a drum steel roller) and to the number of consecutive passes. Previous investigations demonstrated that increasing the number of blows at values above 20 produced almost impermeable specimens [26]. On the other hand, specimens resulted in a very weak structure and greatly subjected to raveling [31], for instance, if subjected to low compaction energy (i.e., less than 5 blows). The specimens were then cured 7 days in a climatic chamber at 20–22 °C and 80% to 90% relative humidity. Several studies [3,32] highlighted the importance of curing of pervious concrete to achieve both short and long-term performance.

400 × 200 mm pervious concrete slabs were also prepared for each mixture to gather data about frictional surface properties. The amount of compacted material was designed to obtain a final void content in accordance with the 10-blow Marshall compacted samples (medium compaction effort). Frictional surface prop-erties are acknowledged to vary depending on the mix void content, among others.

Outcomes from the laboratory investigation are presented in the following section.

5. Laboratory tests and analysis of results

Mechanical, volumetric and functional characteristics of the reference mixes were evaluated as well as the effects of the addition of fine sand.

5.1. Mechanical property analysis

Mechanical characteristics were evaluated by means of the indirect tensile strength (ITS) according to EN 12697-23, stiffness modulus (EN 12697-26, annex F) and cantabro loss resistance; the latter to assess the capability of the material to properly with-stand traffic load stresses (UNI EN 12697-17) without raveling [33]. The specimens were tested after 7 days of curing since the road re-opening to traffic usually takes place within 5–7 days from the surface layer construction. An early strength is therefore recommended. The splitting tensile strength of pervious concrete is between 12% and 15% of its compressive strength [30]. Flexural strength and compressive strength relationship for pervious concrete is also well known but for the goals of the present investigation it was not suitable to consider flexural strength for the following reasons. First, the analysis of different compaction energies was one of the main objectives of this study and it would have been rather difficult to consider flexural strength of differentially compacted pervious concrete beams due to the impossibility of applying different compaction efforts on a beam-shaped mold; standard concrete is consolidated by vibrating the mold but pervious concrete cannot be vibrated due to the great void content and possible formation of bug holes (similar to pitting). In addition, preparing pervious concrete slabs by laboratory roller compaction, for instance, and sawing them into beams would cause raveling and modifications due to water contact during the continuous cur-ing process.

The stiffness modulus was determined using a dynamic asphalt tester machine by applying cyclic loads to the cylindrical samples. A constant strain of 5 μ, load frequency of 2 Hz, 20 ° C, and a Poisson ratio of 0.2 [16,17] were set for the test. The elastic modu-lus greatly depends on the aggregate sieve size distribution, shape/angularity of the aggregate, void content, and water/cement ratio. The determination of the stiffness modulus is fundamental during the pavement designing stage.

Results for the mechanical evaluation are showed in Fig. 3. The red lines describe the trends for the reference mixes.

It can be inferred that Elastic Modulus for each mixture had similar trends to the ITS and Cantabro resistance (which is the opposite of the Cantabro Loss Index trend that represents the amount of particle loss). In addition, increasing the compaction energy led to a greater stiffness, strength, and resistance to particle loss for all the mixes, as expected. About the effect of w/c ratios, the mixes characterized by having greater w/c ratios (MIX A with $w/c = 0.35$, for instance) were generally stiffer, more resistant to tensile stresses, and showed less particle loss. MIX C, which exhib-ited the smallest w/c ratio ($w/c = 0.27$) provided weaker structural properties due to the small quantity of cement paste. MIX B ($w/c = 0.30$) generally showed an intermediate mechanical behav-ior between the MIX A and MIX C.

The addition of sand produced different results in relationship to the water content. Mixes with greater amount of water (w/c more than 0.30, MIXA and MIXB) received major benefits in the structural behavior of the specimens with sand addition. In fact, the sand linked with cement and water to provide a thicker cover-age of the aggregates; contrarily, MIX C (low water) demonstrated a decrease in mechanical properties due to the addition of sand. This phenomenon was due to the sand potential to absorb the small amount of water preventing most of the chemical links with the cement powder. Sand acted as a discontinuity factor in this case.

The mix with the greatest w/c (MIXA) showed an increase in the Elastic Modulus up to 27% after the sand addition (10% of sand). The same mix also provided an increase in ITS up to 59% with a 10% of sand (MIX A s10, ITS = 1.95 MPa). The addition of sand in MIX B ($w/c = 0.30$) produced an Elastic Modulus increase up to + 40% in mixes with 10% of sand (MIX B s10). The same mix showed a consistent increase in ITS by achieving + 65% in strength

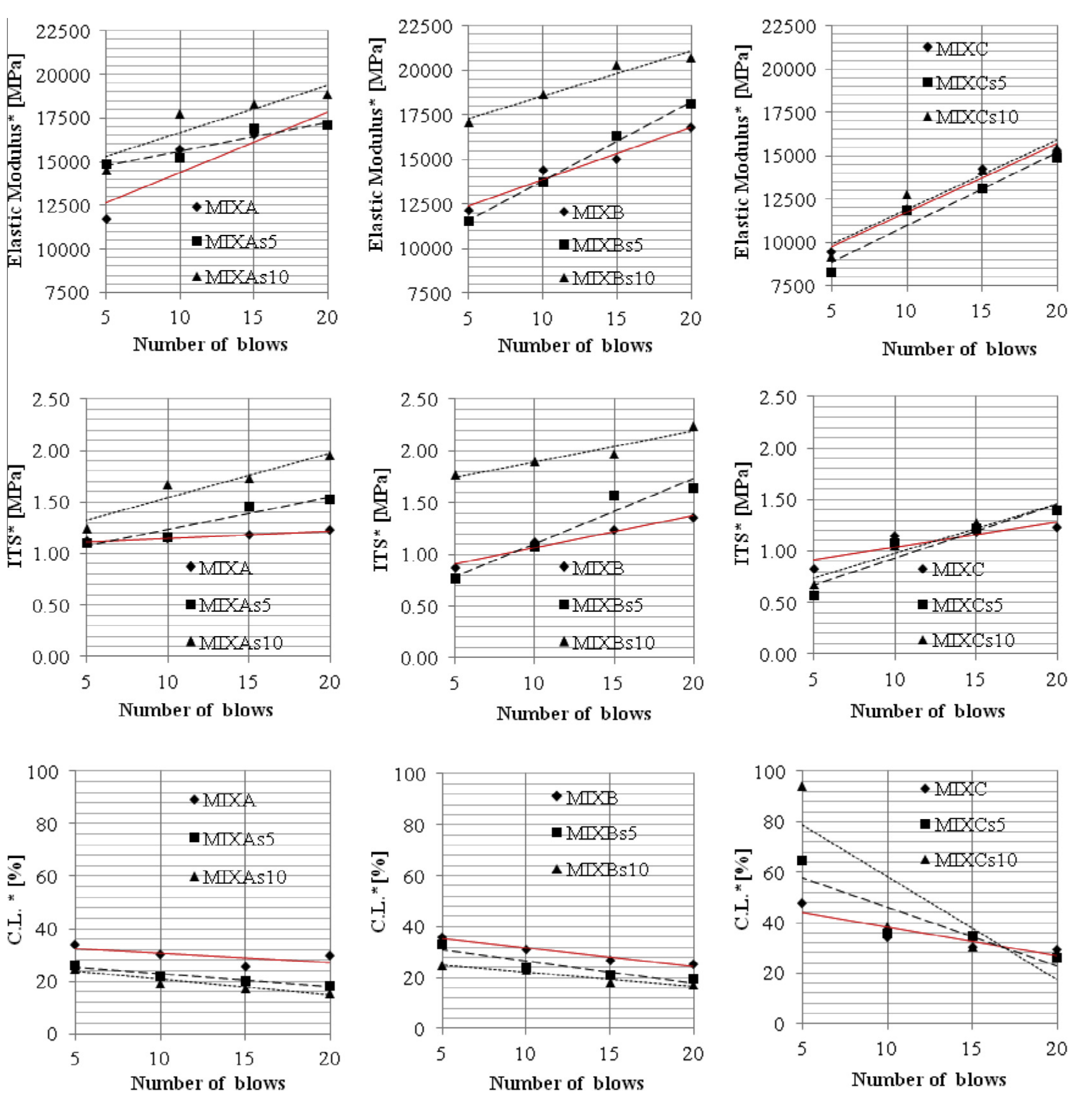

Fig. 3. Mechanical properties of pervious concrete mixes with the addition of fine sand. **Each point in the graph represents the average results among five specimens.* (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Effects of fine-sand addition to the reference mixes: mechanical properties.

		Elastic modulus (MPa)				Indirect tensile strength (MPa)				Cantabro loss (%)			
		5	10	15	20	5	10	15	20	5	10	15	20
MIX A	σ	2677	460	2684	277	0.03	0.02	0.11	0.19	3.25	1.45	0.68	2.61
MIX A s5	σ	335	346	497	535	0.03	0.02	0.17	0.07	4.48	2.79	0.91	1.85
	Δ [%]	+27.1	+3.1	+2.2	+0.1	−2.5	+1.5	+23.4	+24.2	−22.7	−28.1	−20.9	−38.6
MIX As10	σ	328	149	544	752	0.03	0.06	0.11	0.03	0.8	2.2	3.5	0.4
	Δ [%]	+24.1	+13.2	+10.51	+10.2	+10.5	+46.1	+46.2	+58.6	−26.5	−37.8	−31.5	−48.3
MIX B	σ	715	1262	221	1646	0.03	0.04	0.15	0.16	9.6	13.4	2.0	1.5
MIX B s5	σ	275	1017	372	1208	0.06	0.08	0.04	0.26	2.70	1.22	1.25	2.03
	Δ [%]	−4.9	+4.6	+8.9	+7.5	−13.1	+3.9	+27.3	+21.5	−8.1	−22.7	−20.7	−22.7
MIX B s10	σ	475	893	1123	1027	0.15	0.20	0.07	0.19	1.1	1.7	1.7	0.9
	Δ [%]	+40.6	+29.6	+35.1	+23.2	+102.1	+69.5	+59.6	65.9	−30.2	−26.7	−31.4	−31.6
MIX C	σ	488	835	749	1159	0.13	0.17	0.04	0.03	4.2	1.1	2.0	3.7
MIX C s5	σ	561	1091	507	555	0.05	0.02	0.06	0.21	3.62	5.50	2.16	3.85
	Δ [%]	−12.5	−0.6	−8.3	−2.5	−31.2	−6.0	+2.6	+13.8	+35.5	+5.1	+14.1	−11.6
MIX C s10	σ	342	861	923	396	0.10	0.18	0.11	0.04	5.7	2.7	5.3	3.4
	Δ [%]	−2.9	+7.1	−0.7	+0.8	−19.2	−7.7	+7.3	+13.6	+97.6	+13.3	+0.4	−3.5

when 10% of sand was added. In the low-water mix (MIX C, $w/c = 0.27$) the addition of sand prevented the structural properties to clearly increase by showing non-uniform trends. Standard deviations (σ) and percentage of variation respect to the reference mixes are reported in Table 2.

The resistance to particle loss expressed by the Cantabro Loss Index showed evident benefits of sand addition. In fact, the greater volume of paste due to the introduction of fine aggregate led to improve cohesive resistance within the material [5]. The increase in resistance properties was more evident when the amount of

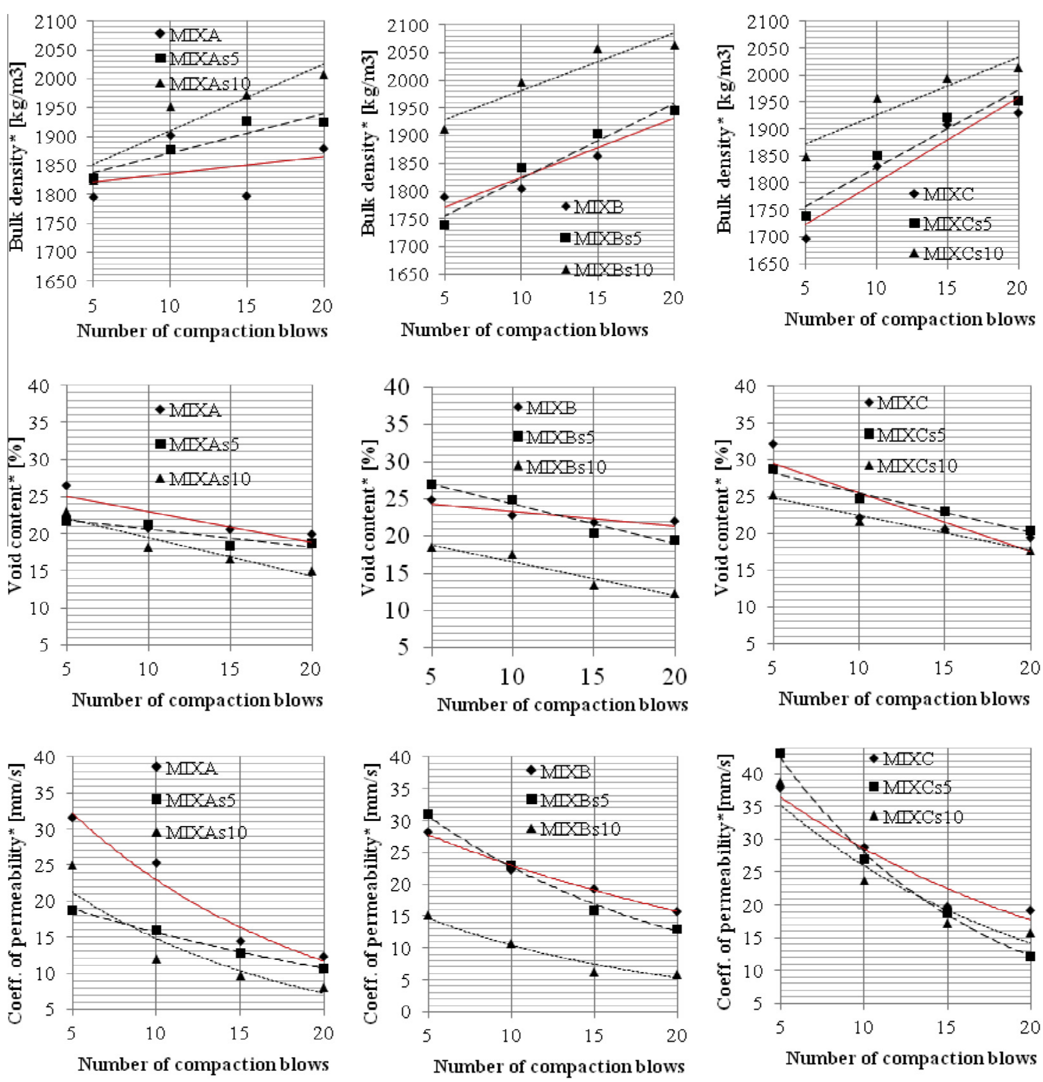

Fig. 4. Volumetric properties of pervious concrete mixes with the addition of fine sand. **Each point in the graph represents the average results among five specimens.* (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sand was greater and the compaction energy stronger. The sand-mix MIX A (high-water) showed a reduction of particle loss up to −48% than the reference mix after adding 10% of sand; MIX B s10 (w/c = 0.30) registered a reduction in C.L. up to −31%. The resistance to particle loss of MIX C (w/c = 0.27) showed no benefit after adding fine sand.

5.2. Volumetric and functional property analysis

The volumetric characteristics (bulk density and void content) and drainability were measured according to the standards EN 12697-6, EN 12697-40 and ASTM D 73063M – 11. In addition, the surface friction was measured on pervious concrete slabs according to the British Pendulum Test specifications (UNI EN 13036-4). Results are provided in Fig. 4. The red lines describe the trends for the reference mixes.

Increasing the compaction energy provided greater bulk densities and a reduction in void contents and drainability, as expected. Compaction therefore resulted to be a main aspect of the volumetric properties of pervious concrete. Applying different compaction energies to the same fixed mix could result in either a satisfactory drainability or even insufficient drainage capabilities if too much compaction is used. This behavior was detected in all the considered mixes. MIX C (w/c = 0.27) exhibited a clear resistance to compaction resulting in having the lowest bulk densities and greatest void content and drainability than MIX A and B for equivalent levels of compaction. The poor water content made the particles flow harder during compaction of fresh pervious concrete.

A good correlation was detected between the void content and the bulk density. Adding fine sand to the reference mixes generally lowered the void content and drainability and raised the bulk density, for equivalent reference mixes and compaction energies. Sand, cement, and water produced a thicker coating of the aggregates, partially closing voids and reducing the void dimensions. A different trend was spotted for MIX C: the addition of sand did not produce a consistent effect. Values of the property variations respect to the reference mixes and standard deviations are reported in Table 3.

Further testing was conducted to evaluate the friction properties of pervious concrete. In particular, friction was evaluated on slabs compacted as to provide the same void content of the 10-blow Marshall compaction on cylindrical specimens. The 10-blow Marshall compaction was proven to be the compaction energy that better balanced between structural performance and permeability. Lower compaction provided a permeable and weak material instead greater compaction energy reduced hydraulic features. The slabs were casted in one layer and compacted by mean of a roller compactor calibrating the amount of material and number of passes depending on the 10-blow void content. Results were summarized in Fig. 5.

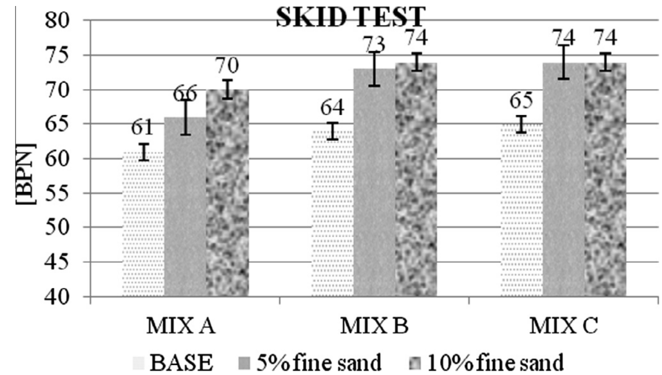

Fig. 5. Skid test results of pervious concrete reference-mixes and sand-mixes.

Good BPN (British Pendulum Number) values were generally measured for all the mixes, abundantly satisfying the usual skid resistance request for road pavements by the technical specifications (i.e., greater than 55–58 for asphalt surface layers). It was found that the addition of sand produced an improved friction due to the cement paste texture that became rougher. Sand seal treatments (asphalt emulsion application followed by sand spraying) are generally acknowledged in road maintenance practices as to provide greater skid resistance and to seal the pavement surface. However, the friction analysis was just preliminary and needs further study.

6. Result analysis

Basic statistic was adopted to identify correlations among the tested variables. In order to determine the relationship between the volumetric and the mechanical properties of pervious concrete, the total amount of results, obtained during the experimental work, were divided into 4 groups: the first one considered the three base mixes (without fine sand added); the second and the third ones referred to the mixes characterized by 5% and 10% of fine sand added; the forth group considered the results of all the tested mixes together. Separating the results permitted to analyze how the correlation between different properties varied after the

Table 3
Effects of fine−sand addition to the reference mixes: volumetric and functional properties.

		Bulk density (kg/m^3)				Void content (%)				Coeff. of permeability (mm/s)			
		5	10	15	20	5	10	15	20	5	10	15	20
MIX A	σ	4.8	186.5	242.7	11.1	0.5	1.8	0.2	1.1	0.6	2.5	6.8	8.9
MIX A s5	σ	8.7	8.5	14.2	4.7	0.25	0.75	0.15	0.79	4.63	1.91	2.28	3.41
	Δ [%]	+1.8	−1.2	+7.2	+2.3	−17.9	1.7	−10.4	−5.9	−40.4	−36.8	−11.2	−12.9
MIX As10	σ	5.5	5.7	9.9	13.9	0.9	0.8	0.5	0.6	5.1	2.0	3.2	1.6
	Δ [%]	+1.5	+2.6	+9.7	+6.7	−13.1	−12.9	−19.2	−24.7	−20.8	−52.3	−33.5	−34.0
MIX B	σ	23	34	10	28	2.2	3.5	1.0	0.6	2.7	2.5	4.9	2.2
MIX B s5	σ	16	18	25	6	1.33	0.71	0.71	0.37	4.26	3.48	3.12	1.67
	Δ [%]	−2.8	+2.0	+2.1	−0.1	+8.0	+9.1	−6.1	−11.2	+9.6	+3.2	−16.9	−17.8
MIX B s10	σ	20	22	25	13	0.7	0.8	1.1	1.9	3.8	1.7	3.2	2.3
	Δ [%]	+6.7	+10.6	+10.4	+5.9	−25.6	−22.9	−38.0	−44.2	−46.0	−52.0	−67.1	−62.7
MIX C	σ	14	12	11	6	2.6	0.1	1.9	1.1	2.0	1.6	2.9	1.8
MIX C s5	σ	20	12	7	14	0.68	0.23	0.23	0.82	5.53	4.36	2.37	9.65
	Δ [%]	+2.4	+1.0	+0.7	+1.0	−10.7	+11.8	+11.8	+5.2	+13.8	−6.2	−4.4	−36.7
MIX C s10	σ	10	24	11	19	0.4	1.5	0.9	1.1	5.1	6.4	5.0	2.9
	Δ [%]	+9.0	+6.8	+4.5	+4.2	−21.5	−2.0	+0.8	−9.2	+2.3	−17.7	−12.4	−18.5

addition of fine sand to the mixes. For each group the correlations between all the variables were calculated by mean of Pearson formula.

The correlation indices were used to develop prediction formulas to determine some interesting variables (properties of the material) by mean of the more significant volumetric and mechanical properties.

6.1. Correlation between mechanical and volumetric lab results

The correlations among void content (V_c), drainability (k), stiffness (E), strength (ITS), particle loss (C.L.), and bulk density (ρ) were studied. The correlation coefficient is the measure of the association between two random variables. Correlation coefficients range between +1 and −1 and the closer the value is to these numbers, the more strictly the two variables are related (for example, if the coefficient is close to 0, there is no relationship between the variables; if it is approximately + 1 it means that a strong direct correlation between the variables exist; if the correlation coefficient is close to −1 it signify that variables have strong inverse correlation).

The correlation matrices of each group of mixes are reported in Tables 4–7.

Table 4
Correlation coefficients between volumetric and mechanical properties of the base mixes.

	V_c (%)	k (mm/s)	E (MPa)	ITS (MPa)	C.L. (%)	ρ (kg/m^3)
V_c (%)	1	0.55	−0.63	−0.66	0.81	−0.69
k (mm/s)	0.55	1	−0.60	−0.48	0.72	−0.61
E (MPa)	−0.63	−0.60	1	0.48	−0.72	0.61
ITS (MPa)	−0.66	−0.48	0.48	1	−0.75	0.58
C.L. (%)	0.81	0.60	−0.72	−0.75	1	−0.70
ρ (kg/m^3)	−0.69	−0.50	0.61	0.58	−0.70	1

Table 5
Correlation coefficients between volumetric and mechanical properties of the mixes containing 5% of sand.

	V_c (%)	k (mm/s)	E (MPa)	ITS (MPa)	C.L. (%)	ρ (kg/m^3)
V_c (%)	1	0.87	−0.92	−0.86	0.76	−0.90
k (mm/s)	0.87	1	−0.89	−0.82	0.85	−0.84
E (MPa)	−0.92	−0.89	1	0.87	−0.85	0.83
ITS (MPa)	−0.86	−0.82	0.87	1	−0.74	0.90
C.L. (%)	0.76	0.85	−0.85	−0.74	1	−0.70
ρ (kg/m^3)	−0.90	−0.84	0.83	0.90	−0.70	1

Table 6
Correlation coefficients between volumetric and mechanical properties of the mixes containing 10% of sand.

	V_c (%)	k (mm/s)	E (MPa)	ITS (MPa)	C.L. (%)	ρ (kg/m^3)
V_c (%)	1	0.87	−0.89	−0.85	0.71	−0.90
k (mm/s)	0.87	1	−0.88	−0.87	0.84	−0.81
E (MPa)	−0.89	−0.88	1	0.90	−0.83	0.78
ITS (MPa)	−0.85	−0.87	0.90	1	−0.73	0.79
C.L. (%)	0.71	0.84	−0.83	−0.73	1	−0.62
ρ (kg/m^3)	−0.90	−0.81	0.78	0.79	−0.62	1

Table 7
Correlation coefficients between volumetric and mechanical properties of all the mixes.

	V_c (%)	k (mm/s)	E (MPa)	ITS (MPa)	C.L. (%)	ρ (kg/m^3)
V_c (%)	1	0.77	−0.82	−0.80	0.61	−0.83
k (mm/s)	0.77	1	−0.83	−0.79	0.76	−0.71
E (MPa)	−0.82	−0.83	1	0.82	−0.75	0.74
ITS (MPa)	−0.80	−0.79	0.82	1	−0.67	0.74
C.L. (%)	0.61	0.76	−0.75	−0.67	1	−0.50
ρ (kg/m^3)	−0.83	−0.71	0.74	0.74	−0.50	1

Drainability, which is one of the main features of the pervious concrete, showed an inverse correlation with all the mechanical properties (as C.L. value represented particle loss, the index was inverse with the resistance, so the sign of correlation between C.L. and k is concordant). That is, great drainability would generally result in lower mechanical performances. However, the use of additives such as reinforcing fibers [14,23] or a controlled fine sand dosage [14,17,18,35], could result in a optimum balance in which hydraulic properties were guaranteed while providing enough mechanical resistance to withstand traffic loads.

After the statistical analysis of the results, the correlation coefficients between the variables of the base mixes appeared the lower ones respect to the other subdivided group of analysis. On the other hand, great correlations resulted for 10% sand mixes. It seemed that with sand introduction, different mixes had more pre-dictable behave. The analysis of all the tested mixes together pre-sented intermediate values of the correlation coefficients.

6.2. Behavior prediction formula using multiple linear regression

A multiple linear regression, using the least-square method, was conducted to identify prediction formulas to estimate both mechanical and functional properties of pervious concrete mixes. Three descriptive variables where chosen as a response measurement (dependent variables) to develop the prediction formulas: drainability, void content, and bulk density. A multiple linear regression was calculated for each variable to find the most accurate model. The analysis of variance (ANOVA) was conducted and the accuracy criterion R^2 adjusted was determined.

First analysis aimed to identify which variables (slopes or coefficients) actually had incidence in the response measurement to eliminate the least significant coefficients in the model and to simplify the final equation to the most representative variables. It was found that the most accurate model was the one with 10% fine sand added. All the determination coefficients were between 0.85 and 0.91, which was considered enough accurate to determine a prediction formula for the material.

The prediction formula for drainability determination is reported below:

$$k\left[\frac{\text{mm}}{\text{s}}\right] = -13.37 + 1.33 * V_c\ [\%] + 0.24 * \text{CL}\ [\%]$$
$$R^2\text{adj} = 0.91$$

where k = coefficient of permeability [mm/s]; V_c = effective void content [%]; CL = Cantabro loss index [%]; R^2adj = coefficient of determination.

Resulting from this statistical analysis the two variables that had greater incidence in drainability were: void content and Cantabro Loss (the two variables in fact, present $|t|$ student values respectively 12.83 and 10.93; these $|t|$ values resulted largely greater than the critical value (tc) related to the 95% of probability (the "tc" was around 1.6 since the observations were 60 and the significance level "α" was equal to 0.05). According to the statistical analysis, the randomness probability of the correlation between the tested variables was considerably lower than 5%). According to previous studies [8] even though drainability can normally be determined by using Darcy's First Law, there is no definitive relationship between porosity and drainability. The distribution of pores has also a significant influence on drainability, as well as porosity. The Kozeny–Carman equation shows a more specific relationship between water drainability and porosity, because it includes the influential factors for drainability, such as porosity, pore-size, distribution, pore roughness, construction of the pore space, and the tortuosity and connectivity of the internal pore channel. The equation resulting from this study instead suggested how to best represent drainability in function of void content adding a mechanical parameter (i.e. Cantabro Loss).

The following formulas permitted to calculate the void content and the density knowing two representative variables (one volumetric and one mechanical property of the material).

$$V_c\ [\%] - 73.885 - 0.0006 * E\ [\text{MPa}] - 0.0228 * \rho\ \left[\frac{\text{kg}}{\text{m}^3}\right]$$

$$R^2\text{adj} = 0.85$$

where V_c = effective void content [%]; E = elastic modulus [MPa]; ρ = bulk density [kg/m^3]; R^2adj = coefficient of determination.

$$\rho = 2184.5431 - 14.5471 * V_c\ [\%] + 31.6399 * \text{ITS}\ [\text{MPa}]$$

$$R^2\text{adj} = 0.86$$

where ρ = bulk density [kg/m^3]; V_c = effective void content [%]; ITS = indirect tensile strength [MPa]; R^2adj = coefficient of determination.

The variables that better fitted to an accurate representation of void content were elastic modulus and bulk density (the influence of each variable was similar, having |t| student values respectively equal to 10.03 and 13.42). The considered variables for bulk density determination were void content and indirect tensile strength. In particular, void content presented considerably greater $|t|$ student value (equal to 12.00) while the contribution of ITS was minor, having $|t|$ student value of 2.84. All the calculated values of $|t|$ student were considerably greater than the critical value associated to the correlation probability of 95% (tc was about 1.6 and the significance level "α" was equal to 0.05) so the probability of random correlations among these variables was very low.

This latter formula was particularly interesting because it could relate two design variables (V_c and ITS) identifying, as a result of the prediction formula, the bulk density value to be achieved during construction.

7. Discussion

Several aspects were considered in the investigation of pervious concrete mix design and compaction. Not the greatest drainability or the best mechanical properties were researched [34] but an optimum balance between strength and functional capacities. In fact, specimens characterized by the optimum drainability often offered weaker mechanical properties reducing serviceability and the pavement service life [35]. On the other hand, achieving great strength significantly decreased the void content and drainability of the material. The laboratory investigation highlighted how compaction resulted to be fundamental for the ultimate pervious concrete properties; changing the applied compaction energy to the same mix could modify the mechanical and functional properties as well.

For these reasons, it was useful to analyze the effect provided by the addition of small amount of fine sand to pervious concrete mixes in order to find the way to enhance mechanical parameters with little disadvantage for functional properties.

Results pointed out that sand addition generally favor improvements in mechanical properties, and the material reached significant strength even if subjected to low compaction. Volumetric and functional properties of pervious concrete were reduced, if compared to the reference mixes, after sand was introduced but, if the appropriate compaction energy was applied, drainability could still be guaranteed. Furthermore, water to cement ratio was also proven to greatly affect sand effectiveness: the positive contribution of the sand in low-water mixes was less appreciable and, in particular, it turned to be negative if the water amount was inadequately low.

8. Conclusions

The effect of compaction energy on pervious concrete mixes was investigated during this study. Moreover, the addition of fine sand to different water-content mixes was analyzed. Four compaction steps were considered and two percentage values of sand were added to the reference mixes. The following parameters were investigated: bulk densities, void content, drainability, stiffness, tensile strength, particle-loss resistance, and surface friction. Results highlighted that:

1. the addition of sand in PCP mixtures favored in improving admissible stresses (up to +70% in tensile strength and +35% in stiffness), increasing friction (up to +9 BPN points), and reducing raveling (up to −40% in C.L.) due to a thicker coverage of the cement paste around the aggregates; although the porosity and drainability were reduced, it was possible to design mixes with both significant drainability and strength;
2. the effectiveness of sand addition also depended on the water content of the mixes: low w/c mixes did not show benefits after adding sand;
3. the same mix can provide significantly different characteristics depending on the compaction energy applied;
4. it is further recommended a full-scale investigation to identify an appropriate equivalence between laboratory and *in situ* compaction and a comparison between laboratory gyratory shear compaction and Marshall compaction applied to pervious concrete.

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