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## EXCAVATABLE AND PERMEABLE CEMENT SUB-BASE FOR REMOVABLE URBAN PAVEMENT

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### ABSTRACT

Modular concrete pavements are being developed for urban applications. In addition to their removability, their purpose aims to ensure an easy access to the sub-base and to the networks underneath for maintenance or extension needs. By relying on its expertise on removable urban pavement (RUP), Eiffel University (UGE), in collaboration with Eiffage, is developing a new type of RUP which is also permitting a true transparency to water during rainfall. The sub-base of RUP, generally made of cementitious materials, should consequently remain excavatable as well as permeable to permit the evacuation of the water collected by the draining RUP.

UGE and Engie developed recently a new promising approach of excavatability characterization for controlled low strength material (CLSM) based on a laboratory punching test. This method takes into account the impact energy of a pick and uses the punching test to predict its penetration depth into the material. A model deducing the excavated volume from this data was then correlated to an excavation difficulty rating on real size backfilled trenches.

The present research focusses on the mix-design of an excavatable and permeable cementitious sub-base for draining RUP where the new excavatability approach is being adapted for porous cement treated materials. This paper first details the general approach of excavatability and the necessary adaptations of the punching test. Then a parametric experimental campaign conducted on different mixes is presented and commented. Finally, manual excavations are realized on real scale trenches to validate the approach.

### KEY WORDS

CEMENT BASED MATERIALS / EXCAVATABILITY / PUNCHING TEST / REMOVABLE URBAN PAVEMENTS / PERMEABILITY / DRAINAGE.

## 1. INTRODUCTION

Modular pavement has been actively studied in the past years for different applications. A first concept of removable urban pavement (RUP) consisting in concrete slabs laid on thin granular layer and a base layer made of cement treated material was proposed at Eiffel University (UGE) (de Larrard, 2008), (de Larrard, et al., 2013). The idea was to design a pavement that can be opened and closed within some hours, with very light site equipment, restoring the initial aspect of the street and all its functional abilities. To do so, the concrete elements on the surface are designed to be easily removed but it is necessary that the cement treated material underneath can be easily excavated, even with a pick at the vicinity of a network, while keeping a sufficient bearing capacity. This kind of properties can be obtained with a low cement content. The excavatability of the so-called Controlled Low Strength Materials (CLSM) can be ensured including in the mix-design procedure, a novel approach developed at UGE and allowing its characterization (Morin, 2009), (Gennesseaux, 2015). This approach, detailed in the first part of the present paper, is based on a simple laboratory-punching test, which permits to predict the penetration to be obtained by the pick's tool during an impact, leading to an excavatability difficulty rating.

Within the framework of the recent French I-street project, a collaboration between Eiffel University and Eiffage has been developing a new version of the RUP concept, which enables a total hydraulic transparency of the pavement. The slabs on the surface are designed to absorb the water during rainfall and to drain it to the sub-base. So, to complete this innovation, the sub-base has to be

excavatable like for the previous concept, but also porous, to ensure the drainability of the whole structure. A 180 m<sup>2</sup> demonstrator of this concept was built in 2022 and is described in (Sedran et al. 2023).

Porous sub-base can be achieved with a low sand content, creating a discontinuous grading curve ensuring the porosity of the material (Cimbeton, 2018), yet its excavatability has to be ensured.

The present paper focuses on the mix-design of excavatable porous cement bases for the draining RUP concept. The main idea of the research is to study the validity of the excavatability approach on porous cement-bases. At first, the excavatability approach, developed for CLSM, is detailed. Then, an experimental campaign, based on the laboratory punching test, is conducted on several mixes of porous and non-porous cement bases. The results are then commented and a predictive model of the punching test penetration in porous cement bases is proposed. Finally, an excavation campaign on trenches is described in order to validate the excavatability approach on porous cement bases.

## 2. A PROMIZING APPROACH TO CHARACTERIZE THE EXCAVATABILITY

In order to characterize the excavatability of a CLSM, Morin proposed a new approach based on a laboratory punching test apparatus (Figure 1), (Morin, 2009; Morin, et al., 2013; Morin, et al., 2017). This method was further validated on a large experimental campaign comparing in-situ manual excavation operated by an experimented worker, to laboratory punching tests (Gennesseaux, 2015) (Gennesseaux, et al., 2017).

The laboratory punching test is able to predict the penetration depth of the pick's tool into a material for a given energy of impact. If  $E_{pi}$  is the penetration depth of the pick's blade into the material, it was shown in (Gennesseaux, 2015) that a correlation exists between  $E_{pi}$  and the measurement of the penetration of the laboratory punching tests  $E_{pc}$  considering the same penetration/impact energy though the following equation:

$$E_{pc}=0.72 \times E_{pi} \quad (1)$$

The test consists of a 18 mm diameter flat-bottomed circular punch, designed to match the area of the flat head of a pick and used to load normally the surface of a material sample at a constant speed of 900 mm/min. A stiff displacement-controlled 150kN compressive testing machine was used to produce all the data.

Cylindrical specimens confined in a metallic mold of 16 cm in height and 16 cm in diameter are used as samples (Figure 1). The thickness of the mold was chosen to disable peripheral strains in order to reproduce the confinement of the material in the trench (Morin, et al., 2017).



Figure 1 – Punching test device

During the test, the displacement is monitored by a potentiometer sensor whose maximum range is 100 mm. The stress is monitored by a load sensor with a 100 kN capacity. The output voltages from the devices are recorded using a computer with an HBM Spider8 acquisition box at a 10 Hz frequency to get a real time plot of the force-penetration curve. The test is repeated on six samples for a given mixture at a given age to account for experimental scattering and a mean curve is plotted.

This curve is then integrated to plot a work-penetration curve used to measure the penetration at a given energy of impact/work. The complete procedure is detailed in a technical guide (Ifsttar et Engie, 2016) edited for the French construction community.

Finally, this punching test apparatus can be used to predict, in laboratory, the pick's tool penetration which would be obtained in-situ for a specific impact energy.

The average impact energy of a traditional operator was estimated at 350 J using a high speed camera to determine the pick speed at the impact but the approach can be generalized for other energy levels (higher than 150 J) using the following relationship (Genesseaux, 2015):

$$E_{pc}(W) = E_{pc}(350) \cdot (0,0021 \cdot W + 0,264) \quad (2)$$

Where  $W$  is the energy level considered (in J).

This generalization should enable further extension of the method for other excavation tools with different levels of energy such as jackhammers.

With the knowledge of the penetration depth of a pick  $E_{pi}$ , a simple prismatic rupture model (Figure 2) permits to predict the excavated volume for 90 impacts (this value was arbitrarily selected to mean the experimental measurements with a reasonable effort) with a mean error of 5.6 L using the following equations:

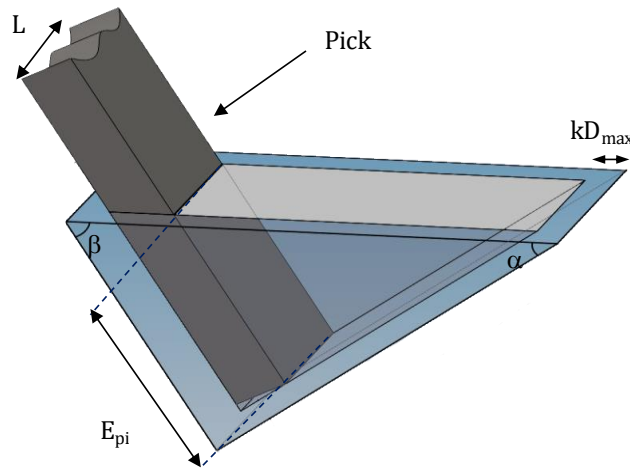


Figure 2 - Rupture mechanism of backfilled materials. A surrounding supplementary volume is accounted for due to aggregate interlocking)

$$V_{\text{theoretical}} = \frac{90}{2} a'^2 \left( \frac{1}{\tan(\beta)} + \frac{1}{\tan\left(\frac{\pi}{2} - \frac{(\beta + \varphi)}{2}\right)} \right) (L + 2k \cdot D_{90}) \quad (3)$$

$$\text{With } a' = E_{pi} \times \sin(\beta) + k \cdot D_{90} [\sin(\beta) + \cos(\beta)] \quad (4)$$

$\varphi$  is the internal friction angle,  $L$  the width of the blade and  $\beta$  the angle of penetration of the blade. The parameter  $k$  describes the fact that during the de-compaction of the material, a supplementary peripheral volume is entrained due to interlocking of aggregates which thickness is  $k \cdot D_{90}$ ;  $D_{90}$  being the diameter through which 90% of the grading curve is passing.

The approach considers the excavated volume as a criterion to differentiate the levels excavation difficulties. Indeed, a good correlation was found between the excavated volume and the difficulty rating given by a manual operator; enabling the determination of excavatability thresholds on the excavated volume (Figure 3).

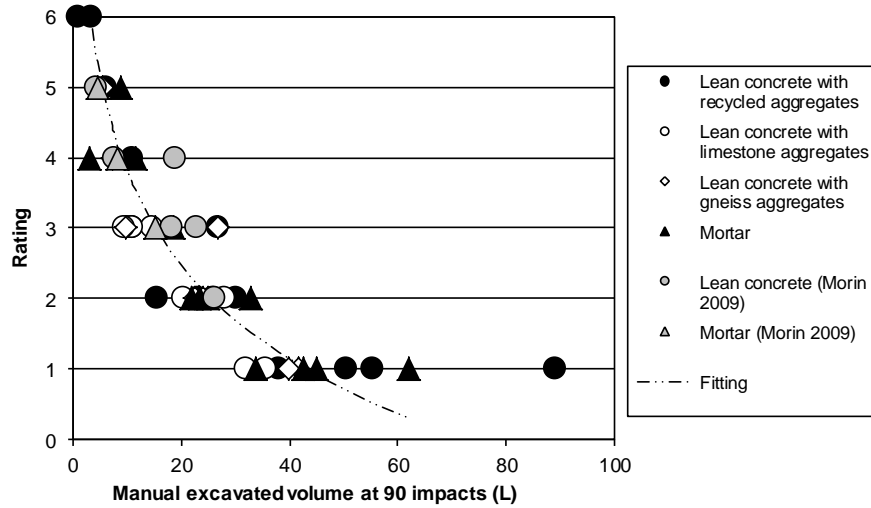


Figure 3 - Comparison between the note (1-very easy to excavate, 6- impossible) and the excavated volume (Gennesseaux, 2015)

Using equations (3) and (4), excavated volume thresholds were converted in an abacus of excavatability (see Figure 4). Knowing the excavatability rating to aim at, and the  $D_{90}$  of the mixture, this abacus gives the mix designer the minimum punching test penetration  $E_{pc}$  to reach in laboratory in order to certify this rating in-situ. A detailed presentation of the method can be found in (Gennesseaux, 2015).

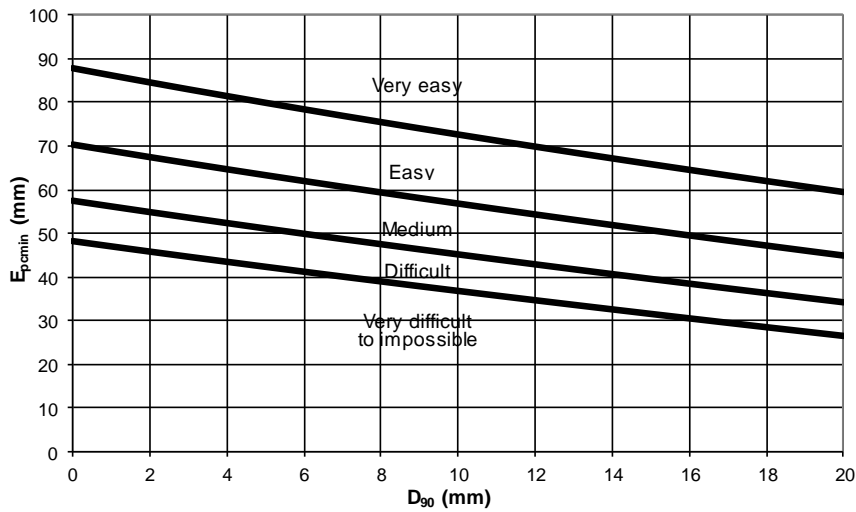


Figure 4 –Excavatability prediction abacus

For the needs of the present study, the laboratory punching test has been adapted for compacted materials. In the case of CLSM, which are fluid materials, the 16x16cm<sup>3</sup> molds are filled by simply pouring the CLSM into a Glanville apparatus (Figure 5), permitting to ensure a self-compaction of the material without any influence of the operator. For compacted materials, the specimen were first compacted using a vibro-compaction apparatus (VCEC) with an adapted piston into plastic molds. Then, at the testing date, the plastic mold is introduced in a metallic counter-mold in order to ensure the confinement of the material (Figure 5). The test is then performed as described above. This procedure has been validated with preliminary laboratory tests.



Figure 5 – Glanville apparatus for self levelling CLSM (left) and metallic counter-mold for compacted materials (right)

### 3. EXPERIMENTAL CAMPAIGN

#### 3.1. Choice of components and mix design

For the present study, local sands and aggregates have been chosen for the different mixtures. (Gennesseaux, 2015) showed that the nature of aggregates had very few influence on the excavatability of a CLSM. Assuming that this result is valid on compacted cementitious materials either, gneiss aggregates were used here since they were easily available. A limestone filler was also used as well as a cement CEM I in order to control the paste volume and its strength. The limestone filler and the cement can be switched volume by volume in order to maintain the same paste volume, but with different W/C ratio. This permits to generate materials with the same granular skeleton, but with different unconfined compressive strength.

Table 1 – Material used for the present study

Material number	Type	Description	Density	Absorption	Packing density
			[kg/m <sup>3</sup> ]	[%]	-
MH-18-052	Cement	CEM I 52,5 St-Pierre-Lacour	3120	0	-
MH-14-123	Limestone filler	Betocarb HP EB	2730	0	-
MH-18-061	Sand	0/4 Cheviré	2620	0,7	0,707
MH-01-021	Sand	2/4 Noubleau	2830	0,5	n.c.
MH-14-120	Coarse aggregate	5,6/11,2 Bréfauchet	2600	0,5	0,581
MH-14-121	Coarse aggregate	8/16 Bréfauchet	2600	0,5	0,573
MH-18-056	Coarse aggregate	14/20 Bréfauchet	2600	0,5	0,559
MH-18-057	Coarse aggregate	20/31,5 Bréfauchet	2600	0,5	0,543

The mix-design of a material in terms of excavatability means that the higher penetration depth with the laboratory-punching test should be obtained for a specific unconfined compressive strength level. In the present study, a reference compressive strength value of 1 MPa will be taken for interpretation. It has been established for CLSM that the main mix-design parameters influencing the punching test penetration are the unconfined compressive strength; the air content (with air-entraining agent in the case of CLSM); the paste volume; the maximum diameter of aggregates ( $D_{90}$ ) and the grading curve through the  $D_{50}/D_{90}$  ratio (Gennesseaux, et al., 2017).

For this study, 9 different compacted cement-treated bases have been designed presenting different granular skeletons with different packing density (to generate different porosities) and different aggregates diameter ( $D_{90}$  – to generate different interlocking during excavations). Those 9 granular skeletons are named GE in the present paper. Their grading curves are presented in Figure 6.

The cement-treated base GE1 is very similar to the one designed for the first RUP experiment and is not porous (de Larrard, 2008).

The cement-treated bases GE2 and GE3 are non-porous either but are optimized in the sense of excavatability with a more adapted grading curve (GE2) and a higher paste volume (GE3).

The cement-treated bases GE4, GE5, GE6 and GE8 have a porosity of about 30% but display different coarse aggregate sizes ( $D_{90}$  from 11.2mm to 31.5mm). Those mixes permit to study the influence of  $D_{90}$  on the punching test penetration and on excavatability since it appears in the equations (3) and (4).

GE7 have a  $D_{90}$  of 11.2mm and a porosity of 12% in order to study the influence of the porosity on the punching test penetration.

GE9 is mainly a mortar with some coarse aggregates inside. It aims at studying if the interlocking effect can be observed while reducing the volume of coarse aggregates.

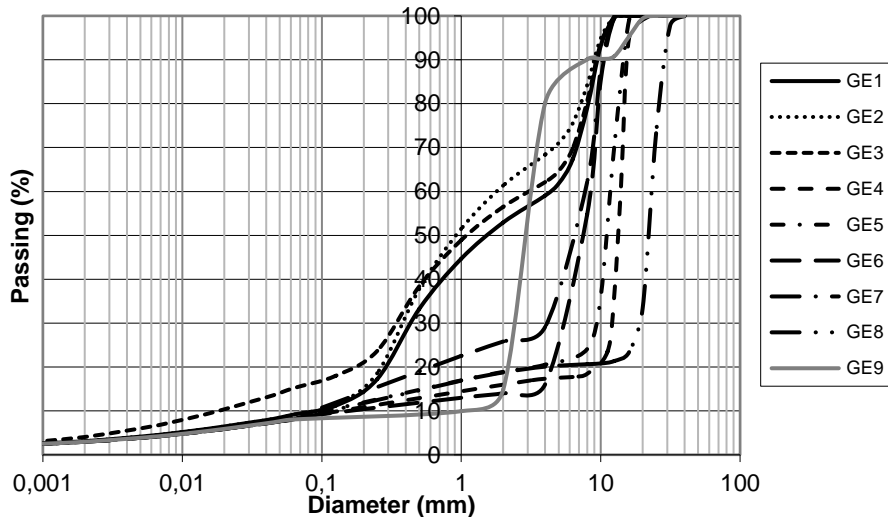


Figure 6 – Grading curves of the compacted cementitious materials

Then, for each granular skeleton, the water content was defined as the maximum value obtained after performing the proctor compaction test following the French standard (NF-98-231). Then, several mixes were generated with different unconfined compressive strength in order to cover approximately the interval 0.5 MPa to 2.5 MPa. This interval enables a priori to cover the different excavatability levels from very easy to very difficult. The strength was controlled by replacing volume per volume filler by cement in order to keep the fines volume constant between the mixes of a same family.

Table 2 details the proportions of all the mixes tested and precise some of their characteristics and measures. The mixes were named as follow:

- GEX : cement-treated base granular skeleton number X
- WY: Added water content Y%
- CZ: Cement content Z%

It can be noted that the GE4 punching tests were performed without blocking the translations of the molds as it was performed for all the other tests. Consequently, the specimens were cast again and the tests repeated by blocking the translation (GE4b).

Each mix designed have been characterized thanks to the following specimens:

- 3  $\emptyset 16 \times 32 \text{cm}^3$  cylinders for unconfined compressive strength measurement cast using the vibro-compression device
- 6  $\emptyset 16 \times 16 \text{cm}^3$  cylinders for laboratory punching tests cast using the vibro-compression device

All the presented data were measured at 28 days and the punching test penetration measured at the energy of 350 J.



Table 2 – Proportions and characteristics of the cement-treated bases tested

	C	F	S	G 5.6/11.2	G 8/16	G 14/20	W	Dry density	Air/voids content	Paste volume without air	D <sub>90</sub>	R <sub>c</sub> at 28 days	E <sub>pc350</sub>
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[kg/l]	[%]	[%]	[mm]	[MPa]	[mm]
GE1-W6.3-C0.5	0.5	9.5	50.0	40			6.3	2.19	4.30%	20.4%	9.56	0.32	44.3
GE1-W6.3-C1	1.0	9.0	50.0	40			6.3	2.19	4.30%	20.3%	9.56	0.71	31.5
GE1-W6.3-C1.5	1.5	8.5	50.0	40			6.3	2.19	4.37%	20.3%	9.56	1.24	25.0
GE2-W6.3-C0.5	0.5	9.5	60.0	30			6.3	2.18	4.52%	20.6%	9.09	0.28	46.5
GE2-W6.3-C1	1.0	9.0	60.0	30			6.3	2.18	5.04%	19.8%	9.09	0.63	33.2
GE2-W6.3-C1.5	1.5	8.5	60.0	30			6.3	2.18	4.52%	20.7%	9.09	1.15	27.4
GE3-W5.5-C0.2	0.2	21.3	43.5	35			5.5	2.25	3.75%	28.6%	9.45	0.50	42.5
GE3-W5.5-C0.4	0.4	21.1	43.5	35			5.5	2.25	4.17%	28.1%	9.45	0.85	35.1
GE3-W5.5-C0.9	0.9	20.6	43.5	35			5.5	2.25	3.62%	28.9%	9.45	1.27	24.2
GE3-W5.5-C1.4	1.4	20.1	43.5	35			5.5	2.25	4.18%	28.1%	9.45	2.67	17.4
GE4-W4-C1.1	1.1	7.9	8.0			83	4.0	1.69	31.19%	10.7%	15.70	0.41	61.8
GE4-W4-C1.6	1.6	7.4	8.0			83	4.0	1.69	30.71%	10.9%	15.70	0.94	53.6
GE4-W4-C2.1	2.1	6.9	8.0			83	4.0	1.69	30.57%	11.3%	15.70	1.40	49.0
GE4b-W4-C1.1	1.1	7.9	8.0			83	4.0	1.76	26.64%	11.4%	15.70	0.46	55.7
GE4b-W4-C1.6	1.6	7.4	8.0			83	4.0	1.76	27.93%	11.3%	15.70	0.96	49.1
GE4b-W4-C2.1	2.1	6.9	8.0			83	4.0	1.76	24.34%	11.6%	15.70	1.86	32.28
GE5-W4-C1.1	1.1	7.9	11.0		80		4.0	1.80	24.87%	12.5%	14.91	0.51	39.7
GE5-W4-C1.6	1.6	7.4	11.0		80		4.0	1.80	24.63%	12.4%	14.91	1.28	31.1
GE5-W4-C2.1	2.1	6.9	11.0		80		4.0	1.80	24.64%	12.4%	14.91	1.72	26.5
GE6-W4-C1.1	1.1	7.9	5.0	86			4.0	1.75	27.19%	11.5%	10.85	0.64	44.1
GE6-W4-C1.6	1.6	7.4	5.0	86			4.0	1.75	27.33%	11.6%	10.85	0.88	37.8
GE6-W4-C2.1	2.1	6.9	5.0	86			4.0	1.75	27.55%	11.3%	10.85	1.42	32.1
GE7-W4.5-C0.5	0.5	8.5	19.0	72			4.5	2.12	11.01%	14.9%	10.51	0.41°	38.0
GE7-W4.5-C0.7	0.7	8.3	19.0	72			4.5	2.12	11.58%	14.7%	10.51	0.76	29.6
GE7-W4.5-C1.1	1.1	7.9	19.0	72			4.5	2.12	11.94%	14.7%	10.51	1.23	24.8
GE7-W4.5-C1.5	1.5	7.5	19.0	72			4.5	2.12	12.01%	14.6%	10.51	1.91	20.9
GE8-W4-C1.6	1.6	7.4	11.0			80**	4.0	1.80	24.11%	13.0%	29.43	1.09°°	36.5
GE9-W5.5-C0.9	0.9	8.1	81*			10	5.5	1.96	20.84%	16.2%	7.96	0.30	53.8
GE9-W5.5-C1.3	1.3	7.7	81*			10	5.5	1.92	22.17%	16.1%	7.96	0.55	47.2
GE9-W5.5-C2	2.0	7.0	81*			10	5.5	1.92	22.50%	15.7%	7.96	1.30°°°	30.7

\*2/4 Noubleau sand - \*\*Bréfauchet 20/31.5 coarse aggregate – Measurement at °21 days. °°23 days and °°°24 days

### 3.2. Results

All the results of punching test penetration at 350J ( $E_{pc350}$ ) were then plotted vs unconfined compressive strength ( $R_c$ ) on different  $E_{pc} - R_c$  curves gathering the families of mixes per granular skeleton. As it can be seen on Figure 7, for each granular skeleton, the data can be satisfactorily fitted with curves according to the following type of equation:

$$E_{pc} = \alpha \cdot R_{c28}^{\beta} \quad \text{with } \alpha \text{ and } \beta \text{ constant for a given granular skeleton} \quad (5)$$

Such a good fitting was also obtained for CLSM previously studied in (Genesseaux, et al., 2017).  $\alpha$  and  $\beta$  describe the marginal effect of parameters other than compressive strength.

The cement-treated bases GE2 and GE3 are voluntarily excluded of Figure 7 for sake of clarity of the figure first, but also because the punching test depths of those materials was rather similar to the ones of GE1. Consequently, one can qualitatively observe from Figure 7 that:

- It can be confirmed that a higher void-content leads to higher level of penetration for a specific unconfined compressive strength value;



- It is not possible to conclude on a possible effect of D90 on the penetration. This parameter seems to have a certain influence, but a classification is not possible;
- The  $E_{pc} = \alpha \cdot R_{c28}^\beta$  curves remain parallel for different air contents. This means that the influence of air content on penetration is independent of the strength level. This point was not observed on CLSM where the benefic influence of entrained air decreases with an increase of strength. However, the nature of the voids is different: air bubbles generated by air entraining agent for CLSM on one hand and compaction voids linked with packing density for the cement-treated bases of the present study, on the other
- The error bars represented on the figure correspond to two times the standard deviation. One can observe that they increase with the D90 of the aggregates despite controlled testing procedures. This could influence the implementation of the material and the in-situ excavatability of the materials. It can be noted here that for GE8, the D90 of aggregates is 2.5 times bigger than the punching test diameter, which could influence the measurement.

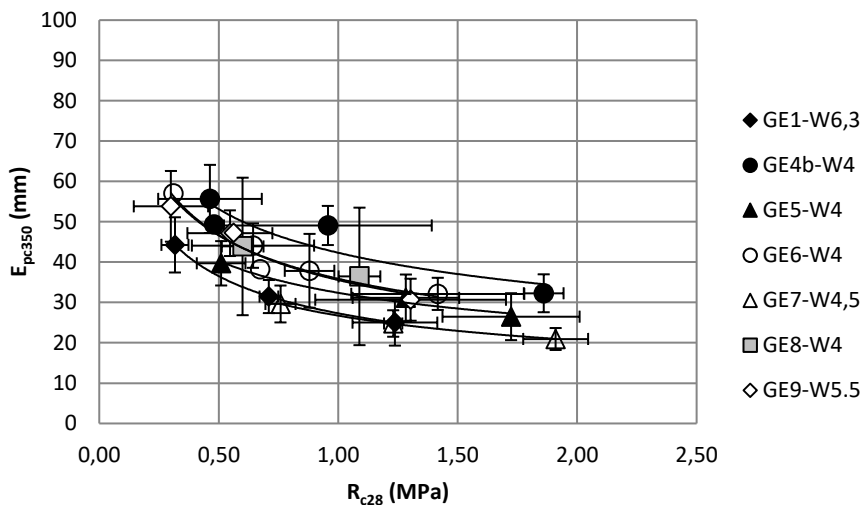


Figure 7 – Punching test penetration at 350 J ( $E_{pc350}$ ) versus unconfined compressive strength at 28 days ( $R_{c28}$ ) for the cement-treated base tested (without GE2 and GE3, and including data from the tests on trenches detailed below)

Figure 8 is representing the excavatability abacus for the different materials tested in this paper. The laboratory punching tests values have been interpolated from the  $E_{pc} = \alpha \cdot R_{c28}^\beta$  curves represented on Figure 7 for unconfined compressive strength values of 0.5, 1 and 2 MPa. This permits to appreciate the expected excavatability level of each material and the influence of the strength on it. This abacus was obtained from the equations (3) and (4) where the internal friction angle of the material appears. This study focuses on porous cement-treated bases while the previous studies focused on CLSM. Consequently, the internal friction angle value was verified on porous cement-treated base performing a triaxle test on 3  $\varnothing 16 \times 32$  cm<sup>3</sup> cylinders of the mix GE6. While the internal friction angle had an average value of 41.5° for CLSM, a value of 50° was measured for porous cement-treated base. This value was used to generate the abacus presented on Figure 8. With this figure, it can be observed that:

- The non-porous cement base GE1 (but also GE2 and GE3 not represented here for clarity of the figure) remains difficult to excavate. even at low strength;
- With higher air content (about 25%) it is possible to ease the excavations until an easy level for manual excavation (in the case of mix GE4 with a strength lower than 1 MPa);
- The mix GE8 is rated “easy” to excavate, but the abacus has not been validated for D90 higher the 20mm (Genesseaux, 2015). This observation should be validated with field excavations;
- The mix GE9 is represented with a  $D_{90}$  of 8mm while it could also be 12.5mm regarding its grading curve (see Figure 6). An in-situ test is also needed here for a better understanding.

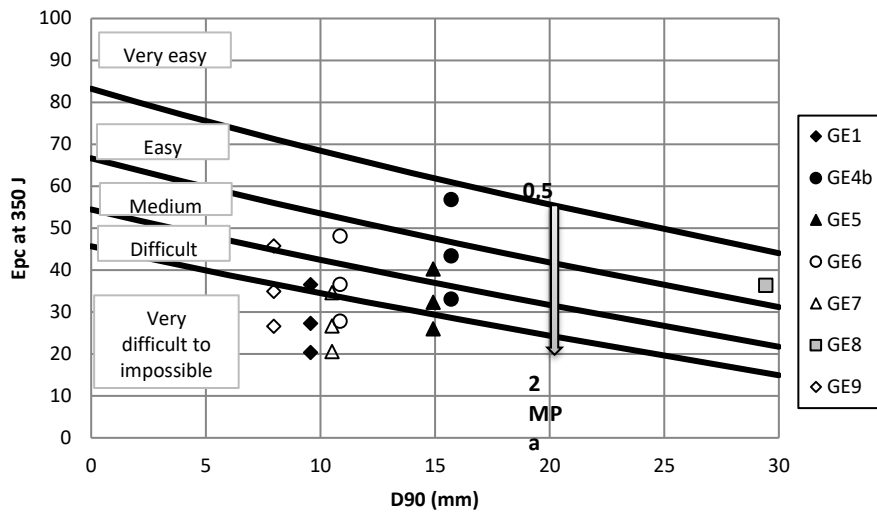


Figure 8 – Excavatability level of the cement treated bases tested (without GE2 and GE3) with  $\phi=50^\circ$  and for the unconfined compressive strength 0.5, 1 and 2 MPa

Those results need to be verified with real scale excavations. Consequently, complementary excavation tests are described below in section 5.

#### 4. PREDICTIVE MODEL OF THE PUNCHING TEST PENETRATION

(Genesseaux, et al., 2018) proposed a prediction model of the punching test penetration at 350 J validated on CLSM. The model is described with the following equation:

$$E_{pc350} = \left( 25 \times V_{p.without.air}^4 + 1567 \times \frac{V_{air}^{2.76}}{R_c \times \sqrt{\max(D_{90}; 1.5)}} - 21 \times \sqrt{\frac{D_{50}}{D_{90}}} + 41.27 \right) \times R_c^{-0.5} \quad (6)$$

Where  $V_{p.without.air}$  is the dimensionless paste volume ratio without the air entrained (i.e. the volume of all the fine particles smaller than 80  $\mu\text{m}$  like cement, filler, aggregates fines and water divided by the overall volume of mix);  $V_{air}$  is the dimensionless air-entrained volume ratio;  $D_{50}$  and  $D_{90}$  are the diameters in mm enabling 50% (respectively 90%) of the complete grading curve (including the fine elements of the mixture such as cement or mineral addition) to pass through;  $R_c$  is the unconfined compressive strength (in MPa) at the moment of the penetration test.

This model permits the prediction of the punching penetration at 350J for self-compacting cementitious materials with an absolute error of 4.7mm. Yet, the prediction of the penetration for porous cement bases is not ensured.

Consequently, Figure 9 compares the prediction obtained with the model to the experimental data collected for the present paper. One can observe that the prediction is not very satisfactory for porous cement bases ( $R^2=0.67$ ). The model tends to over-estimate the penetration measured and the correlation is bad for some mixtures. Since the nature of the materials is different (non-porous/porous; fluid/dry; self-compacting/mechanically compacted), the model needs to be modified for the case of the excavatable porous cement bases.

Following the previously presented experiment, one can comment that:

- The parameter  $D_{50}/D_{90}$  has very few influences in the case of the porous cement-bases since its value is close to 1 in this case (see the grading curves Figure 6).  $D_{50}/D_{90}$  could be taken out of the model's equation.
- In Figure 7 the influence of the air content on the penetration is independent of the unconfined compressive strength (which was not observed on self-compacting concrete). The model could be modified that way.

- The parameter  $D_{90}$  does not have a clear influence on the penetration in cement bases (Figure 7)

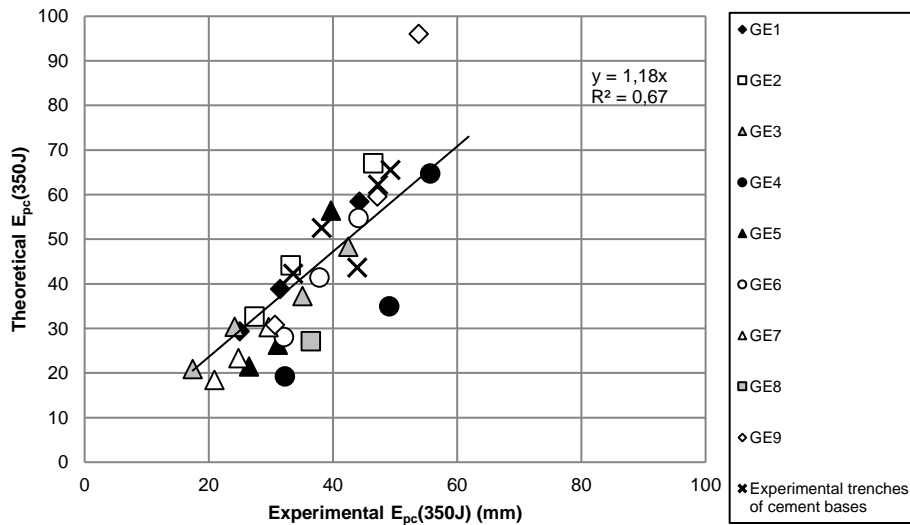


Figure 9 – Comparison of the experimental punching test penetration versus the model prediction (6) at 350J for the cement bases tested in the present study

Consequently, the following prediction model of the penetration in porous cement bases is proposed:

$$E_{pc350} = (25 \cdot V_{p.without.air}^4 + 40 \cdot V_{voids}^{0.74} + 20.27) \cdot R_c^{-0.5} \quad (7)$$

Where  $V_{voids}$  is the compaction voids content.

The constants of the equation (6) were kept constant except the one applied to the compaction voids. The value of  $D_{50}/D_{90}$  was set to 1.

Finally, Figure 10 represents the correlation obtained with the new model (except for the non-porous cement bases GE1, GE2 and GE3 predicted with equation (6)). One can observe a significant improvement of the prediction ( $R^2=0.86$ ).

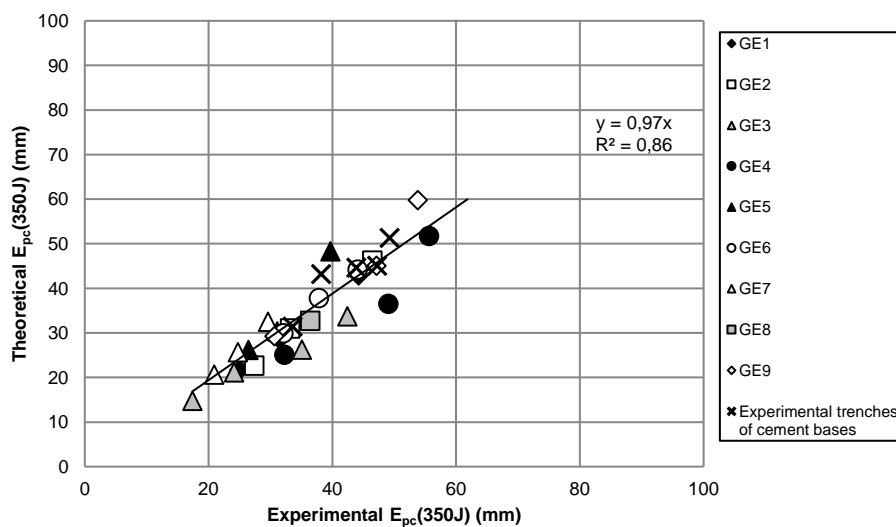


Figure 10 – Comparison of the experimental punching test penetration versus the model prediction (7) at 350J for the cement bases tested in the present study

## 5. VALIDATION WITH MANUAL EXCAVATIONS

The predictive model of the excavated volume from the punching test penetration and the excavability monogram (see 2) was proposed based on excavation tests performed on self-compacted materials. Therefore, a validation of those models and monogram is necessary for the porous cement bases developed in the present paper since their nature is rather different from self-compacting materials.

This part describes the experimental campaign of manual excavations carried out for this purpose. For each tested mixture, 3  $\text{Ø}16 \times 32 \text{cm}^3$  cylinders were cast for unconfined compressive strength measurement; 6  $\text{Ø}16 \times 16 \text{cm}^3$  cylinders were cast for punching tests measurement and one small trench of dimensions  $L70 \times I50 \times H30 \text{cm}^3$  was cast in a wooden mold for excavation tests.

For each mixture, two batches of 75L of material were produced to produce all the specimens (half of the specimens for each batch).

Four porous cement bases were tested, presenting different  $D_{90}$  levels in order to study the influence of this parameter on excavation; which can be seen with the punching test:

- GE4-W4-C1.2 which have  $D_{90}=20\text{mm}$  and is the most easily penetrated by the punching test;
- GE6-W4-C1.1 which have  $D_{90}=11.2\text{mm}$  and has satisfactory results with the punching test;
- GE8-W4-C1.2 which have  $D_{90}=31.5\text{mm}$ . Such a  $D_{90}$  has never been tested with the approach and is expected to give good interlocking of the aggregate to improve the excavability;
- GE9-W5.5-C1.3 where a small amount of big coarse aggregate has been added to have a higher interlocking effect.

A standard self-compacting concrete with low unconfined compressive strength was also tested to validate the experimental campaign regarding the excavability approach.

For porous cement bases, the cylinders were poured by vibro-compaction, and the mini trenches were produced thanks a manual compaction of each layer with an accurate control of the density by the weight of material introduced and the volume of the mold (see Figure 11). In the case of the self-compacting concrete, samples were simply poured with the Glanville apparatus (see Figure 5).

Similar void contents and an “easy” excavability level have been aimed based on the monogram on Figure 4. The mix designs, void contents and unconfined compressive strength measured at the excavation time (28 days) are gathered in Table 3 and Table 4.

Table 3 – Mix design of the self-compacted concrete tested (Quantities in kg/m<sup>3</sup>)

Mix	C	F	S 0/4	G 5.6/11.2	G 8/16	Water	Air content (%)	Rc (MPa)
BA-058	38	101	856	104	920	206	1.39%	0.46

Table 4 – Mix-design of the porous cement bases (Quantities in % of dry material)

Mix	C	F	S 0/4	G 2/4	G 5.6/11.2	G 14/20	G 20/31.5	Water (%)	Voids content (%)	Rc (MPa)
GE4-W4-C1.2	1.2	7.8	8			83		4	28.83%	0.48
GE6-W4-C1.1	1.1	7.9	5		86			4	28.10%	0.67
GE8-W4-C1.2	1.1	7.9	11				80	4	25.65%	0.71
GE9-W5.5-C1.3	1.3	7.7		81		10		5.5	25.06%	0.57



Figure 11 – Manual compaction of the trenches (left); mechanical excavation test (center); manual excavation test (right)

All the trenches and specimens were tested at 28 days. Manual excavation tests were performed following the protocol detailed by (Gennesseaux, 2015) (Ilfsttar et Engie, 2016). The same operator performed three series of 30 impacts with a pick on each trench in blind conditions (see Figure 11). The removed material was weighed after each series and the difficulty rating (between 1 and 5) was given by the operator, after each test.

To verify the punching test penetration prediction, some mechanical tests were also performed with a controlled impact energy in order to measure the pick’s blade penetration into the material ( $E_{pi}$ ) (see Figure 11). Three measurements were performed for each trench with a mechanical test consisting of an arm with a pick’s tool at its end and whose rotation is powered by a falling weight. More details on this test are given in (Gennesseaux, 2015).

All the measurement obtained are gathered in Table 5.

Table 5 – Experimental measurements obtained

Mix design	$D_{90}$	Impact energy of the mechanical test	$E_{pi}$ (mechanical)	$E_{pc}$ at the impact energy	$E_{pc}$ 350J	Excavated volume after 90 impacts	Difficulty rating from the operator	Difficulty rating from excavated volume
-	[mm]	[J]	[mm]	[mm]	[mm]	[L]	-	-
BA-058	14	307	58.33	30.70	33.60	17	Medium	Medium
GE4-W4-C1.2	15.7	301	65.00	44.73	49.28	44	Difficult	Very easy
GE6-W4-C1.1	10.85	307	65.00	34.95	38.22	33	Easy	Easy
GE8-W4-C1.1	29.43	302	51.67	40.67	43.89	36	Very difficult	Easy
GE9-W4-C1.3	7.96	308	68.33	43.80	47.27	18	Medium	Medium

Figure 12 compares the excavatability rating given by the operator to the manually excavated volume.

It can be seen that the correlation between the rating and the excavated volume is validated for the self-compacted concrete (BA) as expected, and for the porous cement bases GE6 and GE9. However, this is not the case for GE4 and GE8 which were rated as “difficult” and “very difficult” while presenting high excavated volumes. This can be explained by the high  $D_{90}$  and the high porosity of the material, creating a strong vibration of the pick at the impact, which does not appear on plain materials or for lower  $D_{90}$ . Indeed, the operator complained of those vibrations.

It is also important to tell that the operator was different from the one who performed the excavations for (Gennesseaux, 2015) and (Morin, 2009); which can influence the rating.

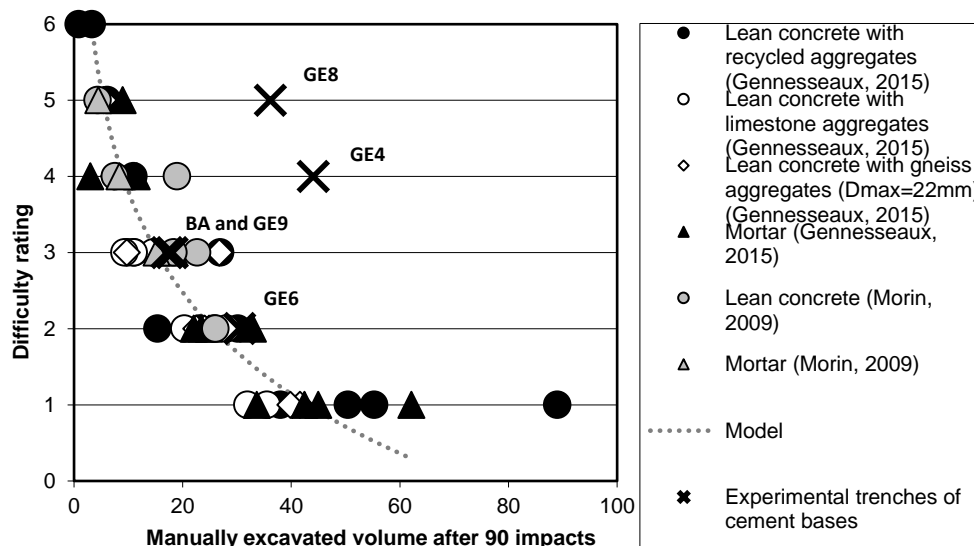


Figure 12 - Comparison between the note and the excavated volume (data from (Gennesseaux, 2015) and (Morin, 2009) and from the present study)

Nevertheless, as shown on Figure 7 which included the data collected for this experimental campaign on trenches, the prediction of the pick penetration remains consistent with the experimental results.

Then Figure 13 compares the laboratory punching test measurements to the penetration of the mechanical tool. One can observe that the correlation obtained on self-compacting materials remains valid for porous cement bases, confirming the interest of the laboratory punching test as a predictive tool.

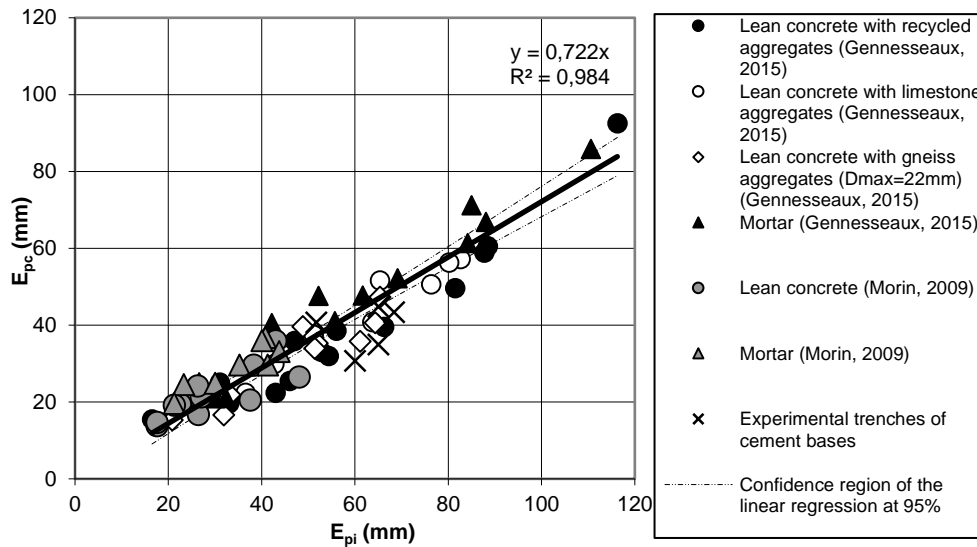


Figure 13 – Punching test penetration measured at the impact energy of the mechanical test versus penetration of the tool of the mechanical test ( $E_{pi}$ )

Figure 14 presents the application of the prediction model of excavated volume to the data collected on porous cement bases, in the present study. The set of parameters used by (Genesseaux, 2015) and the measurement of the punching test penetration at 350 J were used. Only the internal friction angle, measured at  $50^\circ$  on porous cement bases, was adapted (while  $41.5^\circ$  was used for CLSM), and the difference between entrained air and compaction voids was made (see eq. 6 and 7). The correlation appears satisfactory for porous cement bases, which validates the model for this specific case.

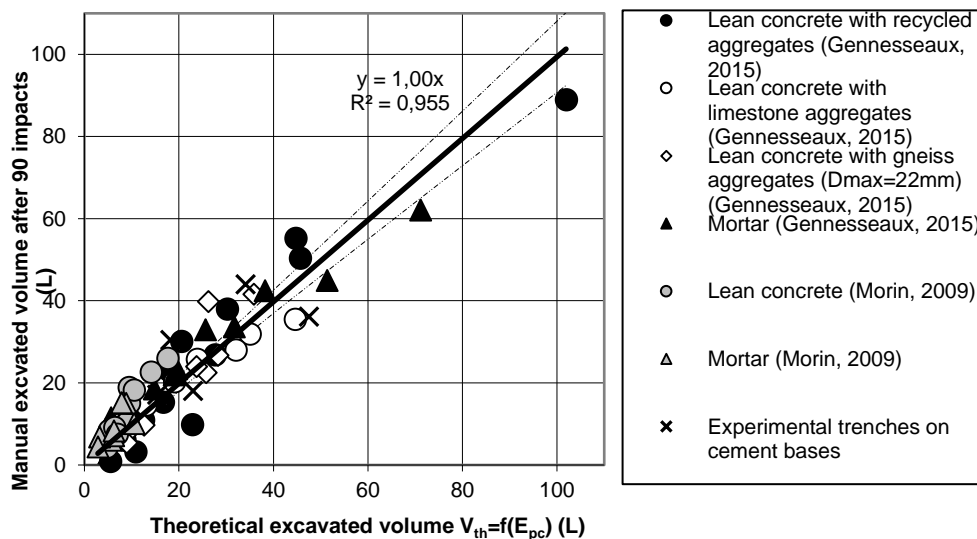


Figure 14 – Manual excavated volume versus theoretical excavated volume calculation from the prediction model detailed above (Figure 2)

Finally, Figure 15 represents the collected data on trenches on the excavability monogram corrected with the internal friction angle measured for porous cement bases and extrapolated until 30mm of  $D_{90}$ .

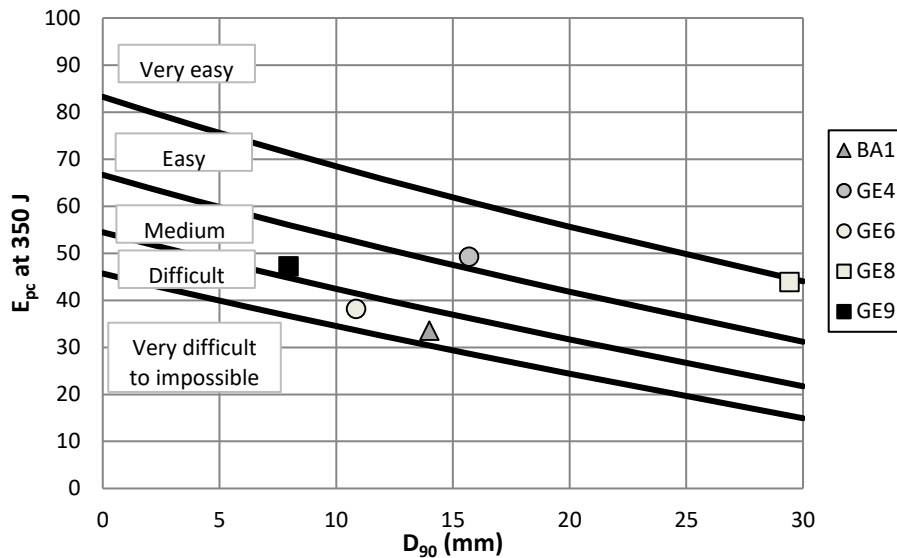


Figure 15 – Excavatability level of the materials tested on trenches

On the previous figure, it can be seen that the reference self-compacting material was rated as « medium » to excavate by the operator and « difficult » by the monogram. In addition, GE6 was rated as “easy” by the operator even if it appears as “difficult” on the monogram. Consequently, the monogram seems to be a bit too severe in its rating.

GE9 was rated as “medium” by the operator and appears as “medium” on the monogram whether a  $D_{90}$  of 8mm or 12.5mm is considered. The addition of some big coarse aggregates to this mix did not seem to improve the excavatability as expected whether considering the monogram (and consequently the punching test) or the excavated volume. More data are needed on this question, with higher content of big coarse aggregates in order to conclude on this point linked with the interlocking effect.

The porous cement bases GE4 and GE8, which have the higher  $D_{90}$  and were rated as “difficult” by the operator, are in the “easy” zone of the monogram. This difference is explained by the vibration felt by the operator during the impact on porous cement-bases with high  $D_{90}$ , which did not appear on self-compacting concrete containing a higher volume of paste. Therefore, the validation of the monogram should be limited to  $D_{90}=12\text{mm}$  for porous materials and high  $D_{90}$  should be avoided to ensure the excavatability of porous cement bases.

Taking into account the previous observation, the mixture GE6 appears as the best candidate as an excavatable cement base to fit the initial requirements of the project of the project. In addition, a laboratory measurement of the vertical permeability was performed. A value of 1.04 cm/s was obtained, confirming the high drainability of the cement base.

## 6. CONCLUSIONS

The present paper focuses on the mix-design of excavatable porous cementitious sub-base for draining removable urban pavement (RUP). A novel approach of excavatability characterization, based on a laboratory punching test and already validated on fluid cementitious materials (CLSM) was tested on porous compacted cement treated aggregates used as pavement base layer. With complete testing of different materials in laboratory and in experimental trenches, the paper shows that the approach remains valid on this new type of material with a good prediction of the pick’s blade penetration and of the excavated volume.

The study also proposes a modified punching test penetration model derived from a model developed on CLSM, accounting on the mix design of the cement base allowing by the way their optimization at the laboratory stage.



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