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An experimental investigation into the permeability and filter properties of pervious concrete for deep draining trenches

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Summary

The reduction of pore water pressures is one of the most effective measures that can be taken to stabilise landslides or to improve the stability conditions of marginally stable water-bearing slopes. To this end, draining trenches have been used long since. When deep trenches are needed, the usual conventional construction techniques fail and recourse must be made to secant piles or to adjacent vertical panels built by means of the methods well established for diaphragm walls. However, unbonded materials cannot be used, since the excavation of a panel adjacent to previously built ones will instabilise these latter. The problem can be solved using pervious concrete rather unbonded material. It must meet the following requirements: relatively high hydraulic conductivity, filtering capacity in order to prevent the internal erosion of the soil in which the trench drain is installed, sufficient residual hydraulic conductivity after possible clogging, sufficient shear strength after a short curing time to avoid the instabilisation of adjacent previously built panels or piles. Results of a laboratory experimental research on the mix-design, the filter capacity, residual permeability and strength of pervious concrete are reported in the paper, proving that proper mix-design can be devised meeting the above requirements; in particular, it is demonstrated that the shear strength of the concrete after a short curing time permits to excavate intermediate panels deep tens of meters without jeopardising the stability of previously built ones.

Keywords Draining trenches; Pervious concrete; Slope stabilisation; Hydraulic conductivity; Durability.

1. Introduction

The improvement of the conditions of stability of slopes in which high interstitial pressures exist can be achieved in a very effective and sustainable way by inducing an increase of effective stresses in the ground by reducing the interstitial pressures [TERZAGHI, 1950]. Many and diverse measures can be implemented to this end, such as subhorizontal drainholes, drainage galleries, and draining trenches [KENNEY *et al.*, 1977; BROMHEAD, 1984; STANIĆ, 1984; DI MAIO *et al.*, 1988; NAKAMURA, 1988; VALLI, 2000; D'ACUNTO and URCIUOLI, 2006; PUN and URCIUOLI, 2008; URCIUOLI and PIRONE, 2013; VALORE and ZICCARELLI, 2015; COTECCHIA *et al.*, 2016]. The draining trenches (also known as trench drains) [HUTCHINSON, 1977] are often the most convenient solution, at least when the slope is not very steep. Deep trenches are usually built using the equipment available for the construction of diaphragm walls and secant piles, whether shallow trenches (whose depth does not exceed about 5 metres) are usually built by means of common excavation techniques and unbonded granular material. In any case, the trenches must be hydraulically continuous. Therefore no open discontinuity and no fine-grained material should be interposed between adjacent panels or between secant piles. This problem can be easily solved using pervious (or permeable) concrete since it has sufficient shear strength and stiffness to permit the excavation of an intermediate panel in-between two previously built ones without instabilising the latter, Fig. 1.

The material used for draining trenches needs to be sufficiently permeable and to comply with filter requirements that are well known in the field of earth dams [FELL *et al.*, 2014]. Another requirement is that the granular particles of the drain should be only partially bonded so that it has true cohesion but, at the same time, interconnected pores.

Pervious concrete has been used long since for draining road pavements. Many researches have been carried out in that field, focused essentially on no-fines concrete containing very little or no sand which has high permeability but poor or no filtering properties [e.g. NEWMAN and OWENS, 2003; TENNIS *et al.*, 2004; HASELBACH et al., 2006; KEVERN, 2006; KEVERN *et al.*, 2006; KEVERN, 2008; SCHAEFER *et al.*, 2006; CHEN *et al.*, 2008; COLLINS *et al.*, 2008; HASELBACH, 2010b; ACI, 2011; MARTIN III *et al.*, 2014; MRAKOVCIC *et al.*, 2014; CHANDRAPPA and BILIGIRI, 2016; MAHESH and LAVANYA, 2016].

In this paper the term "*pervious concrete*" means a concrete with relatively high effective porosity (that refers only to hydraulically interconnected pores) made of coarse aggregates with particle diameters typically from 2 to 60mm, and of sand ($0.06 < d < 2$ mm), cement and water. The addition of sand, or fine gravel ($2.8 < d < 5$ mm), is necessary if the pervious concrete is required to function not only as draining material but as protective filter as well.

Pervious concrete differs from normal concrete as to the following properties: lower density, 1400-2000 kg/m^3 [GHAFOORI and DUTTA, 1995; MAGESWARI *et al.*, 2016], relatively low drying shrinkage (about half that of normal concrete), lower cost due to lower cement content [ABADJIEVA and SEPHIRI, 2000]. The porosity of pervious concrete ranges from 15 to 30% [ACI, 2006; HASELBACH and FREEMAN, 2006; NEITHALATH *et al.*, 2010]; the diameter of pores ranges from 1.5 to 8 mm [ACI, 2011; SOMMERVILLE *et al.*, 2011; MARTIN III *et al.*, 2013; TORRES *et al.*, 2015]. Moreover, it is a sustainable material [MOSS, 1979; NEITHALATH, 2004; PARK *et al.*, 2005; GOEL, 2006; HASELBACH, 2010a; NEITHALATH *et al.*, 2010; STARKE *et al.*, 2010; HASELBACH *et al.*, 2011; SHU *et al.*, 2011; ACPT, 2012; SRIRAVINDRARAJAH *et al.*, 2012; WELKER *et al.*, 2012; NEMIROVSKY *et al.*, 2013; SATA *et al.*, 2013; BARNHOUSE and SRUBAR, 2016].

To the authors' knowledge little research has been devoted to the permeability and filtering properties of pervious concrete for draining trenches. Results of an experimental research on pervious concrete satisfying permeability, filter and strength requirements are reported in the present paper.

2. Requirements of pervious concrete for draining trenches

Pervious concrete for draining trenches must meet the following requirements:

a) Have relatively high hydraulic conductivity to permit the needed reduction of the piezometric head inside the trench. This head is to be selected taking into account the permeability of the soil mass to be drained, the geometry of the problem (spacing of the trenches and their thickness) and the boundary conditions. The thickness of the trench must be sufficient to discharge the maximum anticipated seepage flow rate. It must not undergo unacceptable reductions in hydraulic conductivity over time, as a result of clogging by particles coming from the surrounding soil; in other terms, its residual hydraulic conductivity must be compatible with the draining function of the trench; this property is frequently referred to as durability.

b) Act as a filter to stop the erosion of the soil in which the trench is inserted.

c) Have sufficient strength after a short curing time to allow the excavation of an intermediate deep vertical panel (or secant pile) between two previously built ones, without instabilising them.

Requirement a) can be easily satisfied using no-fines concrete, but it does not comply with requirement b). Requirement c) can be satisfied by carefully increasing the cement content and decreasing the aggregate-cement ratio; however, these two decisions must be properly weighed up to avoid compromising requirements a) and b).

The main aim of the present investigation was to tailor the mix-design of the concrete in order to fit simultaneously all of the above requirements.

To realise the importance of requirement c) for draining trenches it suffices to examine the sketches in Figure 1. The depth limit of the vertical diaphragm panels as far as the side faces stability are concerned depends primarily upon the shear strength of the hardened concrete. It is well known that the height of a slope depends on the geometry of the problem, mechanical properties of soils or rocks that form the slope (stratification of soils, discontinuity etc.) and eventually constitutive minor geological and geotechnical details [TERZAGHI, 1929; ROWE,

1972; LEONARDS, 1982]; these later have a very great influence on the mechanical behaviour of the geotechnical systems [VALORE *et al.*, 2017; ZICCARELLI *et al.*, 2017].
The strength of properly mix-designed pervious concrete is high enough that vertical panels can stand up tens of meters just after a short curing time, as will be evident later (paragraph 6). This allows an efficient and cost-effective organization of the worksite.
Obviously, the vertical frontal (wider) walls of the excavation propaedeutic to the construction of the concrete panel should also be stable. To this end, the walls can be temporarily supported, when necessary, by biopolymers propaedeutic [DAY and RYAN, 1992]
It is hardly necessary to point out, finally, that the pervious concrete is an internally stable material being its particles bonded, on the contrary of what happens for filters made of cohesionless materials [REDDI *et al.*, 2005; MORACI, 2012; MORACI *et al.*, 2016].

3. Materials

The pervious concrete is a material formed by aggregates (gravel and sand), cement, water and, when necessary, additives. The mean characteristics of materials for making up the concretes used in the experimental programme are the following.

3.1 Aggregates

Sand and gravel were used for making the tested specimens of pervious concrete. Sand and gravel particles are from sub-rounded to angular. Four sands and three gravels were used; their index properties are summarised in Table 1, while their grading is shown in Fig. 2. Sands S1-S4 and gravel G1 are composed of silica; gravels G2 and G3 are calcareous; they are almost monogranular with coefficients of uniformity CU ranging from 1.41 to 1.79 for sand and from 1.17 to 1.51 for gravels.
The aggregates were dampened before mixing to facilitate the formation of a uniform cement coating on the particles' surface [NEVILLE, 1995].

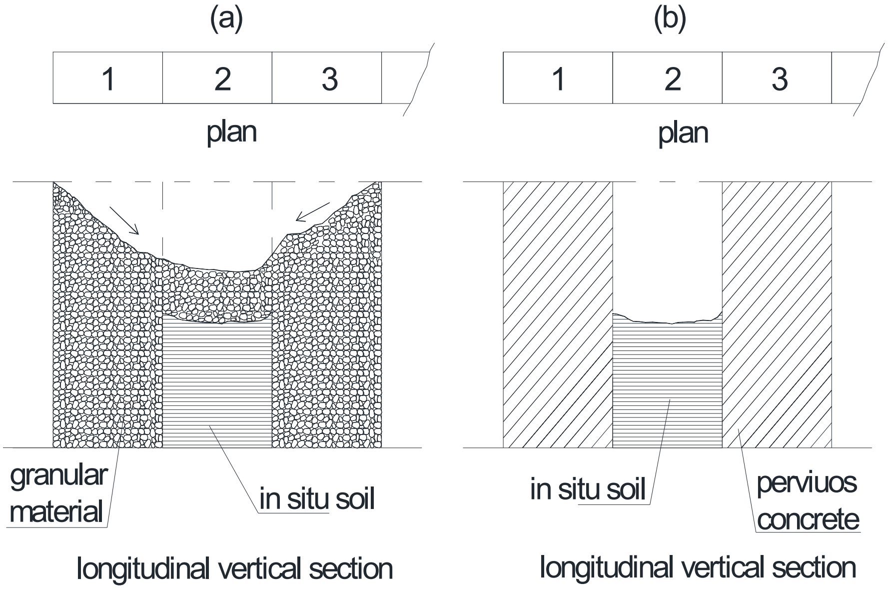


Fig. 1. Construction phases of a deep draining trench consisting of contiguous vertical panels. Firstly odd panels 1 and 3 are excavated and filled with cohesionless granular material (a) or with pervious concrete (b); then the in-between even panel 2 is excavated. In case (a) the granular material of panels 1 and 3 fails and runs down, while in case (b) pervious concrete panels 1 and 3 keep stable.

Fig. 1. Fasi costruttive di una trincea drenante profonda costituita di pannelli verticali contigui. Dapprima si scavano e si riempiono con materiale granulare (a) o con calcestruzzo permeabile (b) i pannelli dispari 1 e 3; poi si scava il pannello intermedio 2. Nel caso (a) il materiale granulare dei pannelli 1 e 3 cade giù mentre nel caso (b) i pannelli 1 e 3 rimangono stabili.

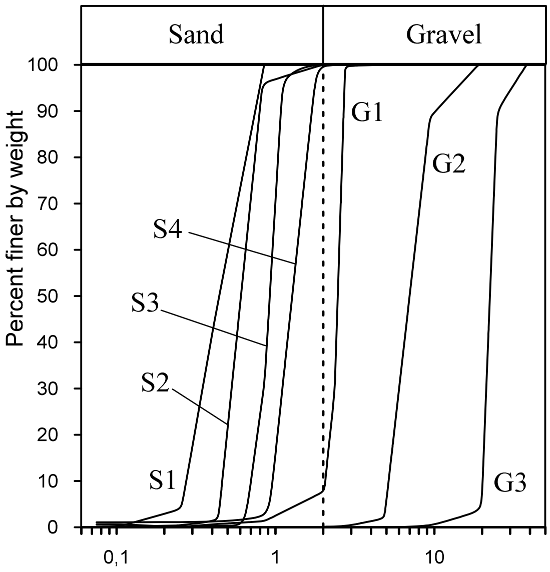


Fig. 2. Initial grading of aggregates used for pervious concrete. Sands S2 and S4 have been used for preliminary tests; their results are not reported in the paper.

Fig. 2. Composizione granulometrica iniziale degli inerti utilizzati per il confezionamento del calcestruzzo permeabile. Le sabbie S2 e S4 sono state usate per prove preliminari i cui risultati non sono riportati nella presente memoria.

Table 1. Properties of sands and gravels used for pervious concrete. n_{min} and n_{max} were determined according to ASTM standards [ASTM, 2004].

Material	Name	G_s	γ_s (kN/m^3)	d_{max} (mm)	d_{60} (mm)	d_{50} (mm)	d_{10} (mm)	d_{min} (mm)	$CU = d_{60}/d_{10}$	n_{min}	n_{max}	$\gamma_{d,\,min}$ (kN/m^3)	$\gamma_{d,\,max}$ (kN/m^3)
Sand 1	S1	2.65	26	0.85	0.50	0.45	0.28	0.075	1.79	0.388	0.473	13.7	15.9
Sand 2	S2	"	"	1.41	0.65	0.61	0.46	0.075	1.41	0.381	0.452	14.2	16.1
Sand 3	S3	"	"	2	0.99	0.95	0.60	0.075	1.4	0.377	0.444	14.5	16.2
Sand 4	S4	"	"	2	1.38	1.27	0.96	0.075	1.4	0.382	0.477	13.6	16.1
Gravel 1	G1	"	"	5	2.55	2.50	2.05	0.3	1.24	0.389	0.455	14.2	15.9
Gravel 2	G2	2.7	26.5	20	8	7.7	5.2	2	1.51	0.392	0.494	13.4	16.1
Gravel 3	G3	"	"	38	23.3	22.5	19.9	2	1.17	0.408	0.509	13	15.7

3.2 Cement

High early strength Portland cement Tecnocem II B-LL 32,5 R, (EN 197-1 – Cem II / B-LL 32,5) was used. Cement composition by mass: Clinker: 65% - 79%; limestone: 21% - 35%; TOC (total organic carbon) ≤ 0,20%; minor constituents (including sulphates such as SO_3, chlorides ≤ 0.10%).

3.2 Water

The municipal water of the City of Palermo, composed as shown in Table 2, was used.

Table 2. Chemical composition of water used for making the pervious concrete and to perform the permeability tests.

Constituent or property	Quantity
Ammonium (mg/l NH_4)	0.2
Calcium (mg/l Ca)	99
Chlorides (mg/l Cl)	48.5
Fluorides (mg/l F)	0.37
Magnesium (mg/l Mg)	2
Nitrates (mg/l NO_2)	<0.02
Nitrites (mg/l NO_3)	5.9
Potassium (mg/l K)	4.6
Sodium (mg/l Na)	161
Sulphates (mg/l SO_4)	161
pH	7.72
Alcalinity (mg/l $CaCO_3$)	194
Conductivity (20° µS/cm)	770

4. Mix-design and texture of tested pervious concrete

Mix-design was selected by trial. It was soon realised that no-fines concrete is not eligible for draining trenches since it does not meet filter requirements.

The “classical” pervious concrete (or no-fines concrete) is a composite material consisting of coarse aggregate made of gravel with no or a very small amount of sand, Portland cement and water. The texture of this kind of concrete is exemplified in Fig. 3a, in which point-to-point contacts between gravel particles, the large size of pores and their interconnection can be clearly noticed.

The texture of a pervious concrete made of gravel, sand, cement and water (shown in Fig. 3b) is quite different as to grain-to-grain contacts and especially as to the size of pores that are smaller than the ones in Fig. 3a; moreover, the possible flow paths are more tortuous.

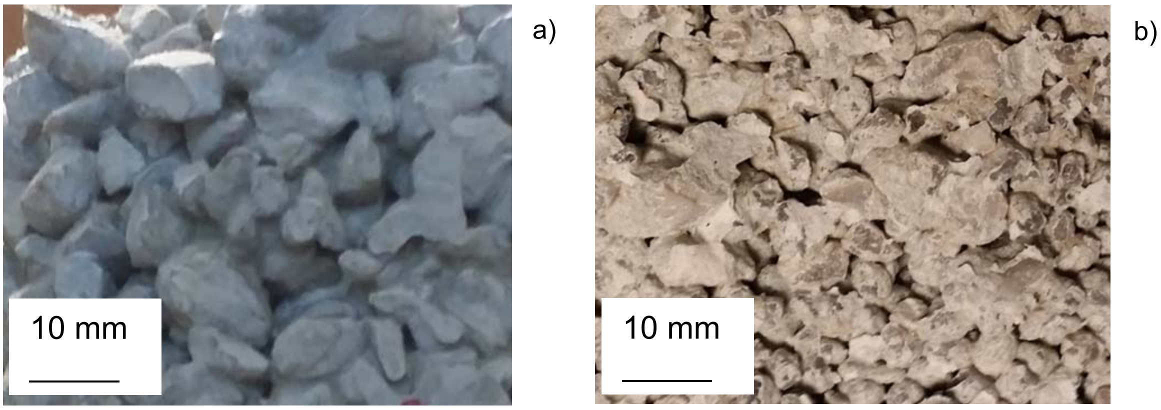


Fig. 3. Texture of pervious concrete made of monogranular coarse aggregates (gravel) and cement a), and of pervious concrete made of monogranular gravel, sand, cement paste and water b).

Fig. 3. a) Struttura di un calcestruzzo permeabile confezionato con ghiaia monogranulare, cemento e acqua. Struttura del calcestruzzo permeabile confezionato con ghiaia monogranulare, sabbia, cemento e acqua b).

Simple schemes of pervious concrete are shown in Fig. 4. The pores are interconnected and form a three-dimensional system, that is a continuous (even though multiconnected) space; therefore, it is possible for flow paths to bypass pores that happen to be clogged by solid particles dragged by the seeping water.

The water-cement ratio W/C was varied between 0.3 and 0.5. Although a value of W/C=0.3 is sufficient for the complete formation of the chemical bonds, for good workability and pumpability, a value of W/C equal to about 0.4 is needed. Larger values of W/C can result in better fluidity of the concrete and thus a better workability and pumpability but it can easily lead to the formation of lenses made of cement paste, as shown in figures 5 and 6.

The presence of such lenses may decrease or even jeopardise the functionality of the draining trenches.

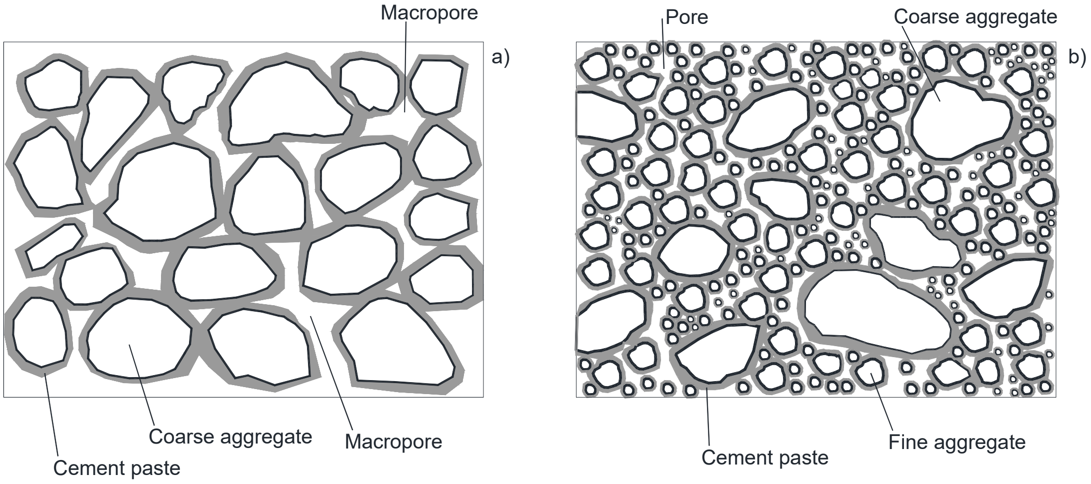


Fig. 4. Texture of pervious concretes: a) made of coarse aggregates, cement and water (no-fines concrete); b) made of coarse aggregates, sand, cement and water.
Fig. 4. Struttura del calcestruzzo permeabile: a) confezionato con pasta di cemento e aggregati grossi (ghiaia) e cemento; b) confezionato con aggregati ghiaia, sabbia, cemento e acqua.

Fig. 5. Segregation of pervious concrete made of gravel G3 (see Fig.2) and cement, with water/cement ratio W/C=0.5. The cement paste flows down due to the high W/C ratio and forms an almost impervious lens.
Fig. 5. Segregazione del calcestruzzo permeabile confezionato con ghiaia e cemento con rapporto acqua/cemento piuttosto alto e pari a 0.5. La pasta cementizia fluisce in gran parte verso il basso e forma una lente pressoché impermeabile.

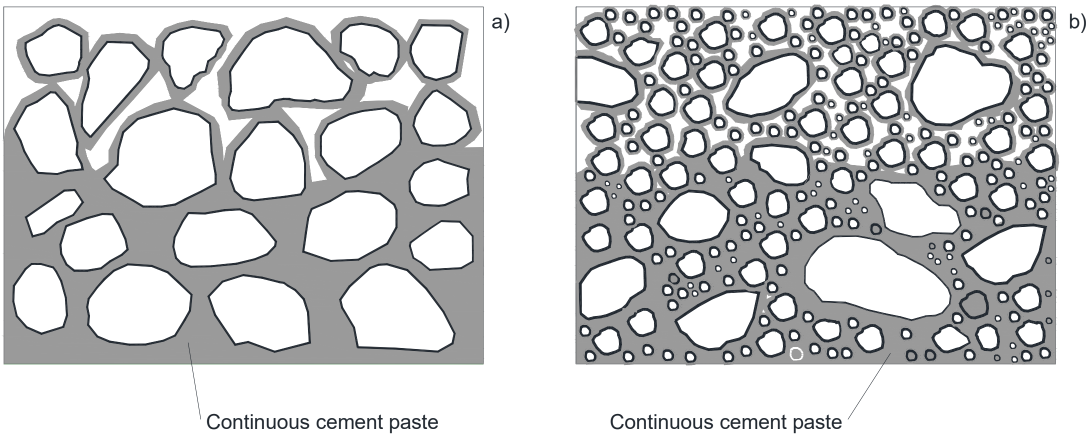


Fig. 6. Segregation of pervious concrete due to high water/cement ratio and/or vibration. Segregation can take place in concrete made of gravel (a) as well as in concrete made of gravel and sand (b).
Fig. 6. Segregazione del calcestruzzo permeabile causata da un alto rapporto acqua/cemento e/o da vibrazione del calcestruzzo. La segregazione può verificarsi sia nel calcestruzzo formato con ghiaia (a) sia in quello formato con ghiaia e sabbia (b).

5. Placing, curing and grain-size distribution of aggregates of the mixtures

It is commonly thought that pervious, and especially no-fines concrete, can be dropped from considerable height without causing segregation. However, this is not the case for pervious concrete containing both gravel and sand nor for no-fines concrete: in fact, the cement paste may separate from the aggregates and tend to form almost impervious lenses. It is therefore clear that in deep trenches pervious concrete must be poured by the tremie pipe method.

The specimens tested within the scope of the present research were made by placing the concrete from very small height and without vibrating or compacting it. Concrete was placed in cylindrical PVC containers with inner diameter and height of 135mm and 300 mm respectively. Specimens were cured in air in the laboratory at temperatures varying from 20 to 22 °C.

The grain size distribution of the aggregates used for making up the pervious concretes are shown in Fig. 7; their mean characteristics and the type of test performed on them are summarised in Table 3.

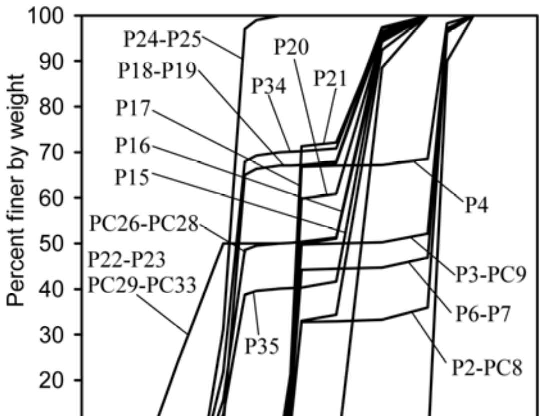


Fig. 7. Grain-size distribution of aggregates used for making up the tested pervious concrete specimens.

Fig. 7. Composizione granulometrica degli aggregati utilizzati per preparare le miscele di calcestruzzo permeabile utilizzato nella sperimentazione.

Table 3. Mix-design of tested concretes and types of test. (Legend: C: clogging; P: permeability; U C: uniaxial compression). Grading of aggregates shown in Fig. 7.

Mix	Aggregate 1 f_1	Aggregate 2 f_2	f_2/ f_1	Cement content C (kg/m^3)	A/C	W/C	Curing time (days)	Type of test
P2	G3	G1	0.5	300	6.8	0.4	28	P
P3	G3	G1	1	300	6.5	0.4	28	P
P4	G3	G1	2	300	6.8	0.4	28	P, C
P6	G3	G1	1.25	300	6.5	0.5	28	P
P7	G3	G1	1.25	300	6.5	0.4	28	P
P13	G3	-	-	300	6.8	0.4	28	P
P14	G2	-	-	300	6.8	0.4	28	P
P15	G2	G1	0.5	300	6.8	0.4	28	P
P16	G2	G1	1	300	6.8	0.4	28	P
P17	G2	G1	2	300	6.8	0.4	28	P
P18	G2	S3	2	150	14.9	0.4	28	P
P19	G2	S3	2	200	10.9	0.4	28	P, C
P20	G2	G1	1.5	300	6.8	0.4	28	P
P21	G2	G1	2.5	300	6.8	0.4	28	P
P22	G2	S1	1	300	6.8	0.4	28	P
P23	G2	S1	1	200	10.9	0.4	28	P
P24	-	S3	-	322	4.6	0.4	28	P
P25	-	S3	-	215	6.9	0.4	28	P
PC8	G3	G1	0.5	204	6.6	0.5	28	U C
PC9	G3	G1	1	225	6.7	0.5	45	U C
PC26	G2	S3	1	187	10.1	0.4	42	U C
PC27	G2	S3	1	241	7.7	0.4	42	U C
PC28	G2	S3	1	312	6.1	0.5	42	U C
PC29	G2	S1	1	170	10.8	0.4	42	U C
PC30	G2	S1	1	227	8.1	0.4	42	U C
PC31	G2	S1	1	227	8.1	0.4	42	U C
PC33	G2	S1	1	187	8.1	0.4	3-31	U C
PC34	G2	S3	0.67	200	9.5	0.4	1	U C, P, C
PC35	G2	S3	2.33	200	9.5	0.4	2	U C, P, C

6. Strength and stiffness of pervious concrete

The strength and stiffness of the tested concretes were determined by means of 22 uniaxial compression tests. The properties of the concrete and the results of the tests are summarised in Table 3. The diameter of the specimens range from 95 mm to 135.76 mm, their height from 92.72mm to 169.65mm.

Table 4. Composition, properties and uniaxial compression strength σ_f of pervious concrete. A/C: aggregate/cement ratio; W/C: water/cement ratio

Test	Mix	Aggregate 1 f_1	Aggregate 2 f_2	f_2/ f_1	Cement content C (kg/m^3)	A/C	W/C	Curing time (days)	Specimen	Diameter *D* (mm)	Height *L* (mm)	γ_d (kN/m^3)	σ_f (MPa)
1	PC8	G3	G1	0.5	204	6.6	0.5	28	P8C-1	95	166.03	16.7	0.49
2									P8C-2	96	165.43	16.6	1.08
3									P8C-3	95.5	165.13	16.7	1.06
4	PC9	G3	G1	1	225	6.7	0.5	45	P9C-1	95.35	169.65	16.8	0.49
5									P9C-2	95.60	169.32	16.6	0.65
6									P9C-3	95.98	169.27	16.7	0.46
7	PC26	G2	S3	1	187	10.1	0.4	42	P26C-1	96.5	115.54	19	2.86
8									P26C-2	95.98	118.70	19.5	2.58
9	PC27	G2	S1	1	241	7.7	0.4	42	P27C-1	95.81	118.7	19.8	3.14
10									P27C-2	96.56	115.43	19.7	3.08
11	PC28	G2	S3	1	312	6.1	0.5	42	P28C-1	95.69	118.73	19.8	6.05
12									P28C-2	95.81	121.86	19.9	6.83
13	PC29	G2	S1	1	170	10.8	0.4	42	P29C-1	96.10	120.96	19.1	1.99
14									P29C-2	97.29	123.6	19.6	2.12
15	PC30	G2	S1	1	227	8.1	0.4	42	P30C-1	97.30	113.75	18.5	2.17
16									P30C-2	96.39	121.23	19	1.91
17	PC31	G2	S1	1	284	6.5	0.4	47	P31C-1	96.46	117.41	19.5	4.08
18									P31C-2	96.89	116.9	19.8	4.98
19	PC33	G2	S1	1	187	10.2	0.4	3	P33C-1	96.39	92.74	19.9	1.80
20								12	P33C-2	96.37	92.72	20	4.66
21								14	P33C-3	96.40	95.14	19.1	5.17
22								31	P33C-4	96.62	94.74	19	7.30
23	PC34	G2	S3	2.33	200	9.5	0.4	1	PC34-1	135.76	121.82	15.8	0.74
24	PC35	G2	S3	0.67	200	9.5	0.4	2	PC35-1	135.76	121.82	14.6	0.81

The high variability of the uniaxial compressive strength ($0.49 \leq \sigma_f \leq 7.44$ MPa) of pervious concrete depends on many factors such as water-cement ratio (W/C), aggregate-cement ratio (A/C), cement content (C), grading of aggregates and curing time. These factors are interdependent and determine the structure, texture, unit weight, porosity, pore distribution and size of pores, that are the main features that determine the values of the uniaxial strength σ_f of pervious concrete.

Some stress-strain curves of concretes differing as to composition and W/C and A/C ratios for curing time ≥ 28 days are shown in Fig. 8. These data demonstrate the high influence of the cement content (C), aggregate-cement ratio (A/C), and of grading of aggregates on the uniaxial compressive strength σ_f and on stiffness (Young's modulus) of pervious concrete.

The influence of curing time on uniaxial compressive strength and on stress-strain relationship is exemplified by Fig. 9 where results of tests on four specimens having the same mix (P33C) but different curing time are shown. The uniaxial compressive strength markedly increases with curing time, from 1.8 MPa after 3 days to 7.3 MPa after 31 days.

The influence of the aggregate/cement ratio A/C and cement content C on σ_f is considerable as shown in figures 10 and 11. In particular, higher σ_f values have been found for high cement content and low A/C ratio, while lower σ_f values have been obtained for low cement content C and high A/C ratios. These results seem to be independent from the type of mixture. In Fig. 12 the relationship between σ_f and the dry unit weight γ_d is shown. σ_f increases with γ_d. It is to be noted that γ_d increases when A/C decreases, if other factors (W/C, C, grading of aggregates) are constant.

The mean secant Young's modulus *E* of the 22 tested pervious concrete specimens ranges from 250 to 1360 MPa. *E* increases with C and decreases with both A/C and W/C ratios, it increases, with curing time, from 225 MPa to 900 MPa and 1200 MPa after 3, 14 and 31 days, respectively. Poisson's ratio ν is approximately 0.2. The above results are in good agreement with data reported in literature for no-fines concrete of similar void ratio [e.g. GHAFOORI and DUTTA, 1996; ABADJIEVA and SEPHIRI, 2000; KEVERN *et al.*, 2008; SOMMERVILLE *et al.*, 2011; ALAM *et al.*, 2012; KEVERN and FARNEY, 2012; SINGH and SCANLON, 2013; THAKRE *et al.*, 2014; USHANE *et al.*, 2014; ZHONG and WILLE, 2016].

The limit depth h_{crit} of the panels constituting the draining trench may be easily calculated according to PASTOR *et al.* [2000] if the concrete is considered, for simplicity as a purely cohesive material:

$$h_{crit} = \frac{3.8\,c}{\gamma_c} \qquad (1)$$

If a conservative characteristic value of σ_f=0.3 MPa for a curing time of 1 day is selected, a critical height of 28.5m results for c=σ_f/2=150 kPa and γ_c=20 kN/m^3; c and γ_c being, respectively the true cohesion and the unit weight of concrete.

In this calculation, partial factors of safety have been considered equal to 1, and 3D effects disregarded for the sake of simplicity.

This example proves that very deep trenches can be built safely and without long delays in the excavation of the even (or intermediate) panels as defined in Fig. 1. This considerably favours an efficient planning of the construction site.

It must be added that when draining trenches are built to stabilise landslides, if they are positioned parallel to the line of maximum slope (i.e. they are "counterfort drains") and are keyed into the underlying stable ground, the shear strength of the pervious concrete may contribute significantly to the stabilisation of the landslide, since the trenches act as "shear keys". This contribution depends on the shear strength of the concrete, and on many other factors such as the thickness and the spacing of the trenches, the shear strength and the stiffness of the ground into which the concrete panels are keyed.

On the contrary, when trenches are constructed transverse to the direction of slope (i.e. they are interceptor drains) "the excavation for the trench made into a pre-existing landslide cut a slot normal to the direction of sliding. Since almost all landslide (including translational landslides) have a net balance of slightly more driving force at their upper end and thus rely on net resistance at the lower end, the cutting of a trench through the landslide reduces support to the ground above the trench. If deep enough the trench excavation renew landslide activity even when the groundwater levels are seasonally low" [CORNFORTH, 2005].

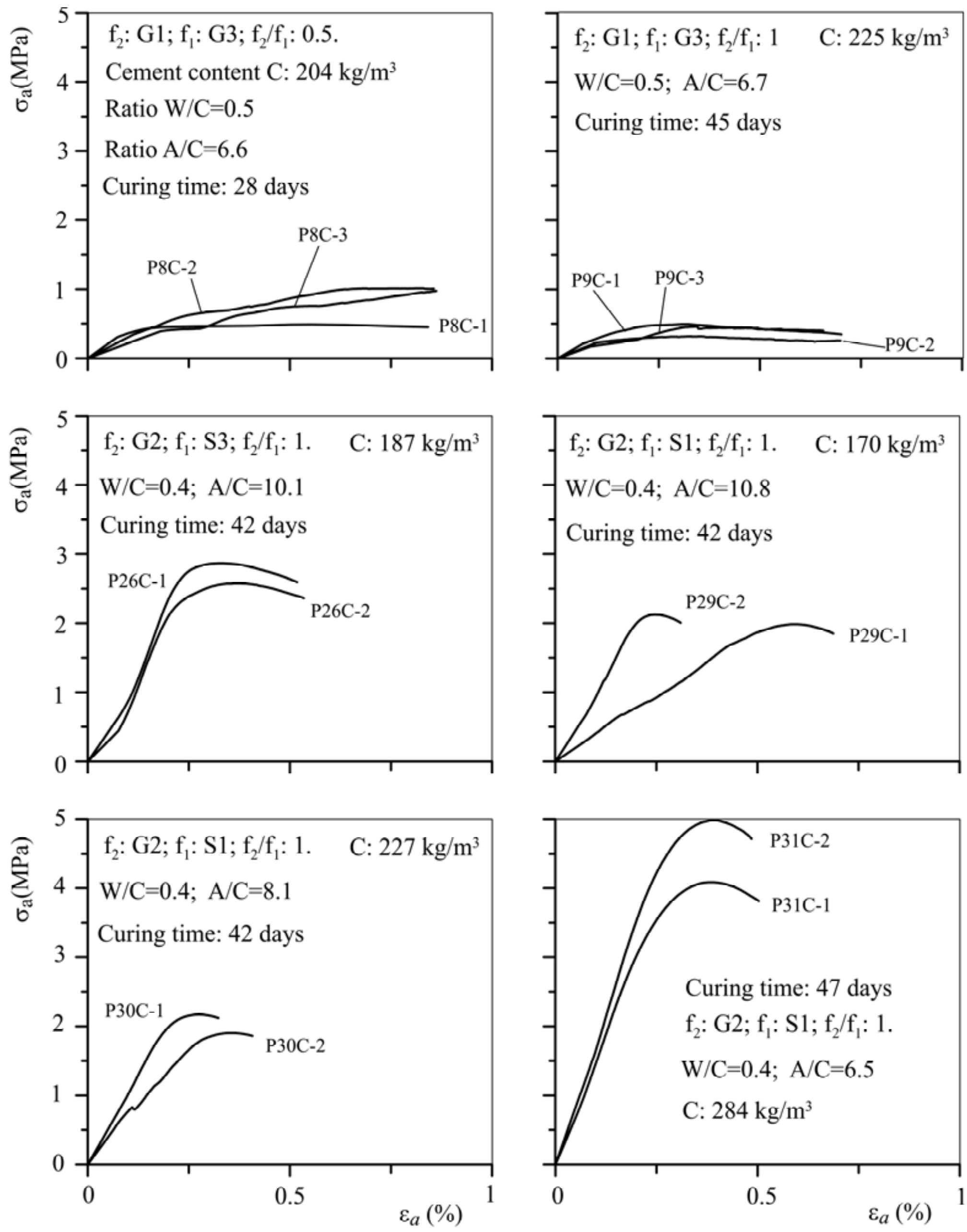


Fig. 8. Stress-strain curves from uniaxial compression tests on different types of pervious concrete and for various curing times. F1

f_1 and f_2: granulometric fractions relative to aggregates; σ_a: applied axial pressure; ε_a: axial deformation. Other symbols: see notation.

Fig. 8. Curve tensione – deformazione ottenute con prove di compressione semplice su differenti tipi di calcestruzzo permeabile e per vari tempi di maturazione.

f_1 e f_2: frazioni granulometriche relative agli inerti; σ_a: pressione assiale applicata; ε_a: deformazione assiale. Altri simboli: v. elenco dei simboli.

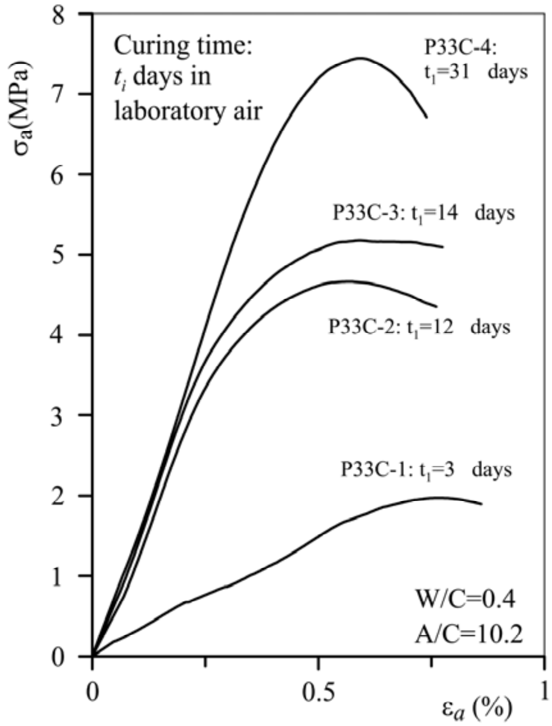


Fig. 9. Influence of curing time on the uniaxial compressive strength σ_f and on stress-strain relationship. Pervious concrete P33C composition: gravel G2: granulometric fraction f_1; sand S1: granulometric fraction f_2; ratio f_2/f_1= 1. Portland cement content: 187 kg/m^3; water/cement ratio W/C=0.4; aggregate/cement ratio A/C=10.2.

Fig. 9. Influenza del tempo di maturazione sulla resistenza a compressione semplice σ_f *e sul legame tensione-deformazione. Calcestruzzo permeabile P33C confezionato come segue: frazione granulometrica* f_1*: ghiaia G2; frazione granulometrica* f_2*: sabbia S1; rapporto* $f_2/f_1=1$*; dosaggio di cemento Portland: 187 kg/m*^{3}*; rapporto acqua/cemento W/C=0.4; rapporto ponderale inerti/cemento A/C=10.2.*

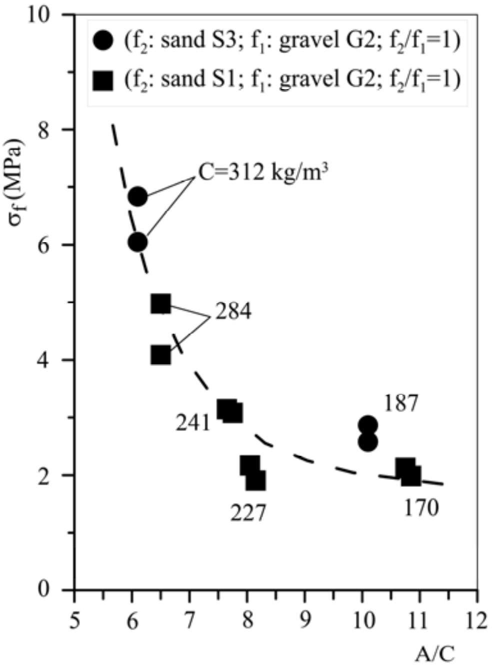


Fig. 10. Uniaxial strength σ_f *vs* aggregate-cement ratio A/C. Water-cement ratio W/C=0.4. Cement content from 170 to 312 kg/m^3. Curing time:≥ 42 days. Size of specimens: see Tab. 4.

Fig. 10. Resistenza a compressione uniassiale σ_f in funzione del rapporto ponderale aggregati/cemento A/C. Rapporto acqua/cemento:0.4. Contenuto di cemento da 170 a 312 kg/m^3. Tempo di maturazione ≥42 giorni. Dimensioni dei provini: vedi Tab. 4.

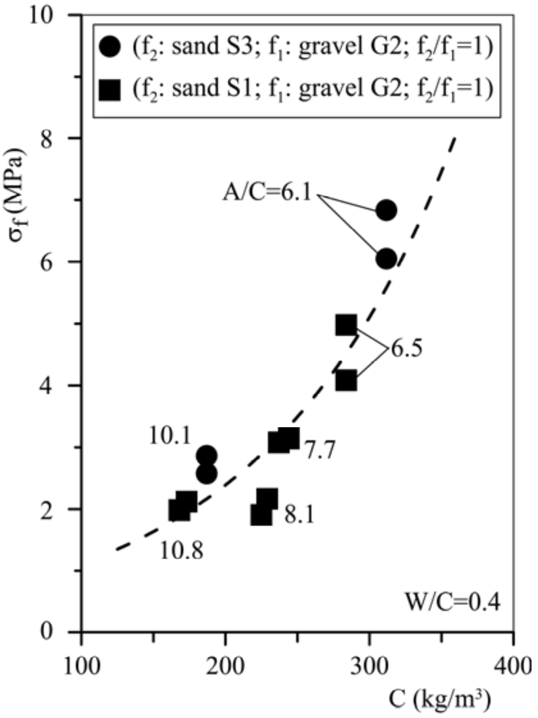


Fig. 11. Uniaxial strength σ_f *vs* cement content C. Curing time:≥ 42 days in laboratory air. Size of specimens: see Tab. 4.

Fig. 11. Resistenza a compressione uniassiale σ_f in funzione del dosaggio di cemento C. Tempo di maturazione : ≥42 giorni. Dimensioni dei provini: vedi Tab. 4.

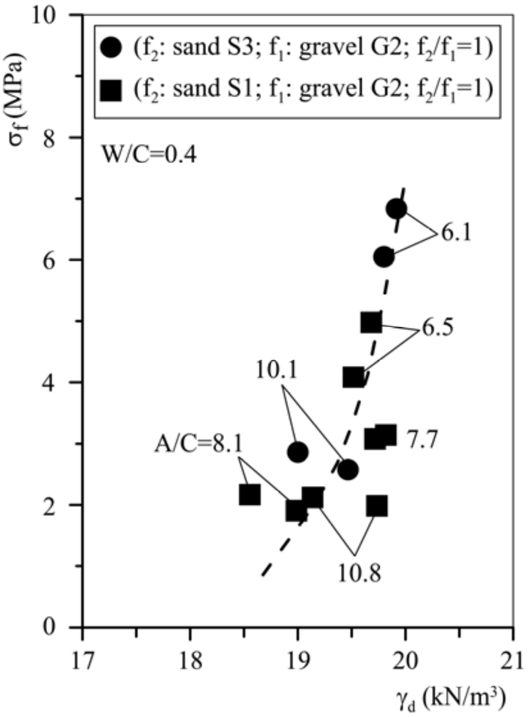


Fig. 12. Uniaxial strength σ_f *vs* dry unit weight γ_d of pervious concrete. Curing time:≥ 42 days. Size of specimens: see Tab. 4.

Fig. 12. Resistenza a compressione uniassiale σ_f *in funzione del peso secco dell'unità di volume* γ_d *del calcestruzzo permeabile. Tempo di maturazione: ≥42 giorni. Dimensioni dei provini: vedi Tab. 4.*

7. Hydraulic conductivity and filter properties

7.1 Permeability

The hydraulic conductivity was determined by means of a falling head permeameter, Fig. 13. Similar tests have been carried out on no-fines concrete by Neithalath [2004], Kevern [2008], Deo *et al.* [2010] Ibraim *et al.* [2014]; Martin III *et al.* [2014], Chandrappa and Biligiri [2016], West *et al.* [2016].

The lateral surface of the specimens was waterproofed with a thin layer of polyurethanic resin, in order to achieve 1-D seepage conditions.

Before performing the permeability tests, the concrete specimens were submerged in water for at least 24 hours, and once they were placed in the permeameter, a series of preliminary tests were carried out to saturate them.

The hydraulic conductivity k was determined by the following well known relation, see Fig. 13:

$$k = \frac{A_1 L}{A_2(t-t_0)} ln(\frac{h_0}{h_t}) \qquad (2)$$

in which A_1 and A_2 are the areas of the cross section of the specimen and of the graduated cylinder tube of the permeameter, respectively (in this case A_1=A_2); L is the sample height; h_0 and h(t) are the initial and the current piezometric heads, at time t_0 and t, respectively. This relation is valid under the assumption of laminar flow and validity of Darcy's law; Montes and Haselbach

[2006] demonstrated that the flow in pervious concrete falls within the laminar or in the transitory domain.

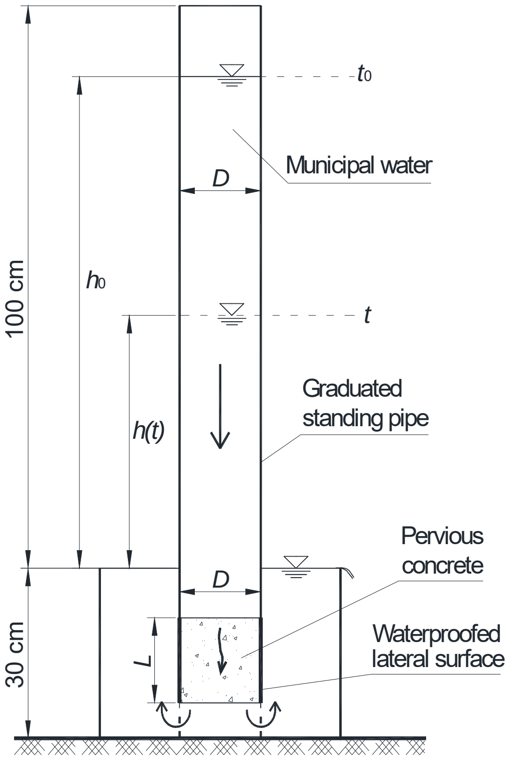


Fig. 13. Falling head permeameter for testing 135 mm diameter specimens of pervious concrete. The lateral surface of specimens was waterproofed by polyurethanic resin; the flow is therefore 1-D. The base of the perspex standpipe rests on three small legs.

Fig. 13. Permeametro a carico variabile utilizzato per le prove su provini di calcestruzzo permeabile del diametro di 135 mm. La superficie laterale del provino è stata impermeabilizzata con resina poliuretanica, il moto di filtrazione è quindi 1-D. Il tubo di perspex poggia su tre piedini.

More than 100 tests have been performed. Some test results are summarised in Tables 5 and 6. The texture of some pervious concrete specimens is documented in Fig. 14.

Table 5. Results of the first series of permeability tests on pervious concrete. The curing time of specimens is higher or equal to 28 days. Diameter of specimens *D*=135.76mm; height of specimens *L*=120mm. *i*: hydraulic gradient; *n*: porosity; *G*1, *G*2, *G*3: gravels, see Fig. 2.

Mix	Aggregate 1 f_1	Aggregate 2 f_2	f_2/f_1	Cement content C (kg/m^3)	W/C	A/C	*n*	Test	*k* (cm/s) mean values for the intervals of *i* shown below			
									0-0.2	0.2-0.5	0.5-1	1-5
P2	G3	G1	0.5	300	0.4	6.8	0.25	P2A-1	-	-	-	0.041
								P2A-2	-	-	-	0.042
								P2A-3	-	-	-	0.043
								P2A-4	-	-	-	0.042
							0.31	P2B-1	-	0.35	0.21	0.125
								P2B-2	0.47	0.32	0.19	0.13
P3	G3	G1	1	300	0.4	6.5	0.32	P3A-2	0.54	0.32	0.21	0.15
								P3A-3	0.39	0.26	0.19	0.13
							0.37	P3B-1	-	-	-	0.19
								P3B-2	-	-	-	0.18
								P3B-3	-	-	-	0.18
								P3B-4	0.43	0.31	0.23	0.15
P4	G3	G1	2	300	0.4	6.8	0.32	P4A-1	-	-	-	0.11
								P4A-2	-	-	-	0.11
								P4A-3	-	-	-	0.106
								P4A-4	-	0.33	0.19	0.105
							0.33	P4B-1	-	0.32	0.21	0.12
P6	G3	G1	1.25	300	0.5	6.5	0.25	P6A-1	-	0.081	0.048	0.023
								P6A-2	-	0.084	0.051	0.024
								P6A-3	-	0.079	0.049	0.025
								P6A-4	0.135	0.066	0.044	0.022
P7	G3	G1	1.25	300	0.4	6.5	0.32	P7A-1	-	0.088	0.057	0.029
								P7A-2	-	0.087	0.055	0.029
								P7A-3	-	-	0.048	0.027
								P7A-4	-	-	0.050	0.027
								P7A-5	-	0.088	0.051	0.027
P13	G3	-	-	300	0.4	6.8	0.43	P13A-1	8.32	6.03	-	-
								P13A-2	8.25	5.98	2.25	-
							0.39	P13B-1	8.06	-	-	-
								P13B-2	-	8.99	7.01	-
P14	G2	-	-	300	0.4	6.8	0.44	P14A-1	8.28	6.09	-	-
								P14A-2	8.35	6.49	4.01	-
P15	G2	G1	0.5	300	0.4	6.8	0.43	P15A-1	5.46	2.95	-	-
P16	G2	G1	1	300	0.4	6.8	0.39	P16A-1	3.62	1.06	0.94	0.70
P17	G2	G1	2	300	0.4	6.8	0.43	P17A-1	2.24	1.68	1.44	-
								P17A-2	3.97	2.24	1.58	0.85

Table 6. Results of the second series of permeability tests on pervious concrete. The curing time of specimens is higher or equal to 28 days. Water-cement ratio W/C=0.4; Diameter of specimens *D*=135.76 mm, height of specimens *L*=120mm. *i*: hydraulic gradient; *n*: porosity; *G*1, *G*2, *G*3: gravels; S1, S3: sands. See Fig. 2.

Mix	Aggregate 1 f_1	Aggregate 2 f_2	f_2/ f_1	Cement content C (kg/m^3)	A/C	*n*	Test	*k* (cm/s) mean values for the intervals of *i* shown below			
								0-0.2	0.2-0.5	0.5-1	1-5
P18	G2	S3	2	150	14.9	0.39	P18A-1	1.17	0.91	0.77	0.58
							P18A-2	1.13	0.87	0.74	0.55
							P18A-3	1.11	0.94	0.86	0.71
							P18A-4	1.12	0.95	0.85	0.70
P19	G2	S3	2	200	10.9	0.34	P19A-1	0.88	0.69	0.60	0.46
							P19A-2	0.80	0.64	0.56	0.44
							P19A-3	0.96	0.78	0.68	0.54
							P19A-4	1	0.8	0.69	0.53
P20	G2	G1	1.5	300	6.8	0.27	P20A-1	2.15	1.33	0.99	0.58
							P20A-2	1.98	1.26	0.96	0.58
							P20A-3	1.97	1.22	0.92	-
							P20A-4	1.95	1.20	0.89	-
P21	G2	G1	2.5	300	6.8	0.33	P21A-1	3.08	1.85	1.35	-
							P21A-2	3.08	1.86	1.35	-
							P21A-3	2.68	1.68	1.39	-
							P21A-4	2.77	1.79	1.37	-
P22	G2	S1	1	300	10.9	0.39	P22A-1	0.027	0.024	0.022	0.019
							P22A-2	0.026	0.024	0.023	-
							P22A-3	0.027	0.022	0.019	-
							P22A-4	0.026	0.021	0.017	-
P23	G2	S1	1	200	10.9	0.34	P23A-1	0.031	0.024	0.022	-
							P23A-2	0.029	0.019	0.018	-
							P23A-3	0.032	0.026	0.024	-
							P23A-4	0.029	0.026	0.024	-
P24	-	S3	-	322	4.6	0.25	P24A-1	0.111	0.055	0.031	-
P25	-	S3	-	215	6.9	0.37	P25A-1	0.19	0.17	0.15	0.13
							P25A-2	0.19	0.16	0.15	0.12
							P25A-3	0.18	0.16	0.14	0.12
							P25A-4	0.17	0.15	0.14	0.11
PC34	G2	S3	2.33	200	9.5	0.44	PC34-1	1.08	0.89	0.78	0.62
PC35	G2	S3	0.67	200	9.5	0.48	PC35-1	1.26	1.01	0.89	0.68

Fig. 14. Texture of perviuos concrete of some specimens tested for permeability. The specimen 13B (a) is made of gravel G3; the specimen 10C (b) is made of gravel G2; other features: W/C=0.4; A/C=6.8; C=300 kg/m^3 (Table 5). Features of specimens 18A (c) and 19A (d) specified in Table 6. Nominal diameter of specimens:135mm.

Fig. 14. Struttura di alcuni provini di calcestruzzo permeabile assoggettati a prove di permeabilità. Il provino 13B (a) è stato confezionato con ghiaia G3, il provino 10C con ghiaia G2; altre caratteristiche: W/C=0.4; A/C=6.8; C=300 kg/m^3 (cfr. Tab. 5). Le caratteristiche dei provini 18A (c) e 19A (d) sono indicate in Tab. 6. Diametro nominale dei provini: 135mm.

The hydraulic conductivity *k* ranges in a wide interval, from 0.022 to 8.99 cm/s for the specimens of the first series (Table 5) and from 0.019 to 3.08 cm/s for the specimens of the second series (Table 6). The values of the coefficient of hydraulic conductivity *k* depends on the grading of the aggregates, the water-cement ratio W/C (it increases as the ratio W/C decreases) the aggregates-cement ratio A/C (*k* is higher for higher A/C ratios), the cement content C (*k* is lower for higher values of C). These factors are interdependent and all influence the texture, the distribution and the size of pores, the porosity *n* of the concrete. The hydraulic conductivity *k* increases with *n*. *k* depends also on the hydraulic gradient *i*: it decreases when *i* increases, as reported for other pervious concretes by Chandrappa and Biligiri [2016].

Typical results are shown in figures 15 and 16 for different maximum values of *i* reached during the test and for different mixes of the concrete. In particular, the results relative to specimens made by coarse aggregates (only gravel) are reported in Fig. 15; *v* increases with the coarseness of aggregates. The same trends hold for other mixes as shown in Fig. 16. Data for *i* ranging from 0 to 1 - that is the range of hydraulic gradient of greatest interest for practical applications – are reported in figure 17.

The relationship between v and i is not linear, as found by other researchers [e.g. MARTIN III *et al.*, 2014; WEST *et al.* 2016]; it can be expressed by the following exponential expression:

$$v = k^* i^b \tag{3}$$

in which k^* and b depend on the mix of the concrete which influences flow characteristics such as the tortuosity of seepage paths, the effective porosity (i.e. related only to the interconnected pores), turbulence, etc. [e.g. CHANDRAPPA and BILIGIRI, 2016; WEST *et al.*, 2016]. The coefficient k^* varies in a wide range, from about 0.03 to about 1.3; increases with the coarseness of aggregates. b ranges from 0.6 to 0.99 and is higher when the coarseness of the aggregates is lower.

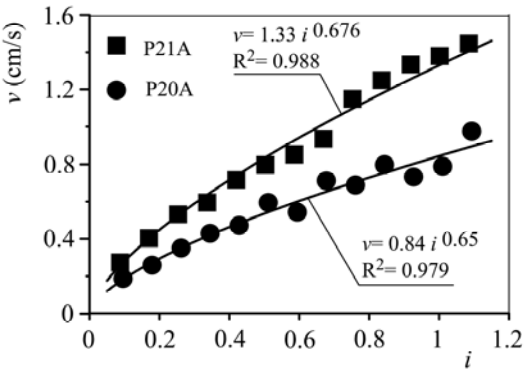
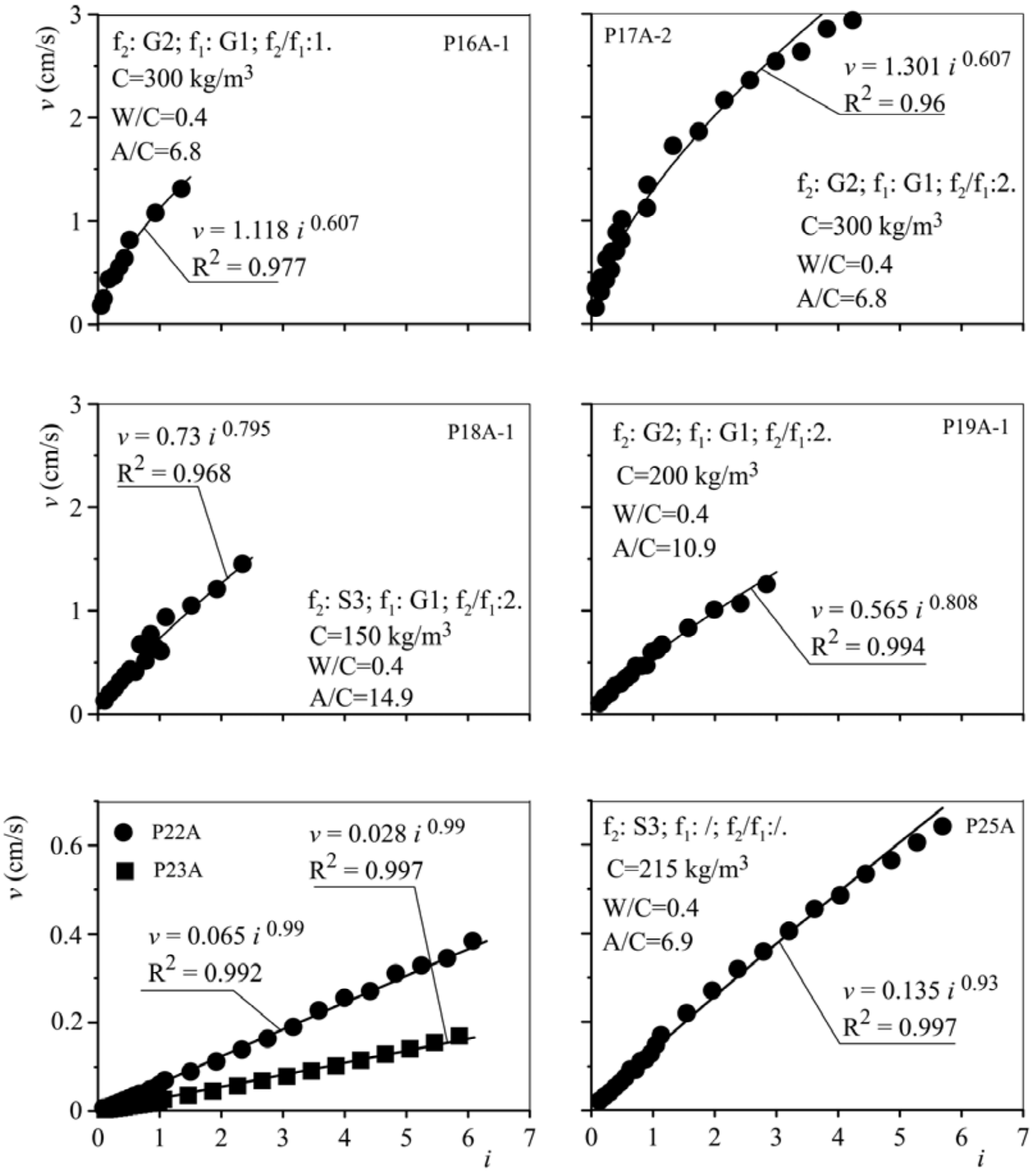


Fig. 15. Nominal seepage velocity v *vs* hydraulic gradient i, for i from 0.1 to 1.1. Specimen P20A composition: gravel G2 (granulometric fraction f_1); gravel G1 (f_2); ratio f_2/f_1= 1.5. Specimen P21A composition: gravel G2 (f_1); gravel G1 (f_2); ratio f_2/f_1= 2.5. Other features of both specimens: Portland cement content: 300 kg/m^3; water/cement ratio W/C=0.4; aggregate/cement ratio A/C=6.8.

Fig. 15. Velocità di filtrazione nominale v in funzione del gradiente idraulico i, per valori di i compresi tra 0.1 e 1.1. Composizione del provino P20A: ghiaia G2 (frazione granulometrica in peso f_1*); ghiaia G1 (*f_2*); rapporto* f_2/f_1*= 1.5. Composizione del provino P21A: ghiaia G2 (*f_1*); ghiaia G1 (*f_2*); rapporto* f_2/f_1*= 2.5. Le altre caratteristiche di entrambi i provini sono: dosaggio di cemento Portland: 300 kg/m*^{3}*; rapporto acqua/cemento W/C=0.4; rapporto inerti/cemento A/C=6.8.*

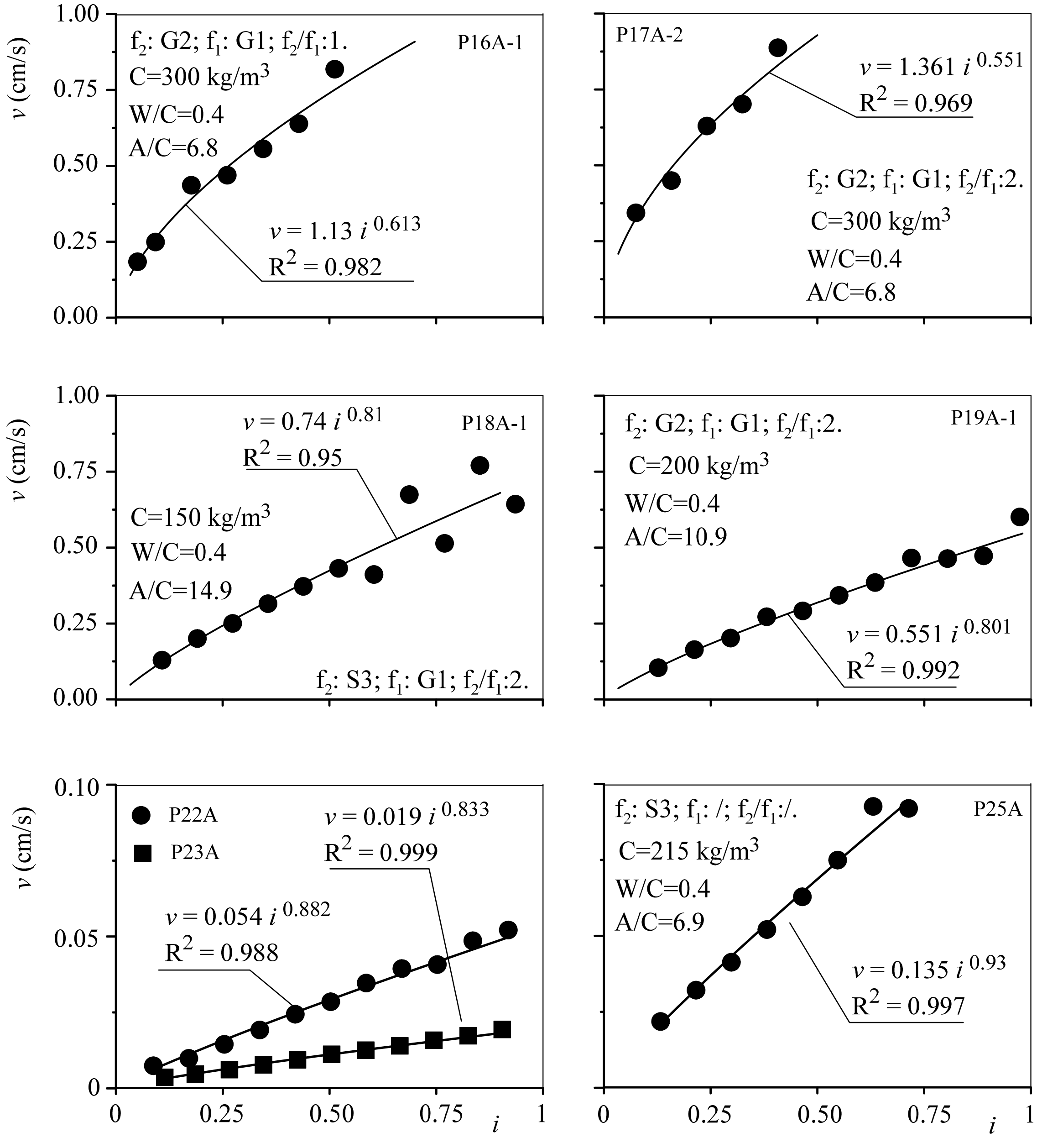
Typical trends of k *versus* i are shown in Fig. 18 for a wide range of the hydraulic gradient i and in Fig. 19 for values of i ranging from 0 to 1 that are usually more relevant for draining trenches. k depends on i, especially within the lower range of i; this dependence is stronger for specimens made by coarse aggregates.



P22A: (f$_2$: G2; f$_1$: S1; f$_2$/f$_1$:1; C=300 kg/m^3; W/C:0.4; A/C:10.9)

P23A: (f$_2$: G2; f$_1$: S1; f$_2$/f$_1$:1; C=200 kg/m^3; W/C:0.4; A/C:10.9)

Fig. 16. Nominal seepage velocity *v vs* hydraulic gradient *i* for different mixes of pervious concrete.
Fig. 16. Velocità di filtrazione nominale v in funzione del gradiente idraulico i per varie composizioni del calcestruzzo permeabile.



P22A: (f_2: G2; f_1: S1; f_2/f_1:1; C=300 kg/m^3; W/C:0.4; A/C:10.9)

P23A: (f_2: G2; f_1: S1; f_2/f_1:1; C=200 kg/m^3; W/C:0.4; A/C:10.9)

Fig. 17. Nominal seepage velocity v *vs* hydraulic gradient i for different mixes of pervious concrete for i lower than 1.

Fig. 17. Velocità di filtrazione nominale v in funzione del gradiente idraulico i per varie composizioni del calcestruzzo permeabile per valori di i minori di 1.

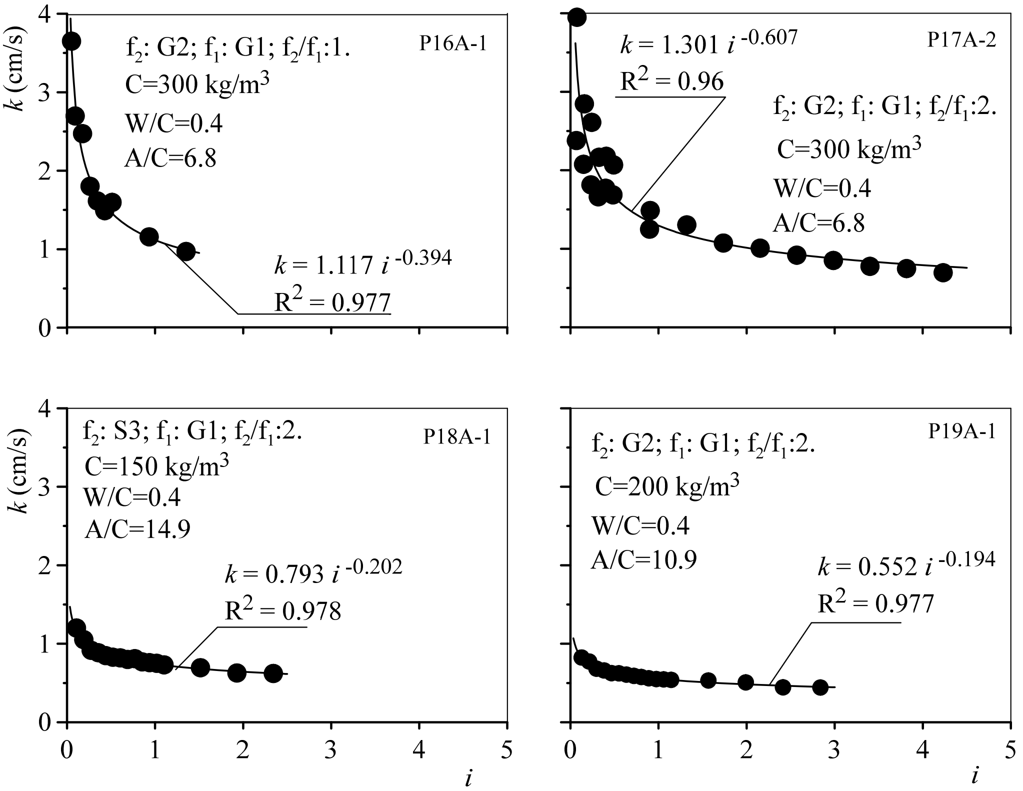


Fig. 18. Hydraulic conductivity *k vs* hydraulic gradient *i* for different pervious concretes.

Fig. 18. Coefficiente di permeabilità k in funzione del gradiente idraulico i per varie composizioni del calcestruzzo permeabile.

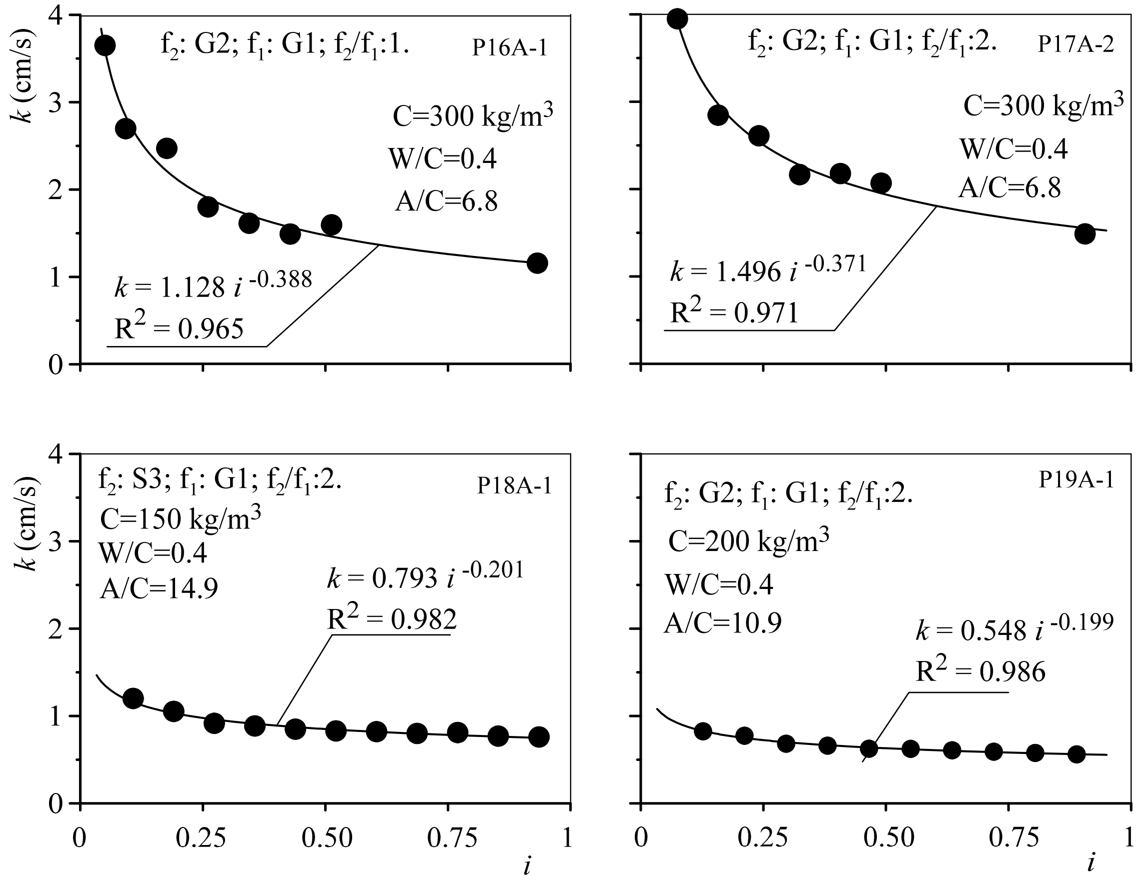


Fig. 19. Hydraulic conductivity *k vs* hydraulic gradient *i* for different pervious concretes for *i* < 1.
Fig. 19. Coefficiente di permeabilità k in funzione del gradiente idraulico i per varie composizioni del calcestruzzo permeabile per i < 1.

The above results show that the hydraulic conductivity *k* of the tested pervious concretes is rather high, as expected. Since draining trenches are most frequently installed in fine grained soils such as clays, silts and fine sands, the flow rate of water entering the draining trench is rather low; therefore the permeability requirement stated in paragraph 2 is met by many different pervious concretes, if the thickness of the trench is properly designed.

Concretes made of at least two different aggregate fractions (gravel and sand) with a rather low cement content (C) of about 200 kg/m^3, a water/cement ratio (W/C) of 0.4, and a high aggregates/cement ratio (A/C) are also convenient as for workability [THOMBRE *et al.*, 2016], pumbability and inexpensiveness.

It must be stressed that all the above values of *k* refer to the uncontaminated and unclogged state of the concrete. As already stated, pervious concrete for draining trenches act also as a filter. As a consequence, reference should be made to the “residual” hydraulic conductivity of the partially clogged concrete.

7.2 Filter properties

Pervious concrete must be able to function also as a protective filter to prevent internal erosion of the soil into which the draining trench is inserted. This requires that the size of a part of the interconnected pores of the concrete must be smaller than the size of the smallest particles of the base soil so to block them when entering the draining trench. Blocked particles cause the partial clogging of the concrete and a decrease of its hydraulic conductivity *k*. However, *k* does not decrease indefinitely if the pervious concrete is fit for the base soil at hand. In that case, the rate of decrease of k progressively slows down and eventually becomes negligible, whilst k tends to approach a "residual" value k_{res}. In the design of draining trenches reference should be made to k_{res}, and not to the hydraulic conductivity of the unclogged or "virgin" concrete, unless they are designed for temporary use. Coarse grained no-fines concrete can hardly behave as an effective filter for sandy and fine-grained soils.

The search for mix-design of pervious concretes fulfilling the above requirements has been carried out by means of falling head permeability tests on concrete specimens subjected to a series of "clogging cycles" until the residual hydraulic conductivity, if any, was reached. A non-plastic silt, obtained by pulverisation of a dark grey volcanic sand whose grading is shown in Fig. 20 (particle sizes range from 3.5 to 75 μm) was used as clogging material.

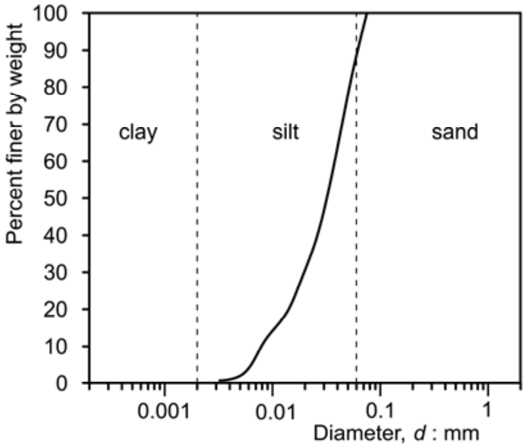


Fig. 20. Grain-size distribution of the clogging material made of pulverized volcanic sand.
Fig. 20. Distribuzione granulometrica del materiale utilizzato per le prove di intasamento costituito di sabbia vulcanica polverizzata.

The experimental procedure used determining the reduction of the hydraulic conductivity due to repeated additions of clogging material dragged by seeping water into the trench drain is similar to that used by other researchers [e.g. KEVERN, 2006; DEO *et al.*, 2010; NEITHALATH *et al.*, 2010; MORACI, 2010; KEVERN, 2015], and consists of the following steps:

1) Determination of the hydraulic conductivity of the unclogged concrete at gradient i varying from very low values up to 0.9.
2) Execution of a clogging cycle consisting in:
   a) Placement on the top of the specimen of a 20mm thick layer of the clogging silt in sub-layers 2-3mm thick, each one gently tamped.
   b) Carrying out a falling head permeability test with an initial head h_0=80 cm (*cp*. Fig. 13). Obviously the results of this test are not significant because the permeability of the concrete-top layer of silt is essentially governed by the silt layer. However, some particles of the silt layer are dragged by the seeping water through the pervious concrete specimen and exit at its bottom face, whether others are blocked by "constriction" voids of the concrete after a relatively short path within the concrete.
   c) Careful removal of the silt from the top surface of the concrete specimen.
   d) Then a new determination of hydraulic conductivity is carried out.

Fourteen clogging cycles (each one followed by a permeability test) have been performed on every concrete specimen.

Typical test results are shown in Fig. 21. The trends of the nominal velocity of flow v *versus* i and of the permeability k *vs* i are shown in figures 21a and 21b, respectively.

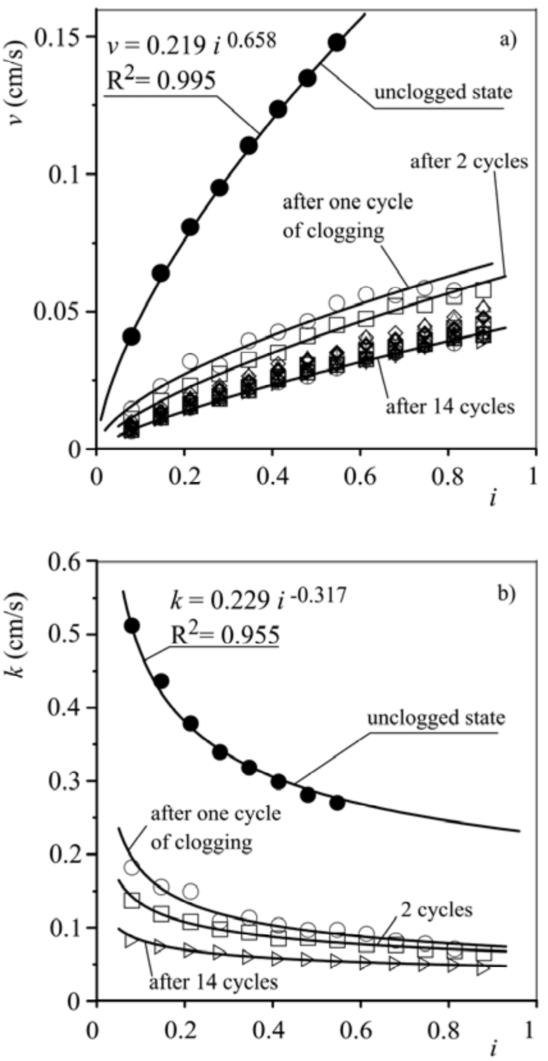


Fig. 21. Results of clogging tests on pervious concrete P4, see Table 2 (specimen P4A consisting of gravel G3 (f_1); gravel G1 (f_2); ratio $f_2/f_1=2$; Portland cement content: 300 kg/m^3; water/cement ratio W/C=0.4; aggregate/cement ratio A/C=6.8. Nominal seepage velocity v (a) and hydraulic conductivity k (b) *vs* hydraulic gradient i in function of the number of clogging cycles. Data pertaining to the unclogged specimen also plotted for comparison.

Fig. 21. Risultati delle prove di intasamento sul calcestruzzo permeabile P4, provino P4A (composizione del provino: ghiaia G3 (f_1); ghiaia G1 (f_2); rapporto $f_2/f_1=2$; dosaggio di cemento Portland: 300 kg/m^3; rapporto acqua/cemento W/C=0.4; rapporto inerti/cemento A/C=6.8. Andamento della velocità di filtrazione nominale v (a) e del coefficiente di conduttività idraulica k (b) in funzione del gradiente idraulico i e del numero di cicli di intasamento. Per confronto sono riportati anche i dati relativi al calcestruzzo nello stato iniziale non intasato.

The data plotted in Fig. 21 clearly show that the hydraulic conductivity k decreases progressively with the number of the clogging cycles, irrespective of the gradient i. The greatest decrease occurs for low values of the hydraulic gradient i. However these reductions decrease with the number of clogging cycles.

Data plotted in Fig. 22, relative to very low values of i, show that k tends to an essentially stable value after about 5 clogging cycles, and that most of the decrease takes place after only a few cycles (2 or 3). Data in Fig. 23 show that almost all the decrease of the residual value of k_{res} takes place in the first 6 cycles, and that for the successive cycles the decrease is negligible.

The decrease of k after a large number of clogging cycles approaches 82% (Fig. 22b); nevertheless, the residual hydraulic conductivity of the pervious concrete is still high enough for trenches installed in fine-grained soils to retain its draining capability, k_{res} is greater than 0.05 cm/s, Fig. 23. Even though the number of clogging tests is limited, the experimental results as yet obtained show that the mix-design of pervious concrete can be devised to meet draining as well as filter and durability requirements, at least for tested clogging material.

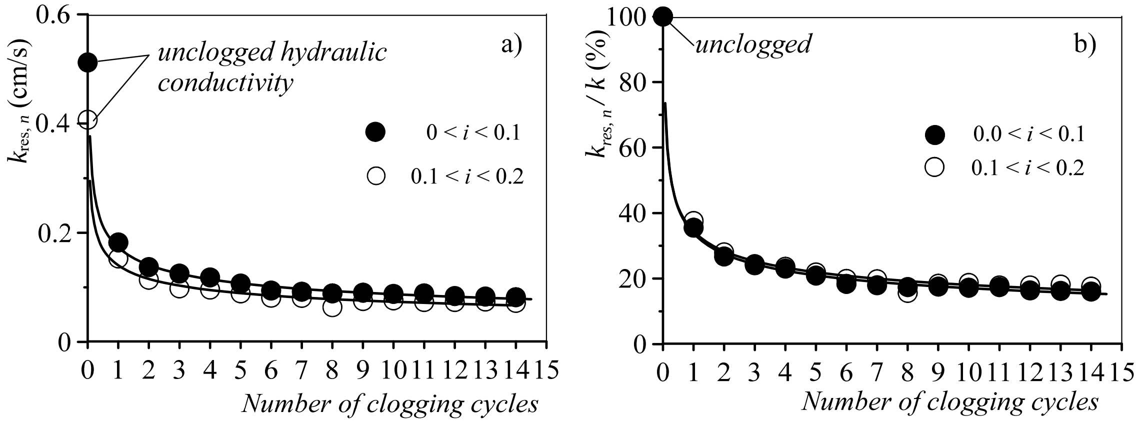


Fig. 22. Specimen P4A. a) Trend of the residual hydraulic conductivity after n clogging cycles $k_{\text{res, n}}$ in function of the number of clogging cycles. b) Trend of the residual permeability ratio $k_{\text{res, n}}/k$ in function of the number of clogging cycles. k: hydraulic conductivity of the unclogged concrete. The concrete of this specimen consisting of gravel G3 (weight f_1); gravel G1 (weight f_2); ratio $f_2/f_1=2$; Portland cement content: 300 kg/m^3; water/cement ratio W/C=0.4; aggregate/cement ratio A/C=6.8. rte

Fig. 22. Provino 4A. a) Andamento della conduttività idraulica residua k_{res} in funzione del numero di cicli di intasamento. b) Andamento del rapporto $k_{res,\ n}/k$ in funzione del numero di cicli di intasamento. k: coefficiente di permeabilità del calcestruzzo non intasato. Il calcestruzzo di questo provino è costituito di ghiaia G3 (peso f_1); ghiaia G1(peso f_2); rapporto $f_2/f_1=2$; dosaggio di cemento Portland: 300 kg/m^3; rapporto acqua/cemento W/C=0.4; rapporto inerti/cemento A/C=6.8.

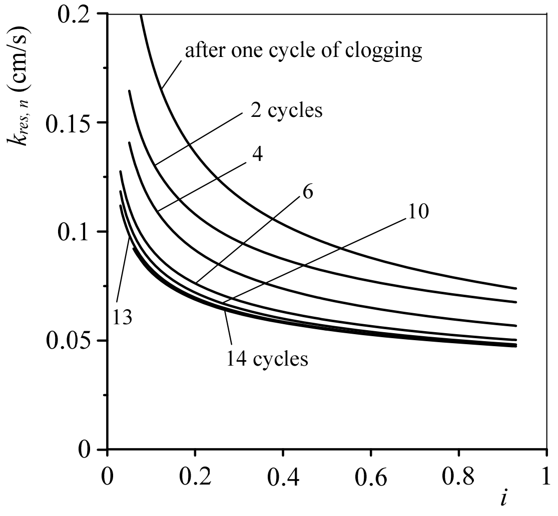


Fig. 23. Specimen 4A, consisting of gravel G3 (weight f_1); gravel G1 (weight f_2); ratio $f_2/f_1=2$; Portland cement content: 300 kg/m^3; water/cement ratio W/C=0.4; aggregate/cement ratio A/C=6.8. Trend of the residual hydraulic conductivity $k_{\text{res, n}}$ *vs* hydraulic gradient i, in function of the number of clogging cycles.

Fig. 23. Provino 4A, confezionato con ghiaia G3 (peso f_1); ghiaia G1(peso f_2); rapporto $f_2/f_1=2$; dosaggio di cemento Portland: 300 kg/m^3; rapporto acqua/cemento W/C=0.4; rapporto inerti/cemento A/C=6.8). Andamento della conduttività idraulica $k_{res,\ n}$ in funzione del gradiente piezometrico i e del numero di cicli di intasamento.

The range of grain-size distributions of aggregates that proved to be satisfactory, as far as draining and filter requirements are concerned, for clogging materials made of silt, silty-sand, sandy-silt and sand is shown in Fig. 24, from which it is evident that the aggregate of the pervious concrete should contain a sand fraction not lower that 40%.

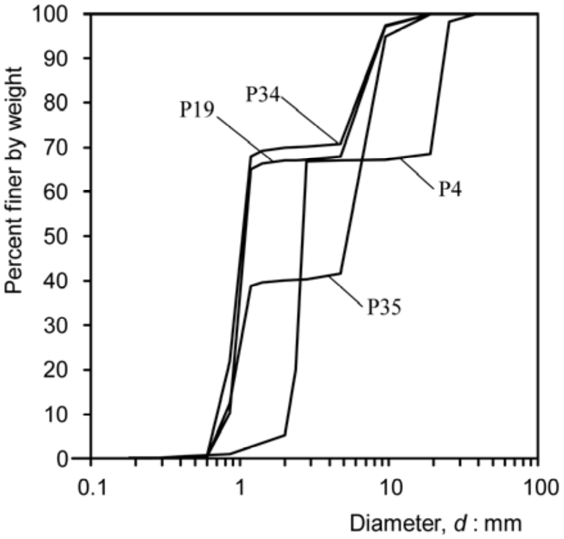


Fig. 24. Range of grain-size distribution of the aggregates that meet both draining and filters requirements for clogging materials made of silt, silty-sand, sandy-silt, sand.
Fig. 24. Distribuzione granulometrica degli aggregati che soddisfano entrambi i requisiti di permeabilità e di filtro per materiale "intasante" costituito di limo, limo-sabbioso, sabbia limosa, sabbia.

Further research is needed for clogging materials other than the tested one.

8 Conclusions

An experimental investigation into the strength, the draining and filter properties of pervious concrete has been carried out. From the results as yet obtained the following conclusions can be drawn.

a) The strength of the pervious concrete is sufficient to build very deep trenches safely and without long delays in the excavation of in-between panels or secant piles, with considerable advantages in costs and in efficient planning of the construction site.
b) The hydraulic conductivity of all the tested concretes is high and in any case adequate for deep trenches installed in sandy and fine-grained soils.
c) It is possible to devise the mix-design for pervious concrete so that it meets, simultaneously, permeability, filter and durability requirements, as well as the strength demand.

It is hoped that the experimental results reported in the present paper can help to design pervious concretes well suited for draining trenches. Furthers research is needed for clogging materials other than the tested silt.

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Notation

A	aggregate (by weight)
A/C	aggregates-cement ratio
A_1	area of the cross section of the specimen of pervious concrete
A_2	area of the cross section of the graduated cylinder of the falling head permeameter
b	exponent in the relation between the hydraulic conductivity k^* and the gradient i
C	cement content (by weight per unit volume of pervious concrete)
c	true cohesive strength of the concrete
CU	uniformity coefficient
D	specimen diameter
$d_{\max}$	maximum particle size of sand or gravel
$d_{\min}$	minimum particle size of sand or gravel
d_{10}	particle diameter corresponding to 10% passing finer by weight
d_{50}	mean particle size
d_{60}	particle diameter corresponding to 60% passing finer by weight
E'	Young's modulus
f_1, f_2	granulometric fraction (by weight) relative to aggregates (made of sand or gravel)
G_s	specific gravity
h_{crit}	limit height of a vertical slope in purely cohesive soil
h_0	initial piezometric head
$h(t)$	current piezometric head
i	hydraulic gradient
k	hydraulic conductivity or coefficient of permeability
k_{res}	residual hydraulic conductivity after a large number of clogging cycles
$k_{res,\, n}$	residual hydraulic conductivity after n clogging cycles
k^*	constant coefficient in the relation between v and i
L	specimen height
n	porosity
$n_{\max}$	maximum porosity
$n_{\min}$	minimum porosity
t_0	initial time
t	time
v	flow velocity
W/C	water-cement ratio
γ_c	unit weight of the concrete
γ_d	dry unit weight of the concrete
$\gamma_{d,\, max}$	maximum dry unit weight of sand or gravel
$\gamma_{d,\, min}$	minimum dry unit weight of sand or gravel
γ_s	specific weight of sand or gravel
ε_a	axial vertical deformation
ν	Poisson's ratio
σ_a	uniaxial applied pressure
σ_f	uniaxial compressive strength

References

ABADJIEVA T. SEPHIRI P. (2000) – *Investigations on some properties of no-fines concrete.* University of Botswana, Gabarone.

ACPT ADVANCED CONCRETE PAVEMENT TECHNOLOGY (2012). *Pervious Concrete*. TechBrief December 2012 - FHWA-HFI-13-006. US Department of Transportation Federal Highway Administration. www.fhwa.dot.gov/pavement/concrete.

ALAM B., JAVED M., ALI Q., AHMAD N., IBRAHIM M. (2012) – *Mechanical properties of no-fines bloated slate aggregate concrete for construction application, experimental study*. International Journal of Civil and Structural Engineering, 3, n. 2, pp. 302-308.

ACI AMERICAN CONCRETE INSTITUTE (2006) – *Pervious concrete.* ACI Committee 522, Technical Committee Document 522R-06.

ACI AMERICAN CONCRETE INSTITUTE (2011) – *Pervious Concrete*. ACI Committee 522, Technical Committee 522R-10 (R2011).

ASTM (2004) - *Standard test methods for maximum index density and unit weight of soils using a vibratory table (D4253-00 and D4254-00).* In: 2004 annual Book of ASTM Standards, Philadelphia PA, American Society for Testing and Materials.

BARNHOUSE W., SRUBAR III W.V (2016) – *Potential for clay clogging of pervious concrete under extreme conditions*. Journal of Hydrologic Engineering, ASCE, 15, n. 1, pp. 67-69.

BROMHEAD E.N. (1984) – *An analytical solution to the problem of seepage into counterfort drains.* Canadian Geotechnical Journal, 21, pp. 657-662.

CHANDRAPPA A.K., BILIGIRI K.P. (2016) – *Comprehensive investigation of permeability characteristics of pervious concrete: A hydrodynamic approach*. Construction and Building Materials, 123, pp. 627-637.

CHEN B., LIU J., LI P. (2008) – *Experimental study on pervious concrete*. Proc. 9th International Conference on Concrete Pavements, San Francisco, California, August 17-21, pp. 202-211.

COLLINS K.A., HUNT W.F., HATHAWAY J.M. (2008) – *Hydrological Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina*. Journal of Hydrological Engineering, 13, n. 12, pp. 1146-1157.

CORNFORTH, D.H. (2005) – *Landslides in Practice*. John Wiley & Sons, Inc., New York.

COTECCHIA, F., LOLLINO, P., PETTI, R. (2016) – *Efficacy of drainage trenches to stabilise deep slow landslides in clay slopes.* Géotechnique Letters, 6, 1–6. http://dx.doi.org/10.1680/jgele.15.00065

D'ACUNTO B., URCIUOLI G. (2006) – *Groundwater regime in a slope stabilized by drain trenches.* Mathematical and Computer modelling, 43, pp. 754-765. Doi:10.1016/j.mcm.2005.02.013.

DAY S.R., RYAN C.R. (1992) – *State of the art in bio-polymer drain construction.* In: Slurry walls: Design, Construction, and Quality Control, ASTM STP 1129, Paul D.B., Davison R.R., Cavalli N.J., Eds., American Society for Testing and Materials, 1992 Philadelphia, pp. 333-343.

DEO O., SUMANASOORIYA M., NEITHALATH N. (2010) – *Permeability reduction in pervious concrete due to clogging: experimental and modeling.* Journal of Materials in Civil Engineering, ASCE 22, 7, pp.741-751.

DI MAIO C., EVANGELISTA A., VIGGIANI G. (1988) – *Analisi dell'efficienza di sistemi di dreni tubolari.* Italian Geotechnical Journal, XXII, pp. 187-199. (In Italian).

FELL R., MAC GREGOR P., STAPLEDON D., BELL G., FOSTER M. (2014) – *Geotechnical Engineering of Embankment Dams.2nd edition Chapter 9:Design, specification and construction of filters, pp. 493-565.* CRC Press, London, UK.

GHAFOORI N., DUTTA S. (1995) – *Laboratory investigation of compacted no-fines concrete for paving material*. Journal of Materials in Civil Engineering, ASCE, 7, n. 3, pp. 183-191.

GOEL P.K. (2006) – *Water pollution: Causes, effects and control*. New Age International, New Delhi, 2006.

HASELBACH L.M. (2010a) – *Pervious concrete testing methods*. Low Impact Development 2010: Redefining Water in the City © 2010, ASCE, pp. 180-192.

HASELBACH L.M. (2010b) – *Potential for clay clogging of pervious concrete under extreme conditions*. Journal of Hydrologic Engineering, ASCE, 15, n. 1, pp. 67-69.

HASELBACH L., FREEMAN R.M. (2006) – *Vertical Porosity Distribution in Pervious Concrete Pavement*. ACI Materials Journal, 103, n. 6, pp. 452-458.

HASELBACH L.M., VALAVALA S., MONTES F. (2006) – *Permeability for sand-clogged Portland cement pervious concrete pavement system*. Journal of Environmental Management, 81, n.1, pp. 42-49.

HASELBACH L., BOYER M., KEVERN J.T., SCHAEFER V.R. (2011) – *Cyclic heat island impacts on traditional versus pervious concrete pavement systems*. Transportation Research Record: Journal of Transportation Research Board, 2240, pp. 107-115.

HUTCHINSON, J.N. (1977) – *Assessment of the effectiveness of corrective measures in relation to geological conditions and types of slope movement*. Bulletin of the International Association of Engineering Geology, 16, pp. 131-155.

IBRAHIM A., MAHMOUD E., YAMIN M., PATIBLANDA V.C. (2014) – *Experimental study on Portland cement pervious concrete mechanical and hydrological properties*. Construction and Building Materials, 50, 524-529.

KENNEY T.C., PAZIN M., CHOI W.S. (1977) – *Design of horizontal drains*. Journal of Geotechnical Engineering Division, Proc. ASCE, 103 (GT11), pp. 1311-1323.

KEVERN J.T. (2006) – *Mix design determination for freeze-thaw resistant Portland cement perviuos concrete*. MS thesis. Iowa State University, Ames.

KEVERN J.T. (2008) – *Advancements in perviuos concrete technology*. Ph.D. Dissertation, Iowa State University. *Retrospective Theses and Dissertations*. 93. http://lib.dr.iastate.edu/rtd/93.

KEVERN J.T. (2015) – *Evaluating permeability and infiltration requirements for perviuos concrete*. Journal of Testing and Evaluation, ASTM, 43, n.3, pp. 544-553.

KEVERN J.T., FARNEY C. (2012) – *Reducing curing requirements for perviuos concrete with a superabsorbent polymer for internal curing*. Transportation Research Record: Journal of the Transportation Research Board, 2290, Transportation Research Record of the National Academies, Washington, D.C., pp. 115-121. DOI: 10.3141/2290-15.

KEVERN J.T., WANG K., SULEIMAN M.T., SCHAEFER V.R. (2006) – *Pervious concrete construction: methods and quality control*. NRMCA Concrete Technology Forum: Focus on Pervious Concrete, May 24-25, 2006, Nashville, TN, USA.

KEVERN J.T., SCHAEFER, V.R., WANG, K., SULEIMAN, M.T. (2008) - *Pervious Concrete Mixture Proportions for Improved Freeze-Thaw Durability*. Journal of ASTM International, vol. 5, n. 2, 2008.

LEONARDS G.A., (1982) – *Investigation of failures*. Journal of Geotechnical Engineering Division, ASCE 108, GT2, 222-283.

MAGESWARI M., KARTHIKEYAN M.P., PAVITHRAN S., RAJKUMAR M., GOVINDARAJAN R. (2016) – *High strength permeable pavement using no fines concrete*. SSRG International Journal of Civil Engineering, 3, n.3, pp. 62-66.

MAHESH B., LAVANYA B. (2016) – *Experimental study of pervious concrete in pavements.* International Journal of Innovative Research in Science, Engineering and Technology 5, N. 7, pp. 12913-12924. DOI:10.15680/IJIRST.2016.0507152.

MARTIN III W.D., PUTMAN B.J., KAYE N.B. (2013) – *Using image analysis to measure the porosity distribution of a porous pavement.* Construction and Building Materials, 48, pp. 78-84.

MARTIN III W.D., KAYE N.B., PUTMAN B.J. (2014) – *Impact of vertical porosity distribution on the permeability of pervious concrete.* Construction and Building Materials, 59, pp. 210-217.

MONTES F., HASELBACH L.M. (2006) – *Measuring hydraulic conductivity in pervious concrete.* Environmental Engineering Science, 23, n.6, pp. 960-969.

MORACI N. (2010) – *Geotexile filter: design, characterization and factors effecting clogging and blinding limit states.* Theme lecture. Proceeding of the 9th International Conference on Geosynthetics, May 23-27, vol. I, pp. 413-435.Guarujá, Brazil.

MORACI N. (2012) – *A new theoretical method to evaluate the internal stability of granular soils.* Canadian Geotechnical Journal, 49, n.1, pp. 45-58.

MORACI N., IELO D., MANDAGLIO M.C. (2016) – *Valutazione della stabilità interna dei terreni granulari.* Italian Geotechnical Journal, 2, pp. 28-43. (In Italian).

MOSS J.K. (1979) – *No-fines building gives energy conserving homes.* International Construction, Sutton, Surrey, England. Publication#c790123.

MRAKOVCIC S., CEH N., JUGOVAC V. (2014) – *Effect of aggregate grading on pervious concrete properties*. Gradevinar, 66, n. 2, pp. 107-113. DOI:10.14256/JCE.977.2013.

NAKAMURA, H. (1988) - *Landslide control works by horizontal drainage works.* V International Symposium on Landslides, Lousanne 1988, 2, pp. 965-970.

NEITHALATH N. (2004) – *Development and characterization of acoustically efficient cementetious materials. Ph.D. thesis.* Purdue University.

NEITHALATH N., SUMANASOORIYA M.S., DEO O. (2010) – *Characterizing pore volume, sizes, and connectivity in pervious concretes for permeability prediction.* Materials Characterization, 61, pp. 802-813.

NEMIROVSKY E.M., WELKER A.L., LEE R. (2013) – *Quantifying evaporation from pervious concrete systems: methodology and hydrologic perspective.* Journal of Irrigation and Drainage Engineering, ASCE, 139, n. 4, pp. 271–277.

NEVILLE A.M. (1995) – *Properties of concrete.* Fourth and final, Longman Group Limited eds, Essex, England.

NEWMAN N., OWENS P. (2003) – *Properties of lightweight concrete.* In NEWMAN N. and CHOO B.S., (eds.) Advanced Concrete Technology, Butterworth-Heinemann, Burlington, Vermont, USA. Edited by: John NEWMAN and Ban Seng CHOO ISBN: 978-0-7506-5686-3.

PARK S.B., SEO D. S., LEE J. (2005) – *Studies on the sound absorption characteristics of porous concrete based on the content of recycled aggregate and target void ratio.* Cement and Concrete Research, 35, n. 9, pp. 1846-1854.

PASTOR J., THAI T-H., FRANCESCATO P. (2000) – *New bounds for the height limit of a vertical slope.* International Journal for Numerical and Analytical Methods in Geomechanics, 24, pp. 165-182.

PUN W.K., URCIUOLI G. (2008) – *Soil nailing and subsurface drainage for slope stabilization.* Keynote paper in: 10th International Symposium on Landslides and Engineering Slopes, Xi'an, China, June 30 July 4 2008. Vol. 2, pp. 85-126. DOI:10.1201/9780203885284-c6. Edited by Zuyu Chen, Jianmin Zhang, Zhongkui Li, Faquan Wu, and Ken Ho.

REDDI L.N., XIAO M., HAJRA M.G., LEE I.M. (2005) – *Physical clogging of soil filters under constant flow rate versus constant head.* Canadian Geotechnical Journal, 42, pp. 804-811.

ROWE P.W. (1972) - *The relevance of soil fabric to site investigation practice.* Géotechnique 22(2): 195-300.

SATA V., WONGSA A., CHINDAPRASIRT P. (2013) – *Properties of pervious geopolymer concrete using recycled aggregates.* Construction and Building Materials, 42, pp. 33-39.

SHU X., HUANG B., WU H., DONG Q., BURDETTE E.G. (2011) – *Performance comparison of laboratory and field produced pervious concrete mixture.* Construction and Building Materials, 25, pp. 3187-3192.

SINGH P., SCANLON A. (2013) – *Sustainability of residential concrete.* PHRC - The Pennsylvania Housing Research Center. Research Series Report N. 112.

SOMMERVILLE J., CRAIG N., CHARLES A. (2011) – *No-fines concrete in the UK social housing stock: 50 years on. Structural survey*. Structural Survey, 29, n. 4, pp. 294-302. Emerald Group Publishing Limited 0263-080X, DOI 10.1108/02630801111162369.

SCHAEFER V. R., WA K., SUILEIMAN M. T., KEVERN J. T. (2006) – *Mix design development for pervious concrete in cold weather climates*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

SRIRAVINDRARAJAH R., HUAI WANG N.D., ERVIN L.J.W. (2012) – *Mix design for pervious recycled aggregate concrete*. International Journal of Concrete Structure and Materials, 6, n. 4, pp. 239-246. DOI 10.1007/s40069-012-0024-x

STANIĆ B. (1984) – *Influence of drainage trenches on slope stability.* Journal of Geotechnical Engineering ASCE, 110, n. 11, pp. 1624-1636.

STARKE P., GOBEL P., COLDEWAY W.G. (2010) - *Urban evaporation rates for water permeable pavements.* Water Science Technology, 62, pp. 1161–1169.

TENNIS P., LEMING M.L., AKERS D.J. (2004) – *Pervious concrete pavements.* Engineering Bulletin 302.02. Portland Cement Association, Skokie, IL, and National Ready Mixed Concrete Association, Silver Spring, MD.

TERZAGHI K. (1929) – *Effects of minor geologic details on the safety of dams*. In: Geology and Engineering for Dams and Reservoirs, American Institute of Mining and Metallurgical Engineers, Technical Publication 215, pp: 31-44. Reprinted in From Theory to Practice in Soil Mechanics. Selection from the writings of Karl Terzaghi. John Wiley & Sons, 1960, New York, London, pp: 119-132.

TERZAGHI, K. (1950) – *Mechanism of Landslides*. In Paige, S. (Ed.), Application of Geology to Engineering Practice (Berkey Volume). The Geological Society of America, New York, pp: 83–123.

THAKRE N., RAJPUT H., SAXENA J., MITANGALE H. (2014) – *Comparative study on strength and permeability of pervious concrete by using nylon and polypropylene fiber.* IJCAT International Journal of Computing and Technology, 1, n. 4, pp. 141-148.

THOMBRE K.B., MORE A.B., BHAGAT S.R. (2016) – *Investigation of strength and workability in no-fines concrete.* International Journal of Engineering Research & Tecnology (IJERT), 5, n. 9, pp. 390-393.

TORRES A., HU, J., RAMOS A. (2015) – *The effect of the cementitious paste thickness on the performance of pervious concrete.* Construction and Building Materials, 95, pp. 850-859.

URCIUOLI G., PIRONE M. (2013) – *Subsurface drainage for slope stabilization. Landslide Science and Practice.* The Second World Landslide Forum, Margottini C., Canuti P., Sassa K. (eds), vol. 6, pp. 577-585. DOI: 10.1007/978-3-642-31319-6-74.

USHANE K. S., KUMAR K.J.P., KAVITHS C. (2014) – *Investigation of no-fines concrete in building blocks.* IJSCE International Journal of Structural and Civil Engineering Research, 3, n. 4, pp. 170-177

VALLI, P.P. (2000) – *Numerical study to stabilise landslides by trench drains*. Computers and Geotecnics, 27, pp. 63-77.

VALORE C., ZICCARELLI M. (2015) – *The stabilization of a slope-viaduct system without closing traffic*. Proceedings of 16th European Conference on Soil Mechanics and Geotechnical Engineering - Edinburg, Scotland, 13-17 September 2015. pp. 367-372. ISBN: 978-0-7277-6067-8; doi:10.1680/ecsmge.60678.

VALORE C., ZICCARELLI M., MUSCOLINO S.R. (2017) - *The bearing capacity of footings on sand with a weak layer*. Geotechnical Research, 4, n.1, pp. 12-29. http://dx.doi.org/10.1680/jgere.16.00020.

WELKER A.L., BARBIS J.D., JEFFERS P.A. (2012) – *A side-by-side comparison of pervious concrete and porous asphalt.* JAWRA Journal of the American Water Resources Association, 48, n. 4, pp. 809-819.

WEST D., KAYE N.B., PUTMAN B.J., CLARK R. (2016) – *Quantifying the non-linear hydraulic behavior of pervious concrete.* Journal of Testing and Evaluation, 44, n. 4, pp. 2172-2181.

ZICCARELLI M., VALORE C., MUSCOLINO S.R., FIORAVANTE V. (2017) - *Centrifuge tests on strip footings on sand with a weak layer*. Geotechnical Research, 4, n.1, pp. 47-64. http://dx.doi.org/10.1680/jgere.16.00021.

ZHONG R., WILLE K. (2016) – *Compression response of normal and high strength pervious concrete.* Constructions and Building Materials, 109, pp. 177-187.

Ricerche sperimentali sulle proprietà drenanti e filtranti del calcestruzzo permeabile per trincee drenanti profonde

Sommario

La riduzione delle pressioni interstiziali rappresenta uno degli interventi più efficaci per stabilizzare le frane e per migliorare le condizioni di stabilità di pendii marginalmente stabili che siano sede di una o più falde idriche sotterranee. Per tale finalità sono state impiegate da molto tempo le trincee, realizzate con comuni escavatori e riempite di materiali sciolti. Tali modalità costruttive non possono essere impiegate se si devono realizzare trincee drenanti profonde, per le quali occorre ricorrere a mezzi di scavo da tempo disponibili per la realizzazione dei diaframmi e dei pali secanti. Tuttavia, gli uni e gli altri non possono essere realizzati con materiali sciolti, ossia non cementati, dal momento che lo scavo di un pannello (o di un palo) intermedio in adiacenza a pannelli già realizzati provocherebbe il collasso di questi ultimi. Questo problema si può risolvere con l'impiego del calcestruzzo permeabile. Abitualmente si impiega il calcestruzzo senza frazione fina, confezionato con inerti con la granulometria della ghiaia media, cemento e acqua. Tale tipo di calcestruzzo è caratterizzato da alta permeabilità, ma non ha proprietà di filtro protettivo nei riguardi dei terreni a grana medio-fina nei quali la trincea drenante è incassata. La capacità del calcestruzzo di funzionare anche come filtro è fondamentale per prevenire processi di erosione interna nei terreni adiacenti alla trincea drenante.

Il calcestruzzo permeabile non soffre, naturalmente, il problema della stabilità interna, essendo gli inerti legati dal cemento.

Con la ricerca della quale si riferiscono i principali risultati è stato dimostrato per via sperimentale che è possibile escogitare composizioni (*mix-design*) del calcestruzzo permeabile che soddisfano simultaneamente i requisiti riguardanti la permeabilità residua (ovvero dopo una lunga serie di cicli di intasamento), la funzione filtro e la resistenza a taglio. Quest'ultimo requisito è indispensabile per poter realizzare le trincee profonde con le tecniche impiegate per i diaframmi e i pali secanti. Al riguardo è stato provato che si possono confezionare calcestruzzi permeabili con resistenza a compressione semplice sufficiente per assicurare la stabilità di pareti verticali dei pannelli alte parecchie decine di metri dopo tempi di maturazione brevi. Si ritiene che i dati sperimentali riportati nella memoria, ancorché limitati, colmino una lacuna nelle conoscenze sull'argomento in esame e possano costituire un utile riferimento per la progettazione delle trincee drenanti profonde.