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FORMULATION OF OPTIMIZED EXCAVATABLE CEMENT TREATED MATERIALS USING A NEW PUNCHING TEST APPARATUS

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ABSTRACT

Classical techniques for backfilling of trenches use unbounded materials. Unfortunately, they have been presenting several drawbacks regarding compaction such as noise disturbance, time of implementation and long-term settlement. In that context, Controlled Low Strength Materials (CLSM) could be a good alternative solution thanks to their fluidity and cementitious setting, provided that they remain excavatable, even manually with a pick. In fact, it is essential to ensure a rapid and easy permanent access to the underlying networks, in case of emergency or maintenance. Yet, the excavatability was not well defined, nor well measured so far. A fortiori, no mix design process is available to control the excavatability of these materials. It is the purpose of this article to develop one.

Recently, a new approach based on a simple punching test in laboratory was proposed to provide a quantitative characterization of cement treated materials excavatability, accounting for the pick impact energy (Morin, 2009; Morin, et al., 2013; Morin, et al., 2017). The present paper first briefly describes how, in the continuation of this study, the testing set-up was improved, the approach was validated and the underlying theoretical models were calibrated on an important campaign of manual excavation on real scale trenches, in parallel with laboratory punching tests.

Once the laboratory method developed, it was possible to proceed a large parametric campaign at the laboratory stage to identify the mix design parameters that influence the excavatability of cementitious materials. The second part of the paper describes the methodology used and the empirical model deduced to link the mix proportions of a cementitious material to its excavatability.

Finally, manual excavations were realized on real scale trenches to confirm the relevance of the model. In conclusion, a global mix design method is proposed for excavatable cement treated materials, with a brief economical simulation.

KEYWORDS

CONTROLLED LOW-STRENGTH MATERIALS / CEMENT BASED MATERIALS / FORMULATION / EXCAVATABILITY / PICK / PUNCHING TEST / TRENCH.

1. INTRODUCTION

For network owners, the use of Controlled Low Strength Materials (CLSM) has always been an interesting solution for backfilling of trenches since it presents several advantages (Bonnet, et al., 1998). Indeed, those materials provide an easy implementation thanks to their fluidity and to a self-compacting capacity that can be given to them (ACI-229R-99, 1999). This can lead to a general economy in-situ by avoiding heavy compacting equipment, reducing the implementation time and further settlements. Nevertheless, the excavatability of this solution needs to be ensured to allow further maintenance operations on the underlying networks. Moreover, because networks are often fragile, the excavation is generally finished with a manual pick and excavatability must be ensured for that critical case. Yet this aspect has not been well managed up to now, because excavatability was not well defined, nor well measured. Consequently, the relationship between mix design of

cementitious materials and excavatability was not clearly established. This is the aim of this paper to establish it.

The classical excavatability evaluation methods of those cementitious materials are based on excavated volumes quantification (Pons, et al., 1998) or on subjective difficulty rating obtained after heavy in-situ real scale excavations (Crouch, et al., 2003; NCHRP, 2008). Those methods appeared to be unsatisfying because they are difficult to perform (heavy equipment), they only permit a characterization after the implementation of the material in the trench (and not in laboratory before placing) and they do not take into account the excavation energy (pick, jackhammer, backhoe…). Consequently, a new method was developed at IFSTTAR based on a laboratory punching test that gave preliminary encouraging results tests to evaluate efficiently the excavatability of cementitious materials (Morin, 2009; Morin, et al., 2013; Morin, et al., 2017).
Regarding the influence of mix design parameters on excavatability of cementitious materials, the literature review realized at the beginning of this research led to identify some potential parameters to focus on. Thereby, the unconfined compressive strength appears to be the most generally admitted influencing parameter. It is in fact, considered as the criterion of excavatability in France (CERTU, 1998) and in the USA (ACI-229R-99, 1999) where a specific strength value (2 MPa for CERTU and 1,4 MPa for ACI) is defined as a limit between excavatable and non-excavatable materials using a backhoe. Nevertheless, it is a main concern that the criterion differs from a country to another and does not depend on the excavation tool power. Moreover, those yield values appeared to be insufficient in some cases (Crouch, et al., 2003; NCHRP, 2008; Morin, 2009), and too restrictive in others (Webb, et al., 1998). In conclusion, even if compressive strength is undoubtedly a major parameter, secondary parameters have probably to be accounted for. For example, the increase of air content was identified to facilitate excavation aside its direct influence on compressive strength (Crouch, et al., 2003). On the same subject, a excavatability criterion named Removability modulus (RE) is described in several papers (Hamcin, 1996) whose calculation depends on the specific density of the material and consequently on the air content.
In (Krell, 1989; Crouch, et al., 1998; Halmen, 2005) the authors suggest that the volume of paste influences the excavatability. It seems relevant as the paste is the weak part in CLSM compared to the granular skeleton. Finally, the maximum aggregate diameter seems to play a role on excavatability as it controls interlocking when material is pulled off (Morin, 2009), as it will be described in the next chapter. In conclusion, only little information is available so far.

In that context, the present paper first briefly describes the new laboratory method developed at Ifsttar, based on a punching test. It explains how during the present study, the testing set-up was improved, the approach was validated and the underlying theoretical models were calibrated on an important campaign of manual excavation on real scale trenches. Once the laboratory method developed, it was possible to proceed a large parametric campaign at the laboratory stage to identify the mix design parameters that influence the excavatability of cementitious materials. The second part of the paper describes the methodology used and the empirical model deduced to link the mix proportions of a cementitious material to its excavatability. Finally, a validation of the model is done on real scale trenches. In conclusion, a global mix design method is proposed for excavatable cement treated materials and a way for optimization of CLSM in the sense of excavatability is suggested.

2. VALIDATION AND IMPROVEMENT OF A NEW APPROACH TO CHARACTERIZE THE EXCAVATABILITY

To tackle the issue of the excavatability of controlled low strength materials (CLSM) for backfilling of trenches Morin had proposed a new approach based on a laboratory punching test apparatus (Figure 2), (Morin, 2009; Morin, et al., 2013; Morin, et al., 2017). Because Morin had only made a preliminary validation of the method on a limited number of materials, the first stage of the present study was to improve, validate and calibrate it, on a large experimental campaign comparing in-situ manual excavation operated by an experimented worker on trenches, to laboratory punching tests mixes.

The approach considers the excavated volume as a criterion of differentiation between excavation difficulties. Indeed, a good correlation was found between the excavated volume and the difficulty

rating given by the manual operator; enabling the determination of excavatability thresholds on the excavated volume.
A simple prismatic rupture model (Figure 1) was proposed by Morin to predict the excavated volume V (in L) for 90 impacts (this value was arbitrarily selected to mean the experimental measurements with a reasonable effort), leading to the following equations.

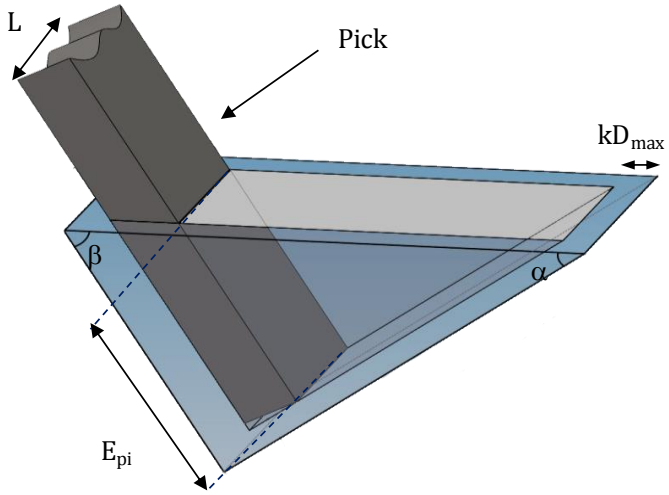

Figure 1 - Rupture mechanism of backfilled materials. A surrounding supplementary volume is accounted for due to aggregate interlocking

$$V_{theoretical} = \frac{90}{2} a'^{2} \left(\frac{1}{\tan(\beta)} + \frac{1}{\tan(\alpha)} \right) (L + 2k.D_{90}) \quad (1)$$

$$\text{With } a' = E_{pi} \times \sin(\beta) + k.D_{90}\left[\sin(\beta) + \cos(\beta)\right] \quad (2)$$

$$\alpha = \frac{\pi}{2} - \frac{(\beta + \varphi)}{2} \quad (3)$$

where, E_{pi} is the penetration depth and β (in rad) the angle of penetration of the pick's blade into the material. They are measured directly on the trench after the pick impact. L is the width of the pick blade (in mm), φ is the internal friction angle of the material (in rad) and finally α is determined by limit analysis. 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 $k.D_{90}$; D_{90} being the diameter through which 90% of the grading curve is passing (in mm).

A large campaign on trenches was realized during which excavated volume and pick penetration were systematically measured, on different materials (Gennesseaux, 2015). It was confirmed that this set of equations is relevant to predict the volume from the pick penetration with a mean error of 5.6 L (for volumes of about 30 to 45 L for an easy excavation level) provided that k and φ are fitted to 0.6 and 41.5° respectively. The value obtained for k is consistent with the fact that the interlocking effect can take place only if aggregates are sufficiently anchored in the main part of material extracted by the blade, while fitted φ is in accordance with the mean value obtained on different materials through a direct measurement in triaxial tests (Morin, et al., 2013). A mean value of 60° was obtained by measurement for β.

As a second step, the laboratory punching test setup proposed by Morin was improved to be more rapid and precise. 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. Morin initially selected a penetration speed of 9.5 mm/min. For convenience, it was increased up to 900 mm/min within the present study. This acceleration was proven without influence on the results after some specific comparison tests (Gennesseaux, 2015). A stiff

displacement-controlled 150kN compressive testing machine was used to produce all the data collected for this paper.

Figure 2 - Punching test device

Cylindrical specimens confined in a metallic mold of 16 cm in height and 16 cm in diameter are used as samples (Figure 2). 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).
During the test, a potentiometer sensor whose maximum range is 100 mm monitors the displacement, while a load sensor with a 100 kN capacity monitors the stress. A computer with an HBM Spider8 acquisition box recorded the output voltages from the devices 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 mix 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) recently edited for the French construction community.

Once the testing procedure was stabilized, punching tests were realized on the same materials as those used for the trenches (Gennesseaux, 2015). The results highlighted a strong correlation between E_{pi} and the measurement of the penetration of the laboratory punching tests E_{pc} considering the same penetration/impact energy (Figure 3).

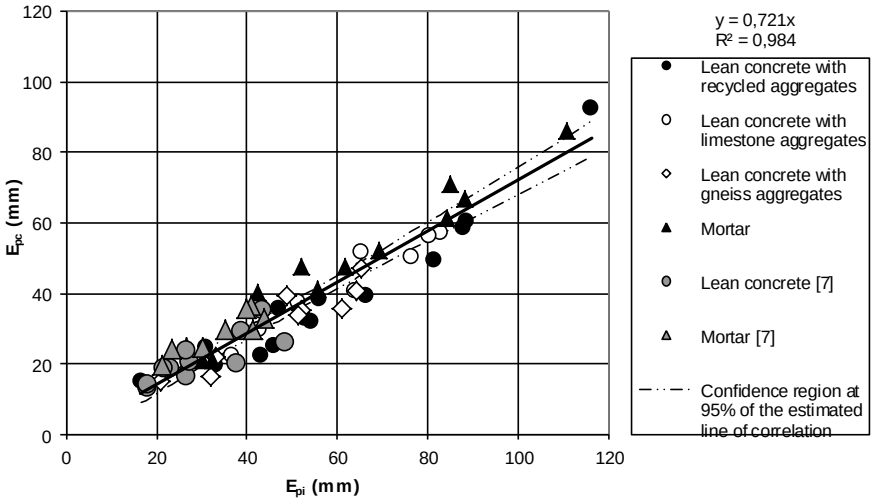

Figure 3 - Correlation between the punching test penetration E_{pc} and the in-situ tool penetration E_{pi} (dotted lines delimit the confidence region at 95% of the estimated line of correlation)

Thus, the deduced equation (4) is sufficient to predict the pick penetration from the laboratory test.

$$E_{pc}=0.72 \times E_{pi} \quad (4)$$

Nevertheless, experiments were realized to understand why the value of the coefficient differs from 1, even if a first explanation could be the dynamic character of pick penetration on trench while the punch test is done in quasi static conditions. First, the cylindrical punch was replaced by a punch with the same shape as the pick head, but the geometry was proven almost without influence. A second set of tests were realized by changing the angle of penetration of the punch from 90° to a 55° to have a value very similar to the angle obtained with the pick β. The results shows that $E_{pc}(90°)=0.66\ E_{pc}(55°)$ for the same energy. So, the attack angle explains mainly the coefficient value of the coefficient in equation (4). In fact, with an angle of 55°, the punch generates chips at the free surface of the material that facilitate the penetration. However, because cylindrical punch gives more stable measurements, and because having an angle of 55° could generate sliding or torsion of the punch, it was decided not to change the test conditions while equation (4) appeared precise enough.

Using equations (1) to (4), it was then, at this stage, possible to calculate the volume and the excavatability of a material just by knowing the D_{90} of the mixture, and measuring the punch penetration E_{pc} in laboratory, at the same energy as for pick impact. A detailed presentation of the method can be found in (Gennesseaux, 2015) and in (Ifsttar et Engie, 2016).

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

$$E_{pc}(W) = E_{pc}(350) \times (0{,}0021 \times W + 0{,}264) \quad (5)$$

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.

Consequently, the next sections focus on the determination of the mix parameters influencing the excavatability through the single evaluation of pick penetration using the punching test apparatus, which allows to lighten the tests compared to trench evaluation and to multiply the mixes to be tested.

3. EXPERIMENTAL CAMPAIGN

3.1. SELECTION OF STUDIED PARAMETERS AND MIXES COMPONENTS

Let´s consider here that an excavatable CLSM is a material made of two phases:

- The aggregate skeleton, which is the hard phase since it strength is much higher than the unconfined compression strength of CLSM itself (less than 8.3MPa according to (ACI-229R-99, 1999));
- The cement paste, considered as the weakest phase.

The pick´s head, during the penetration, will hit those two phases until being stopped when the impact energy is finally dissipated. Consequently, it seems reasonable to imagine that an increase of the weak phase volume (the paste volume) would make the penetration easier.

The literature review suggests the air entrainment is a good way to improve excavatability. A first effect could be linked to an increase of the paste content itself. But it is also intuitive that a porous paste could collapse more easily than a compact paste, as the area near the pick head is in confined conditions.

The grading curve is also an intuitive parameter. Two aspects should be considered, the maximum diameter of the aggregates (D_{90}) and the shape of the grading curve itself. Indeed, it is showed in (Morin, 2009; Morin, et al., 2013) that the D_{90} has a positive influence on the excavated volume due to interlocking after pick impact. But we can wonder if the size and proportion of coarse aggregates have a direct influence on pick penetration itself as they probably play a role on the probability to intercept the pick course and then dissipate more energy as hard particles of the

material. For this study, we will consider the coarse aggregate/sand mass ratio (CA/S) as an indicator of the grading curve, since it is commonly used for concrete.

Finally, the following parameters were studied, in addition to the compressive strength of the mixes:

- The paste volume (i.e. the aggregate volume);
- The nature (hardness) of the aggregates, through sand friability or Los Angeles value;
- The grading curve of the skeleton through the maximum aggregate diameter D_{90} and the coarse aggregate to sand mass ratio (CA/S);
- The percentage of entrained air.

Preliminary punching tests were done on mortars with two sands with the same friability and the same grading curve, but one rounded and the other crushed. No differences were observed due to the morphology of the sand, so it was decided to discard this parameter to limit the number of tests.

The evolution of excavatability with time is not a studied parameter in this paper but it is implicitly taken into account through the unconfined compressive strength value at the same age. Here, all the tests were performed at 28 days.

Table 1 summarizes some characteristics of the materials used for that purpose. An identification number was given to them for sake of clarity.
In addition, the same cement CEM II A/LL 42.5 from Airvault (ρ=3120 kg/m^3) and limestone filler Betocarb HP EB (ρ=2730 kg/m^3) were used for the different mixes. Finally, to study the influence of air content on penetration, a stable air entrained agent Betomouss was selected to generate mortars and lean concretes with air content going from 2% up to 30%.

Table 1 – Characteristics of the aggregates used for the mixes

N°	Material	Nature	Sand friability/Los Angeles value	Density [kg/m^3]	Water Absorption [%]
1	Sand 0/4 St-Colomban	Rounded Silica-pliocene	21	2620	0.3
2	Sand 0/4 Pilier	Sea sand Silica-limestone	27	2600	0.9
3	Sand 0/4 St-Maurice-la-Clouère	Crushed limestone	62	2530	2.8
4	Coarse aggregate Raon l'étape 4/6.3 and 6.3/14	Crushed andesite	7	2800	0.4
5	Coarse aggregate Maraichères 6/10. 10/14 and 14/20	Crushed gneiss	20	2630	0.5
6	Coarse aggregate St-Fraignes 6/12	Crushed limestone	40	2380	5.2
7	Coarse aggregate Jaillon 4/10 et 10/20	Crushed limestone	50	2360	5.5

3.2. CHOICE OF THE MIXES TESTED

For this experimental campaign, we tried to compare similar families of mixes grouped in clusters and differing by the value of only one parameter. For each family of mixes the components and the grading curves were first selected. Then the water content was adjusted to ensure a reasonable self-compacting property of the material. Finally, for each family, several mixes were generated with different unconfined compressive strength in order to cover approximatively 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 fine volume constant between the mixes of a same family.
Table 2 details the mixes tested for the study of the parameters "paste volume" and "air entrained". The mixes composition are given in kg and not exactly in kg/m^3 to read more easily the components that were kept constant and those who were changed.

Table 2 – Proportions (in kg) and characteristics of the mixes of the clusters "Paste volume" and "Air entrained" (C=Cement; F=Filler; S=Sand; G1 and G2 are the different fractions of coarse aggregates, from the finest to the coarsest; AEA=Air-entraining Agent; Vp=paste volume including all particles< 80µm; W=efficient water). Masses are given for dry aggregates.

Cluster	Family	Sand n°	Gravel n°	C [kg]	F [kg]	S [kg]	G1 [kg]	G2 [kg]	AEA [kg]	W [kg]	Air [%]	Vp without air [%]	R_{c28} [MPa]	E_{pc350} [mm]	D50 [mm]	D90 [mm]
M_Vp	M_Vp_40%	2	-	84	250	1480				258	1,0%	39,7%	1,45	22,8	0,5	2,2
				98	237	1480				258	1,3%	39,5%	2,00	21,4	0,5	2,2
				59	272	1480				258	1,9%	39,3%	0,55	35,7	0,5	2,2
	M_Vp_50%	2	-	116	550	1480				296	1,5%	48,1%	2,21	21,3	0,4	1,9
				99	564	1480				297	1,4%	48,1%	1,07	29,4	0,4	1,9
				68	591	1480				297	1,6%	48,0%	0,64	36,7	0,4	1,9
	M_Vp_70%	2	-	135	795	780				343	0,8%	68,9%	2,15	25,6	0,1	1,6
				117	805	780				353	1,0%	69,0%	1,31	35,1	0,1	1,6
				80	843	780				353	2,1%	68,3%	0,68	49,5	0,1	1,6
	M_Vp_100%	-	-	80	1393					460	1,0%	99,0%	0,73	65,7	0,0	0,1
				130	1349					460	1,0%	99,0%	1,56	43,1	0,0	0,1
				190	1296					460	1,0%	99,0%	3,50	30,8	0,0	0,1
C_Vp	C_Vp_30%	2	5	65	77	856	104	920		197	1,8%	25,4%	1,32	26,3	4,5	13,6
				38	100	856	104	920		197	2,1%	25,3%	0,40	42,7	4,5	13,6
				73	70	856	104	920		197	2,3%	25,3%	1,52	23,3	4,5	13,6
				83	62	856	104	920		197	2,9%	25,1%	1,69	20,5	4,5	13,6
	C_Vp_40%	2	5	66	410	724	88	778		201	0,5%	38,1%	2,07	20,6	1,6	13,3
				77	400	724	88	778		201	1,4%	37,8%	2,66	16,4	1,6	13,3
				27	444	724	88	778		201	0,5%	38,1%	0,44	40,7	1,6	13,3
	C_Vp_50%	2	5	91	557	603	73	648		240	0,6%	48,3%	2,61	23,5	0,8	13,1
				44	638	608	74	654		229	1,2%	48,0%	0,84	32,0	0,8	13,1
				70	610	603	73	648		228	1,6%	47,8%	2,00	19,6	0,8	13,1
				64	615	603	73	648		228	1,4%	47,9%	2,00	25,1	0,8	13,1
				36	649	612	74	657		230	0,9%	48,2%	0,66	39,0	0,8	13,1
	C_Vp_70%	2	5	120	847	362	44	389		327	0,3%	68,9%	2,64	27,1	0,1	12,3
				107	816	362	44	389		343	0,4%	68,8%	1,74	36,7	0,1	12,3
				65	866	367	45	395		347	0,6%	68,7%	0,71	56,5	0,1	12,3
M_Air	M_Air_3%	2	-	53	144	1480				258	2,0%	36,1%	0,37	52,9	0,6	2,4
				94	109	1480				258	3,0%	35,6%	1,33	25,9	0,6	2,4
				81	121	1480				258	3,3%	35,5%	0,97	31,8	0,6	2,4
	M_Air_15%	2	-	179	35	1480			0,20	258	10,1%	33,1%	3,52	19,1	0,6	2,4
				179	35	1480			0,23	258	14,5%	31,7%	2,06	22,7	0,6	2,4
				61	138	1480			0,34	258	14,7%	31,7%	0,31	84,2	0,6	2,4
				128	79	1480			0,19	258	15,6%	31,4%	1,26	35,7	0,6	2,4
				99	104	1480			0,19	258	15,6%	31,4%	0,96	40,0	0,6	2,4
				116	89	1480			0,42	258	16,7%	31,1%	1,23	37,4	0,6	2,4
	M_Air_21%	2	-	123	84	1480			0,58	258	19,6%	30,2%	1,28	39,3	0,6	2,4
				179	35	1480			0,46	258	20,1%	30,1%	2,01	29,8	0,6	2,4
				144	65	1480			0,64	258	20,6%	29,9%	1,46	38,5	0,6	2,4
				61	138	1480			0,59	258	19,8%	30,1%	0,31	108,8	0,6	2,4
				179	35	1480			0,92	258	24,1%	29,0%	1,71	35,8	0,6	2,4
	M_Air_29%	2	-	194	22	1480			1,59	258	26,4%	28,4%	1,90	31,6	0,6	2,4
				179	35	1480			1,59	258	26,9%	28,3%	1,63	44,7	0,6	2,4
				153	58	1480			2,36	258	32,7%	27,0%	0,80	84,7	0,6	2,4
C_Air	C_Air_2%	2	5	The same mixes than the family C_Vp_30% were used												
	C_Air_11%	2	5	118	30	856	104	920	0,26	238	9,9%	26,3%	1,41	24,7	4,5	13,6
				78	65	856	104	920	0,11	197	10,3%	23,4%	1,09	32,6	4,5	13,6
				53	87	856	104	920	0,16	197	10,8%	23,3%	0,38	42,8	4,5	13,6
				130	20	856	104	920	1,49	197	11,3%	23,1%	2,08	20,7	4,5	13,6
				101	45	856	104	920	0,26	238	11,4%	25,9%	1,17	25,3	4,5	13,6
				60	81	856	104	920	0,20	197	11,5%	23,1%	0,64	40,0	4,5	13,6
				145	7	856	104	920	0,62	197	12,8%	22,8%	2,62	18,7	4,5	13,6
	C_Air_17%	2	5	98	47	856	104	920	0,62	197	13,0%	22,8%	1,29	29,0	4,5	13,6
				130	20	856	104	920	1,49	197	16,5%	22,1%	1,89	24,7	4,5	13,6
				115	33	856	104	920	0,62	197	17,9%	21,8%	1,21	32,2	4,5	13,6
				60	81	856	104	920	0,50	197	19,6%	21,5%	0,31	55,6	4,5	13,6
	C_Air_25%	2	5	60	81	856	104	920	1,00	197	23,3%	20,8%	0,29	92,2	4,5	13,6
				60	81	856	104	920	3,00	197	21,5%	20,5%	0,25	96,2	4,5	13,6
				175	0	856	104	920	1,49	197	25,4%	20,9%	1,63	29,9	4,5	13,6
				110	37	856	104	920	1,49	197	25,8%	20,4%	0,70	50,7	4,5	13,6
				209	0	856	104	920	1,49	197	26,5%	20,0%	1,74	23,9	4,5	13,6

The clusters of mixes were named as follow:

- M or C for mortars or concrete respectively;
- V_p or Air if the studied parameter is the paste volume or the air-entrained parameter, respectively. The paste volume is calculated here including all the fine particles smaller than 80µm (cement, filler, fines of aggregates) and the water but not the air entrained. Vp and Air are expressed as percentages of the total volume of the mix.

The name of the families is a concatenation of the cluster name and XX% referring to the volume of paste or of air aimed for the mixtures, respectively.
The same components and grading curves are used within each cluster.

Table 3 – Proportions (in kg) and characteristics of the mixes of the parameters "aggregates strength", "maximum diameter" and "CA/S ratio" (C=Cement; F=Filler; S=Sand; G1 and G2 are the different fraction of the gravel used for the mix, in size order; AEA=Air-entrained Agent; Vp=paste volume without a paste volume including all particles< 80µm; W=efficient water). Masses are given for dry aggregates.

Cluster	Family	Sand n°	Gravel n°	C	F	S	G1	G2	AEA	W	Air	Vp without air	R_{c28}	Epc350	D50	D90
				[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[%]	[%]	[MPa]	[mm]	[mm]	[mm]
M_FS	MFS_21	1	-	42	155	1500			0,16	237	14,5%	30,9%	0,48	54,8	0,5	1,9
				54	144	1500			0,16	237	14,6%	30,8%	0,38	70,2	0,5	1,9
				70	130	1500			0,16	237	10,8%	32,0%	0,79	47,4	0,5	1,9
				112	93	1562			0,16	239	9,8%	31,7%	2,06	25,7	0,5	1,9
	M_FS_27	2	-	The same mixes as the family M_Air_15% were used												
	MFS_62	3	-	80	122	1500			0,18	258	19,9%	30,9%	0,37	84,3	0,6	3,7
				120	86	1500			0,10	258	22,5%	30,2%	0,91	55,3	0,6	3,7
				80	122	1500				258	17,7%	31,5%	0,74	53,7	0,6	3,7
				120	86	1500				258	21,4%	30,5%	1,54	33,9	0,6	3,7
C_LA	CLA_7	2	4	30	124	879	908			183	3,8%	25,7%	0,41	51,7	3,0	11,8
				60	98	879	908			183	3,1%	25,9%	1,61	26,6	3,0	11,8
				90	72	879	908			182	3,2%	25,9%	3,84	18,0	3,0	11,8
	CLA_20	2	5	30	124	879	528	420		207	2,8%	26,8%	0,25	53,6	3,4	12,2
				90	72	879	528	420		207	2,9%	26,8%	2,47	19,2	3,4	12,2
				60	98	879	528	420		207	2,9%	26,8%	0,87	30,1	3,4	12,2
	CLA_40	2	6	30	124	879	975			188	4,3%	23,8%	0,40	55,0	3,5	12,0
				43	113	879	975			183	6,4%	22,9%	0,71	41,8	3,5	12,0
				68	91	879	975			188	5,9%	23,4%	1,95	23,9	3,5	12,0
	CLA_50	2	7	30	124	879	580	390		204	2,7%	25,5%	0,32	60,2	3,2	14,4
				60	98	879	580	390		204	3,4%	25,4%	1,04	31,4	3,2	14,4
				90	72	879	580	390		204	3,4%	25,4%	2,82	19,6	3,2	14,4
C_D90	C_D90_4	2	5	40	99	1800				284	6,2%	31,1%	0,19	114,9	0,7	2,4
				80	64	1800				284	5,4%	31,2%	0,53	49,3	0,7	2,4
				120	29	1800				284	5,0%	31,3%	1,18	30,9	0,7	2,4
	C_D90_10	2	5	30	108	856	1030			217	7,3%	25,1%	0,17	71,8	4,4	9,7
				60	82	856	1030			217	5,4%	25,6%	0,76	36,8	4,4	9,7
				90	55	856	1030			217	5,1%	25,6%	2,30	22,9	4,4	9,7
	C_D90_14	2	5	The same mixes as the family C_Air_11% were used												
	C_D90_20	2	5	30	108	856	104	220		167	7,4%	21,7%	0,40	47,5	5,5	18,4
				60	82	856	104	220		167	7,6%	21,7%	1,48	20,6	5,5	18,4
				90	55	856	104	220		167	6,2%	22,0%	3,60	15,4	5,5	18,4
C_CAS	C_CAS_0			The same mixes as the family M_Air_15% were used												
	C_CAS_0,3	2	5	40	99	1440	42	393		230	9,0%	26,0%	0,33	75,3	0,9	12,0
				75	69	1440	42	393		230	8,0%	26,2%	1,14	42,3	0,9	12,0
				110	38	1440	42	393		230	6,8%	26,5%	2,57	27,1	0,9	12,0
	C_CAS_0,6	2	5	30	108	1170	72	635		211	9,0%	24,7%	0,27	85,1	1,4	13,0
				60	82	1170	72	635		211	10,4%	24,4%	0,99	39,3	1,4	13,0
				90	56	1170	72	635		211	11,6%	23,8%	2,21	25,0	1,4	13,0
	C_CAS_0,9	2	5	30	108	990	91	798		177	7,2%	22,5%	0,32	56,8	2,2	13,4
				60	82	990	91	798		177	7,9%	22,4%	1,29	29,6	2,2	13,4
				90	56	990	91	798		182	7,9%	22,8%	3,18	19,7	2,2	13,4
	C_CAS_1.2	2	5	The same mixes as the family C_Air_11% were used												
	C_CAS_1,5	2	5	30	108	753	114	1015		178	10,2%	22,0%	0,27	51,2	8,1	13,7
				60	82	753	114	1015		178	9,4%	22,1%	0,91	27,8	8,1	13,7
				90	56	753	114	1015		178	9,7%	22,1%	1,19	26,7	8,1	13,7

Table 3 details all the mixes tested for the study of the parameters “aggregates strength”, “maximum diameter” and “CA/S ratio”. The clusters of mixes were named as follow:

- M or C for mortars or concrete;
- YY characterizing the parameter to be studied (FS: sand friability; LA: Los Angeles value; D90: diameter where 90% of the complete grading curve is passing; CAS: CA/S ratio)

The name of the families is a concatenation of the cluster name and XX referring to the volume of the parameter YY studied

The same paste volume and air content were aimed at within each cluster. Others parameters were constant depending on the cluster:

- In the C_LA cluster, the same sand but different coarse aggregates displaying different Los Angeles values were used. Yet care was taken to keep very similar skeleton grading curves.
- In the same way for the M-FS cluster, even if different sands were used to have a wide range of friability values only slight differences of grading curves were observed.
- The same nature of aggregates was used within the C_D90 cluster containing 3 lean concrete with different maximum coarse aggregates sizes. A mortar was also added to the analysis.
- The same nature of aggregates was used within the C_CAS cluster. Figure 4 is presenting the different grading curves obtained for the different CA/S ratio.

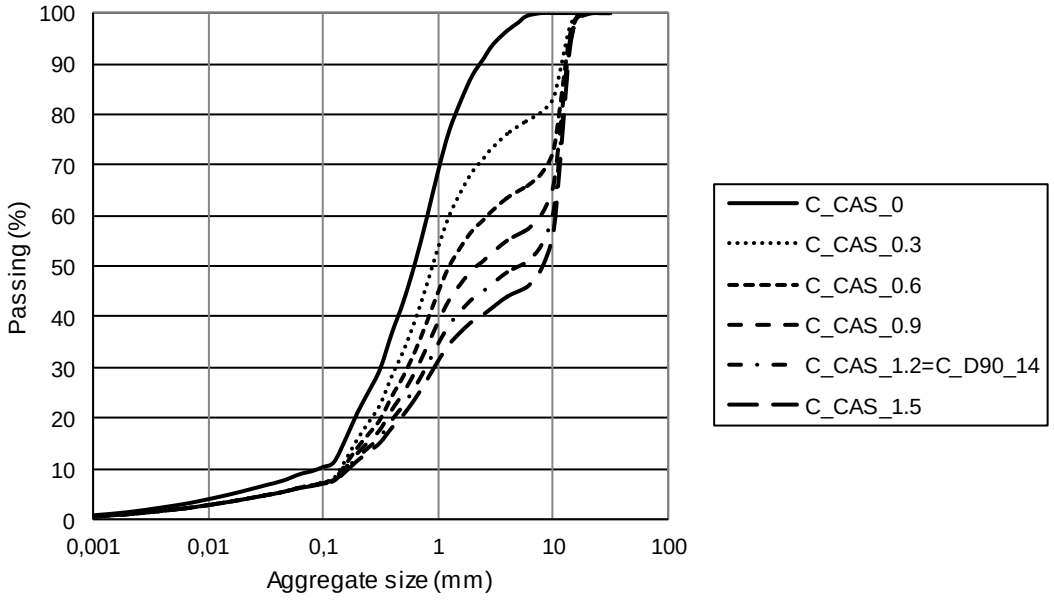

Figure 4 - Aggregate grading curves for concretes used to study the influence of the CA/S ratio

For each mix, a 50 liters batch was produced from which the following specimens were cast:

- 3 ø16x32 cm^3 cylinders for unconfined compressive strength tests ;
- 6 ø16x16 cm^3 cylinders for the punching tests.

The specimens were cast using a modified Glanville (BS 1881-103, 1983) apparatus consisting in a reversed metallic truncated cone (upper diameter: 254 mm – lower diameter: 127 mm – height: 227 mm) The bottom of the cone is equipped with a hatch (Ifsttar et Engie, 2016) and is set 20 cm from the top of the mold. The material is first poured in the cone. Then the hatch is opened and the material flows on its own weight into the mold. This method enables a repeatable casting of CLSM with no influence of the operator. Ø16x32 cm^3 plastic molds (for lean concrete), Ø16x32 cm^3 cardboard molds (for mortars) or Ø16x16 cm^3 metallic molds were used, all closed by a plastic cover and stored at 20°C. All the presented data were measured at 28 days and the punching test penetration measured at the energy of 350 J.

3.3. METHOD OF ANALYSIS: EXAMPLE OF THE PASTE VOLUME

The literature review showed that the unconfined compressive strength of the material influences the excavatability and the punching test penetration but also that it is not the only relevant parameter. Consequently, it is necessary to discard it of the analysis in order to put the highlights on others. To do so, the main strategy adopted for this paper was to make comparisons between penetration measurements obtained for a same unconfined compressive strength level. Since it would be very difficult to obtain experimentally the exact same strength for two different mixes we decided to proceed by interpolation of penetration – compressive strength curves obtained with at least three experimental measurements per family of mixes. The method is detailed below, taking the study of the influence of the paste volume on penetration in mortars as an example.

To test the parameter "paste volume", 4 families of mortars presenting values of paste volume of 40%, 50%, 70% and 100% were formulated using the same sand and gneiss aggregates, in the same proportions with an air content of about 2% (see cluster M_VP in Table 2). Then each family was declined in at least three mixtures aiming at three different unconfined compressive strengths to cover approximatively 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.
All the results of punching test penetration at 350J (E_{pc350}) were then plotted vs unconfined compressive strength (R_c). As it can be seen on Figure 5 for mortars, for each value of paste volume, the data can be satisfactorily fitted with curves according to the following type of equation:

$$E_{pc} = \alpha \times R_{c28}^{\beta} \quad \text{with } \alpha \text{ and } \beta \text{ constant for a given family of mixes} \qquad (6)$$

Such a good fitting was also obtained for the other parameters studied and the evolution of α and β then describe the marginal effect of the other parameters.

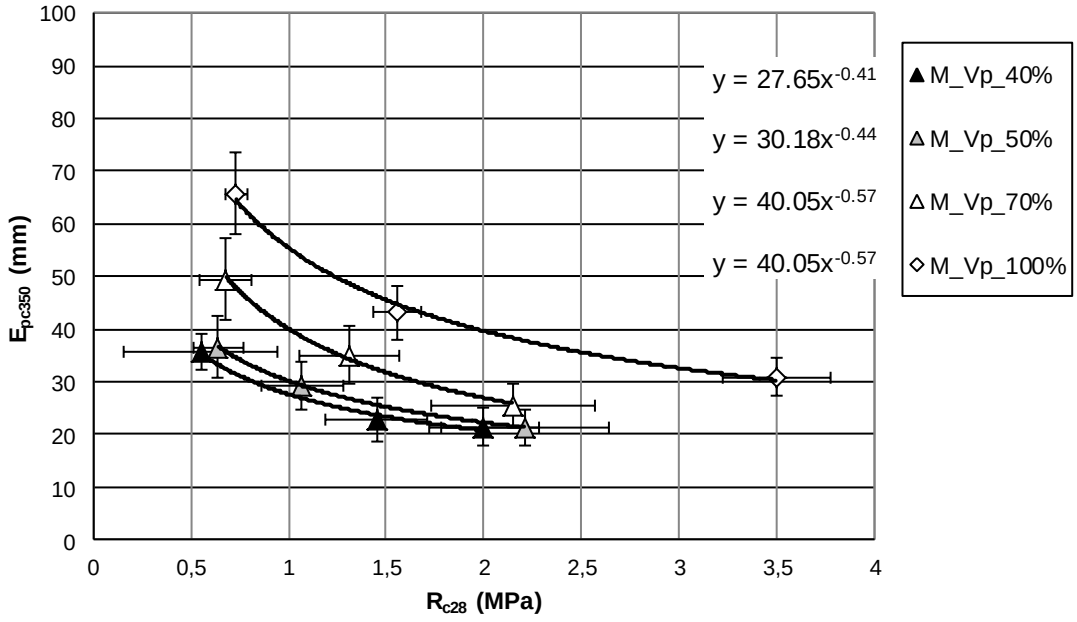

Figure 5 - Punching test penetration at 350 J (E_{pc350}) versus unconfined compressive strength at 28 days (R_{c28}) for mortars with different paste volumes without air from cluster M_VP

One can observe that an increase in paste volume leads to a higher penetration value for the same energy and R_c levels. For example, at 1 MPa, it is possible to double the penetration by increasing the paste volume from 40 % to 100 %.
This state of fact appears more clearly on Figure 6 representing the evolution of E_{pc350} normalized by E_{pc350} for a paste volume of 40% and the same R_c. In addition, it can be observed that the influence of the paste volume on penetration is almost independent of the unconfined compressive strength considered as the different curves are superimposed (in the limits of the studied materials performances).

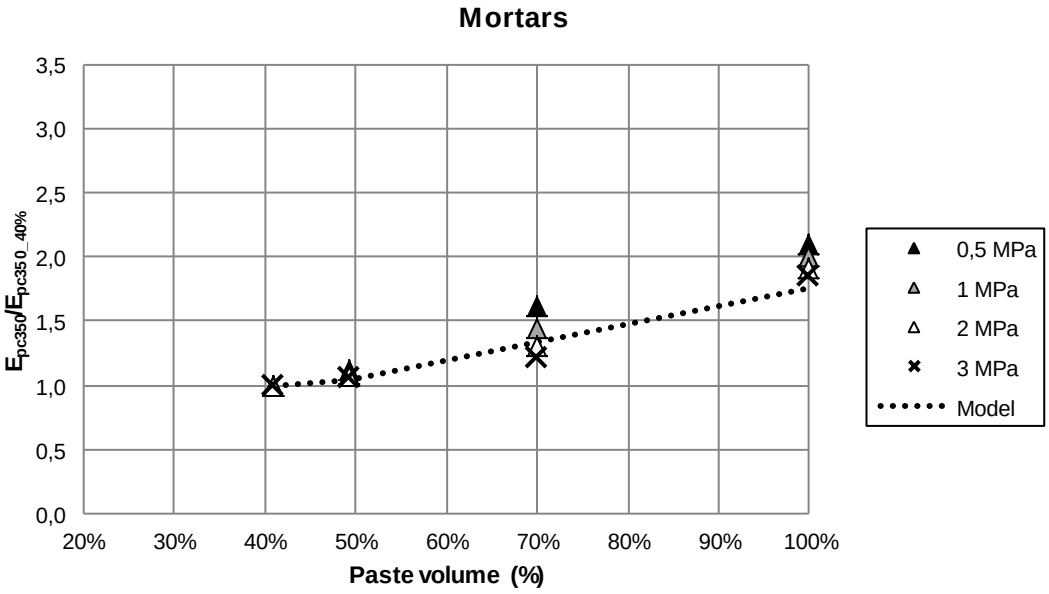

Figure 6 - Evolution of the penetration normalized by the penetration of the mixes with a paste volume of 40% at the same R_c for mortars in the C_VP cluster. Dotted line calculated with equation (7)

4. RESULTS, ANALYSIS AND PREDICTION MODEL OF THE PUNCHING TEST PENETRATION

From the experimental campaign described above, a large database of mixes is available. This chapter is aiming at the presentation of the results and its analysis. To do so, a predictive model of the punching test penetration is first proposed. Then, its form will be commented thanks to the experimental results collected with the tests described above. A detailed presentation of all the results can be found in (Gennesseaux, 2015).
The following model was proposed to predict the penetration at 350J:

$$E_{pc350} = \left(25 \times V_{p.without.air}^{4} + 1567 \times \frac{V_{air}^{2.76}}{R_c \times \sqrt{\max(D_{90}; 1{,}5)}} - 21 \times \sqrt{\frac{D_{50}}{D_{90}}} + 41.27 \right) \times R_c^{-0.5} \qquad (7)$$

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 µm 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.

The constants were optimized by minimizing the mean-square error of the model. Figure 7 compares the theoretical punching test penetration at 350J calculated with the previous model versus the experimental data collected during all the collaboration ENGIE/Ifsttar. A satisfying correlation is obtained with an absolute error of 4.7 mm, which is two times lower than the width of the range of punch penetration covering the “difficult” excavatability area, enabling a sufficient excavatability levels differentiation. This error is also implying an error on the theoretical volume, which is lower than the error given by Equations (1) to (3) in the prismatic model (5.6 L).

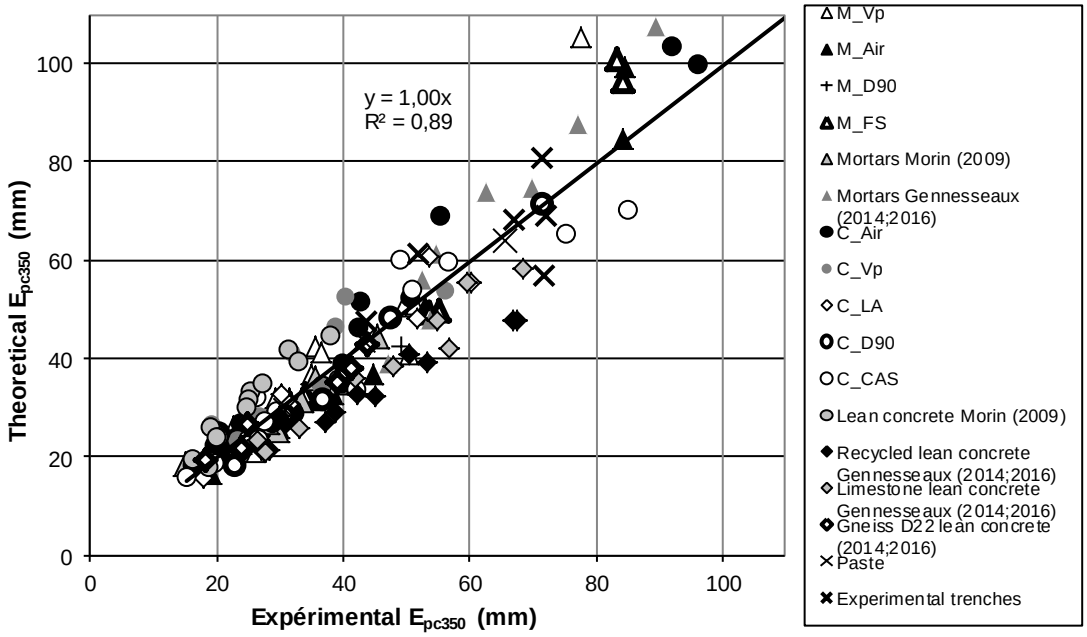

Figure 7 - Prediction of the punching test penetration model for all the mixes tested. Experimental data from this study and from (Morin, 2009; Gennesseaux, 2015)

The model is built on the parameters "unconfined compressive strength", "paste volume without air", "air-entrained" and "D_{50}/D_{90}" expressing both the effect of the ratio CA/S and maximum size of aggregate. D_{50} was chosen as a good indicator of the differences between the grading curves of mixes with different CA/S ratio (see Figure 4). The model was built step-by-step, on the basis of the different clusters of mixes in Table 2 and Table 3. The quality of the fitting and the accordance of the model with the general trends observed with each main parameter can be observed on Figure 6, Figure 8, Figure 9 and Figure 10.

Unconfined compressive strength

This parameter was known to largely influence the penetration into the material. Considering the shape of the E_{pc} – R_c curves (see an example in Figure 5) and the test results, the model tried to express the fact that the penetration decreases significantly when R_c is getting higher.

Paste volume

As it appeared above (Figure 5 and Figure 6), the paste volume without air is an important influencing parameter of the penetration: the higher the paste volume, the easier the penetration. This state of fact was observed on mortars as well as on lean concrete, with the same level of influence. Moreover as seen in Figure 6, the influence of paste volume is independent of the R_c. Consequently, the parameter linked to the paste volume in the model is logically constant and positive.
Another intuitive parameter could have been the thickness of paste surrounding the aggregate, considering that this part of paste is more exposed to the cracks propagation during the pick impact than the paste part filling the voids of the aggregate skeleton. So we tried to link the maximum paste thickness (MPT) calculated with the compressible packing model (de Larrard, 1999), (Fennis, et al., 2013) to the pick penetration. However we observed a bad correlation.

Air entrained

Figure 8 presents the normalized E_{pc350} calculated for different strength levels and plotted versus the air content in the mix for the mortars tested. The air content appears to have a strong impact on the penetration since, for example, it is possible to increase the E_{pc350} value from 30 mm to 70 mm even if R_c is kept at1 MPa, by introducing about 30% of air entrained in a mortar. On the other hand, this impact appears to be weaker when the unconfined compressive strength is higher.

The same trends are observed on concrete (see Figure 9) but with a lower efficiency of air-entrainment.

The proposed model expresses these results by including the air entrained with a positive constant. Yet it was necessary to include a negative effect of R_c and D_{90} by adding them in the denominator of the air parameter.

In (Gennesseaux, 2015), some slurries incorporating polystyrene beds to simulate 20% to 30% of air entrainment were tested with the punching test. The slurries displayed a compressive strength ranged from 0.5 to 2 MPa and a D_{50}/D_{90} ratio almost constant around 0.25 and a D_{90} of 0.08 mm.

Because D_{90} appears in the denominator, with such a low value the equation (7) tends to greatly overestimate the effect of the air on the penetration depth. To fit the experimental values it was then necessary to put an upper limit of 0.816 to the effect of D_{90}, corresponding to a D_{90} of 1.5mm. This justifies the term Max [D_{90}; 1.5] in equation (7).

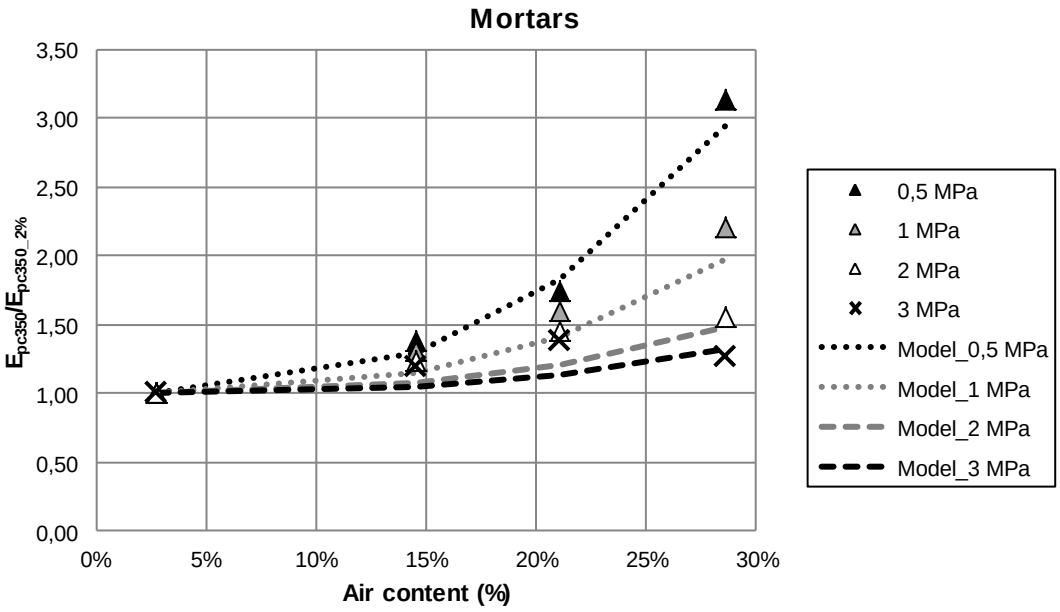

Figure 8 - Evolution of the penetration in mortars normalized by the penetration of the mix with 2% of air entrained and the same R_c vs the air content for mortars in the M_Air cluster. Dotted lines calculated with equation (7)

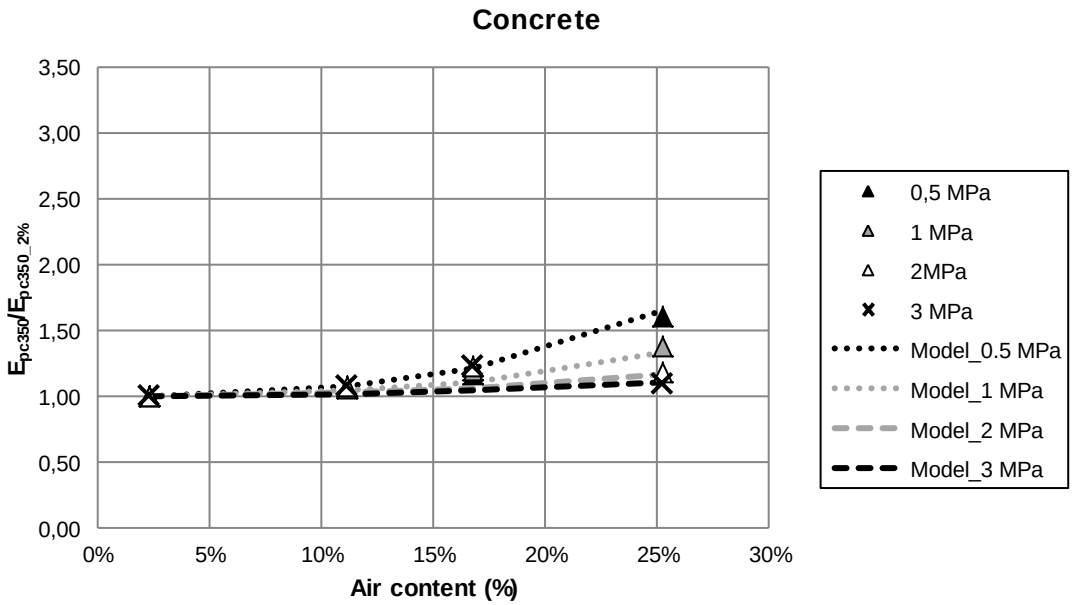

Figure 9 - Evolution of the penetration in concrete normalized by the penetration of the mix with 2% of air entrained and the same R_c vs the air content for concrete in the C_Air cluster. Dotted line calculated with equation (7)

Coarse aggregates to sand mass ratio (CA/S)

Figure 10 plots the normalized E_{pc350} measured versus the D_{50}/D_{90} ratio for different values of unconfined compressive strength. The figure shows that an increasing D_{50}/D_{90} ratio leads to a more difficult penetration (a smaller E_{pc350}) in the same range whatever the unconfined compressive strength level. The penetration can be higher of 50% when the ratio goes from 1.5 to 0.3. The point at D_{50}/D_{90}=0.27 is a particular case of mortar (CA/S=0) but it can be seen that the model gives an acceptable prediction even in that case. This conclusion seems reasonable when considering that a hard coarse aggregate will probably dissipated more energy that the same volume of material made of sand grains stuck together by a weak cement paste.

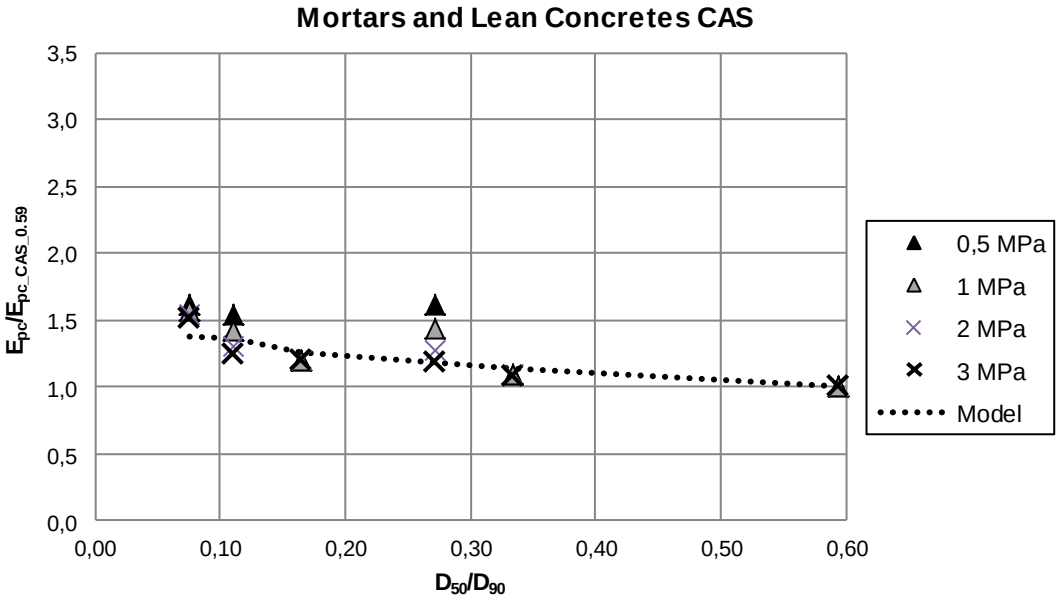

Figure 10 - Evolution of the penetration normalized by the penetration of the mix with CA/S=1.5 and the same R_c vs D_{50}/D_{90} ratio, for concrete in the C_CAS cluster. Dotted line calculated with equation (7)

In the model, the ratio CA/S is traduced by a parameter D_{50}/D_{90}, judged closer to the description of the grading curve. The constant linked to it has a negative value, which appears logical: the lower the CA/S the easier the penetration and the higher and the D_{50}/D_{90} ratio (see the grading curves Figure 4).

Aggregates hardness;

It appeared for clusters M_FS and C_LA, that both sand or coarse aggregate hardness do not influence significantly the punching test penetration into the material, whatever the level of unconfined compressive strength. This seems relevant as, even weak, the aggregates are much harder than the paste and cracks propagation probably occurs mainly in paste. This parameter was then not included in the model.

Maximum aggregate diameter

In the same way, in cluster C_D90, no direct effect of the maximum size of aggregate was observed that was not already captured by the term D_{50}/D_{90} or in the denominator for air parameter. Thus no specific term was added in the model for that purpose.

At this point of the study we proposed equation **(7)** as a predictive model of the punching test penetration at 350J giving satisfying results for all the mixes tested. From this prediction, and using the prismatic rupture model described in chapter 2 (equations (1) to (3)), it is possible to predict the excavated volume (and consequently the difficulty of excavatability) from the mix design.

5. VALIDATION ON TRENCHES

Using the previous model, it is then possible to design CLSM mixes while optimizing the excavatability for a given unconfined compressive strength by aiming at a higher excavated volume. To do so, two strategies are available; maximize the pick penetration; or/and maximize the D_{90} of the aggregate to increase the interlocking effect of the pick during the decompaction (peripheral volume of the rupture model (see equations (1) to (3)). To apply the first strategy, equation (7) shows that the mix design should have:

- The highest possible air content;
- The highest possible paste volume;
- A CA/S ratio optimized to give a good compromise between a low D_{90} and a low D_{50}/D_{90}

Equations (1) to (3) were proposed based on typical trench mixes. So before going further it is necessary to verify that these equations remain relevant for mixes optimized according to these different strategies, ie:

- High air volume mortars;
- Low aggregate volume lean concrete;
- Air entrained concrete with optimized CA/S ratio.

Consequently, 8 experimental trenches with 0.6mx0.6mx0.5m in dimensions were cast and tested at 28 days following the procedure described in (Gennesseaux, et al., 2014; Gennesseaux, 2015) consisting in:

- Controlled manual excavation with 90 pick impacts measuring the excavated volume and the pick penetration each 30 impacts;
- Unconfined compressive strength tests on three ø16x32 cm^3 cylinders;
- Punching tests on six ø16x16 cm^3 metallic cylinders.

The following mixes were tested:

- 2 mortars with 30% of air entrained;
- 4 lean concrete presenting an excavatability “easy” including:
  - One reference lean concrete (CA/S=1.2 – V_p=26%);
  - One lean concrete with CA/S=0.6 and V_p=26%;
  - One lean concrete with CA/S=0.6 and V_p=50%;
  - One lean concrete with CA/S=0.6 and V_p=70%;
- 2 lean concrete aiming at “easy” and “medium” excavatability with CA/S=0.6 and 30% of air-entrained;

The water to cement ratio of each mix was adjusted to aim at the desired excavatability according to the global model (the punching test model and the excavated volume model combined). The same cement, limestone filler and air-entraining agent as in the campaign described above were used here, with the 0/4 Pilier sand and the 6/10 and 10/14 Maraichères gneiss coarse aggregates. The mixes were done with a 100L Couvrot mixer and each trench was cast in three layers homogenized manually.
Table 4 presents the mixes tested and their characteristics.

Table 4 – Quantities (kg) and characteristics of the mixes designed to be tested on trenches (C=Cement; F=Filler; S=Sand; G1 and G2 are the different fraction of the gravel used for the mix, in size order; AEA=Air-entrained Agent; Vp=paste volume without a paste volume including all particles< 80µm; W=efficient water)

Mixtures	C	F	S	G1	G2	AEA	W	Air	Vp	R_{c28}	E_{pc339}	D50	D90
	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[%]	[%]	[MPa]	[mm]	[mm]	[mm]
MT_30_0,7	83	101	1141	-	-	1,6	147	32,4%	24,8%	0,79	70,2	0,6	2,4
MT_30_1,4	121	67	1141	-	-	1,6	147	35,6%	24%	1,09	69,7	0,6	2,4
BT_1,2	30	75	883	107	949	-	201	4,4%	26%	0,19	65,3	4,5	13,6
BT_0,6_0,3	36	103	1171	72	636	-	211	3,9%	28.9%	0,32	50,7	1,4	13,0
BT_0,6_0,5	39	631	817	50	443	-	235	1,3%	50.6%	0,65	42,5	0,5	12,3
BT_0,6_0,7	57	914	501	31	272	-	319	1,5%	69.0%	0,62	70,0	0,1	11,3
BT_30_0,4_1,1	71	468	588	36	319	2,4	144	33,5%	72,0%	0,28	178,9*	0,5	12,3
BT_30_0,4_1,5	98	444	588	36	319	2,4	144	33,5%	69.8%	0,71	72,9	0,5	12,3

**extrapolated value*

All the mixes were evaluated as “very easy” to “easy” to excavate by the manual operator who was asked to estimate the difficulty of excavatability on a scale from 1 (very easy) to 5 (difficult to impossible).
Figure 11 plots the manual excavated volume calculated from equations (1) to (3), versus the experimental volume. The model was implemented with the laboratory punching test values measured at 339J corresponding to the exact average impact energy of the operator who performed the tests (evaluated on all the tests performed for the collaboration ENGIE/Ifsttar). For the mix BT_30_0.4_1.1 where the punching test measurement wasn’t available (higher than 100 mm), the volume was calculated using directly the in-situ pick´s tool penetration E_{pi}.

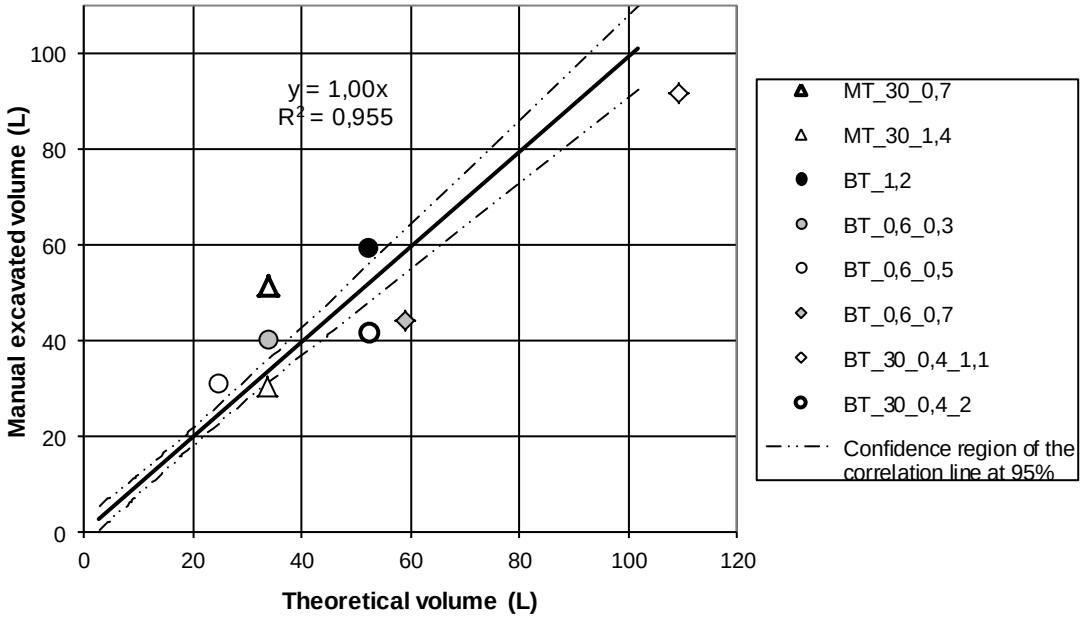

Figure 11 - Manual excavated volume versus theoretical volume calculated from the punching test penetration at 339J

The good agreement between theoretical and experimental value confirms the relevance of equations (1) to (3), even for optimized mixes. Therefore optimizing with equation **(7)** the mix design in terms of punching test penetration at the laboratory stage will allow to optimize the excavated volume and thus the excavatability of the cementitious material.

6. HEADING FOR THE IDEAL MIX: A METHOD OF FORMULATION

Following the previous results presented, it is now possible to propose a mix design method in order to obtain cement treated materials – mortars or lean concretes - with a required excavatability. Generally, a minimum compressive strength R_{cmin} is also required to ensure that the upper part of the trench is not punched, for example, by the wheel of a truck.

The method is described below step by step:

- First of all, using the abacus presented in (Ifsttar et Engie, 2016), the mix designer should define the minimum punching test value at 350 J to aim at to ensure the desired excavatability level for the D_{90} value of the mix to be designed. This abacus was drawn from equations (1) to (3) and the relationship between difficulty ratio and excavated volume (Gennesseaux, 2015).;
- Then, composition objectives should be fixed, like the paste volume, the air content and the D_{50};

- Using the punching test penetration model of equation **(7)**, it is now possible to evaluate the maximum unconfined compressive strength R_{cmax} enabling to reach at least the minimum penetration required for the desired excavatability;
- Verify that R_{cmax} is higher than required R_{cmin}. If not, chose another set of mixture parameters leading to a theoretical higher R_{cmax}.
- Make batches of the selected mix to verify for example if the air content can be reached, define the water content to obtain the fluidity and adjust the cement/limestone filler ratio to reach the good R_c.
- Once the mix is designed, if possible, the pick penetration is verified according to the laboratory punching test presented at the beginning of the paper.

In addition, the experimental campaign presented here gave some interesting guidelines to follow in order to reach the ideal mix. Indeed, the air entrained appears to be an essential lever for the optimization of this kind of materials. It appears that without air-entrained, a CLSM will be likely un-excavatable with a pick.
This study also concluded that the mechanical properties of the aggregate skeleton itself have almost no influence on the excavatability of the material. Consequently, the use of recycled aggregates to replace natural aggregate appears to be a green and economical solution to produce excavatable CLSM. This was confirmed in (Gennesseaux, et al., 2014) and (Gennesseaux, 2015).
Despite the negative effect of D_{90} on the positive effect of air on excavatability, D_{90} may have a concurrent positive influence due to the interlocking effect described by the parameter k in Equations (1) and (2).

Another parameter which will have its importance to spread this variety of material is the question of its cost. To tackle this issue, a quick economic analysis was performed to enable prices comparisons between classical backfilling materials (mortar with 10% of air entrained and lean concrete without air-entrained) and some theoretically “optimized” excavatable CLSM using the previous models. The following mixes made of the same cement and limestone filler were evaluated:

- Mortar with 15% of air and 30% of paste;
- Lean concrete with 2% of air, 25% of paste, CA/S=1.2 and D_{90}=13mm;
- Mortar with 30% of air and 40% of paste;
- Lean concrete with 30% of air, 40% of paste, CA/S=0.6 and D_{90}=17mm;
- Cement paste with 30% of air;
- Cement paste with 30% of air and 500 kg/m^3 of Maraichères coarse aggregate 14/20 (n°5);
- Lean concrete with 30% of air, 40% of paste, CA/S=0.6 and D_{90}=28mm)

For each mix considered, the maximal unconfined compressive strength allowed to ensure an easy excavatability was calculated with the punching penetration predictive model (Equation (7)). The Water to Cement ratio was then calculated using the following modified Feret’s law with some roughly fitted parameters (Morin, 2009; Gennesseaux, 2015):

$$R_c = 180.\left(\frac{V_c}{V_c + V_w + 0.5.V_{air}}\right)^2 \quad (8)$$

Where V_c, V_w and V_{air} are the volumes of cement, water and air-entrained.

With this method, it was possible to determine the mix design of each material and to estimate it price using the constituent prices listed in Figure 12. Only the costs of the primary constituent were taken into account here. The transport and mixing cost were not included in the simulation because considered equivalent for all the mixtures compared.
Figure 12 displays the price of the material versus the maximum unconfined compressive strength to ensure an easy excavatability.

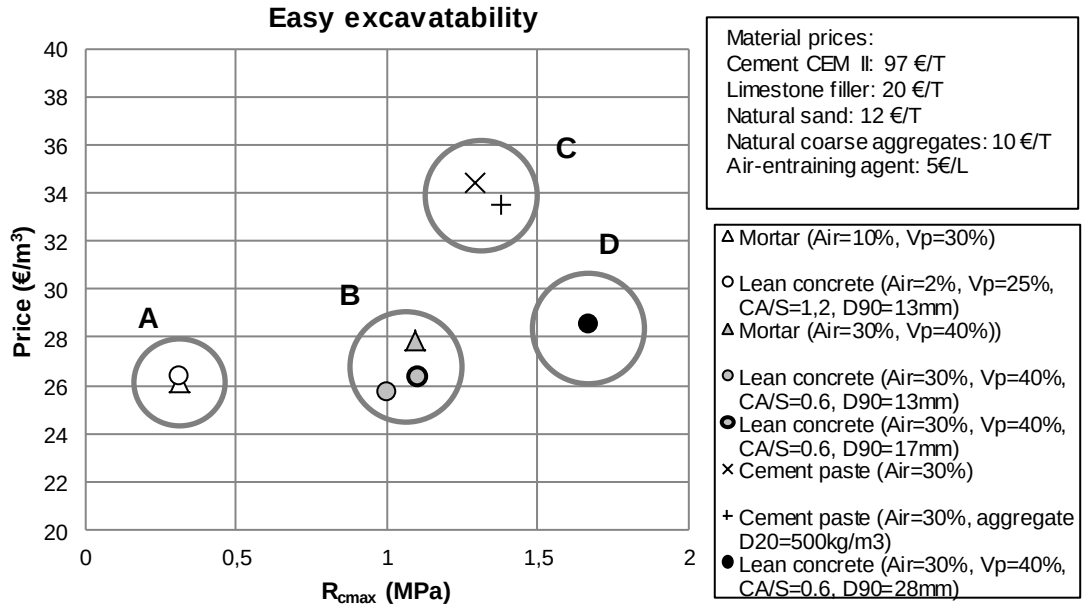

Figure 12 - Price simulation of different easy excavatable materials versus its theoretical maximum unconfined compressive strength

From the previous figure, it can be observed that:

- It is possible to vary the maximum unconfined compressive strength for a given excavatability by optimizing the mix design
- The traditional CLSM presently available on the market (Group A) needs to keep a very low unconfined compressive strength (lower than 0.3 MPa) to be easily excavatable;
- The optimization of mortars and lean concrete performed in the limits tested in the present paper (air entrained up to 30%; paste volume up to 40% and D_{90} up to 20mm) allows a maximum unconfined compressive strength of about 1.1 MPa, without significant increasing of the material cost (Group B). This value is sufficiently high to avoid most of the risks of punching of the trench or of fatigue rupture for an urban traffic (Gennesseaux, 2015);
- The use of air-entrained slurries (Group C) would be a solution to reach high levels of unconfined compressive strength for an easy excavatability. A slightly higher value could even been reached thanks the addition of some coarse aggregates. However, in that latter case, an experimental validation must be made, since we reach here the validity limits of the interlocking model. Moreover, the cost of such materials is significantly higher, and the replacement of limestone filler with less expensive inert fines should be necessary;
- Finally, the use of coarser fractions of aggregate could be the best option to reach high levels of unconfined compressive strength (from 1.5 to 2 MPa) while ensuring the excavatability (Group D). But here again, the material simulated, with a D_{90} of 28mm, goes out of the validation limits of the proposed method. Experimental validation should be performed in that case.

7. CONCLUSIONS

The study detailed in the present paper focuses, on the mix design of optimized excavatable materials for trenches. Based on a new laboratory punching test presented at the beginning of the paper, a large parametric campaign is realized and a model is proposed, which allows the prediction with an mean accuracy of 4.7 mm of the penetration of a pick in a cementitious material, for a given impact energy. Coupled with a geometrical model describing the excavation process, it is then possible to calculate the volume excavated after a given number of pick impacts (arbitrarily, 90 here) and so the excavatability level of the material.

This model accounts for the compressive strength as usually seen in the literature, but also for the paste volume, air volume, grading curve and maximum size of aggregate of the granular skeleton. It confirms, by the way, that compressive strength is not a relevant indicator of excavatability alone, as generally admitted.
The model shows that increasing the paste volume, the air volume, the maximum size of aggregate are the most efficient way to increase the excavatability of a material while keeping its compressive strength constant. 8 mixes were optimized with the proposed model and cast in one-scale trenches. A manual excavation made by a professional operator with a pick, in blind conditions, showed that the prediction of excavated volumes was satisfactory, confirming the relevance of the model and the influence of those parameters on excavatability.
A practical method is then proposed to design, at the laboratory stage, cementitious material following both requirements in terms of minimal compressive strength (for bearing capacity of the trench) and high excavatability level.
A simple economical simulation is also proposed to see the influence of the required compressive strength on the cost of materials with the same excavatability level but with different compositions suggested by the model.
Finally, it should be noted here, that the model links the excavatability level for a given age to the compressive strength at the same age. Yet, trenches owners need in general an evaluation of the excavatability at long-term. So the knowledge of the evolution of the compressive strength is needed to enable predictions from data obtained in reasonable laboratory times (28 days or 90 days…). Further researches are needed regarding this point.

COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest.

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