Mechanical characterization of DEEP SOIL MIX material – procedure description

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ABSTRACT

Since several decennia, the deep soil mix (DSM) technique has been used for ground improvement (GI) applications. In recent years, soil mix walls (SMW) have become an economical alternative to traditional excavation support systems. The Belgian building market has also witnessed such development with the growing use of the Cutter Soil Mix (CSM), the Tubular Soil Mix (TSM) and the CVR C-mix® systems (Denies et al., 2012a). Unfortunately, standardized guidelines for SMW design are not currently available. For the purpose of developing such standard, mechanical characteristics of DSM material must be investigated. Within the framework of a Flemish regional research program (IWT 080736), DSM materials from 38 Belgian construction sites, with various soil conditions and for different execution processes, have been tested. Test results are detailed in Denies et al. (2012b).
Beyond the site conditions and the execution technique, the preparation of the test specimens is an important issue and can have an influence on the test results. For that reason, the present paper focuses on the sampling, the transport, the storage, the handling and the preparation of the DSM test specimens. In addition, two methods to quantify the volume of unmixed soil inclusions in the mix are presented.

1. INTRODUCTION

Since several decennia, the deep soil mix method (DMM) has been used for GI applications. In recent years, SMW have increasingly been used – in Belgium and in several other countries – for the retaining of soil and water in the case of excavations. Indeed, SMW represent a more economical alternative to concrete secant pile walls and even in several cases to king post walls.
The main structural difference between SMW and the more traditional secant pile walls is the constitutive DSM material which consists of a soil – cement mixture instead of traditional concrete.
Unfortunately, up to now, guidance rules and recommendations concerning the realization of SMW with a soil and/or water retaining function have been lacking while various DSM systems are active on the Belgian market such as the CVR C-mix®, the Tubular Soil Mix (TSM) and the Cutter Soil Mixing (CSM). However, the number of applications is fast increasing (Denies et al. 2012a). As part of QA/QC development and of the European standardization, basic rules are required with regard to design, execution and control of these different DSM execution processes.
These issues encouraged the Belgian Building Research Institute (BBRI) to initiate research actions that address the execution, design and testing of DSM systems in Belgium. For the purpose of investigating the DSM technology and its applicability in the various Belgian soils, a "Soil Mix" project was initiated in 2009 in collaboration with the KU Leuven and the Belgian Association of Foundation Contractors (ABEF). Financial support has been obtained from IWT, the Flemish government agency for Innovation by Science and Technology (http://www.iwt.be/).
Within the framework of the BBRI 'Soil Mix' project, numerous tests on in situ DSM material have been performed. A good insight has been acquired with regard to mechanical characteristics that can be obtained with the different DSM systems in several Belgian soils (Denies et al., 2012b).
If the design and the QC of the execution are generally based on laboratory tests performed on cored material, each sample is characterized by its own history influencing the test result and its interpretation. Beyond the question of the representativeness of the core samples with regard to the in situ executed material, discussed in Denies et al. (2012b), the present paper concentrates on the sampling, the transport, the storage, the handling and the preparation of the test specimen which constitute the main preliminary stages to the mechanical characterization.
For the geotechnical survey, these topics are addressed, in a general view, in the European and American standards, respectively EN ISO 22475-1 and ASTM D 420 - 93. For DSM material, the Annex B of EN 14679 (2005) – the European standard for the execution of deep mixing – gives some indications with

regard to the laboratory testing on core samples but the preparation of the test specimen is not detailed. In order to take into account the specific nature of the mixing of the DSM material, the test procedures, developed within the framework of the BBRI 'Soil Mix' project, have been based on various soil, rock and concrete standards. Special attention has been given to the presence of soft soil inclusion in the DSM material. Two methodologies to quantify the volume of soft soil inclusions have been developed. In addition, a handling procedure for the preparation of the DSM test specimens has been established. Table 1 illustrates the timeline of the DSM sample life with regard to the standards or test methodologies supporting its several stages.

2. SAMPLING

For geotechnical investigation, it is imperative to obtain samples adequately representing each subsurface material significant to the project design, construction and control. The size, the type and the amount of samples required depend on the tests to be performed, the relative amount of coarse particles present, and the limitations of the test equipment to be used.

In the case of DSM material, the sampling also depends on the amount of unmixed soil inclusions in the mix. The heterogeneous character of the DSM material must be taken into account.

Each sample must be accurately identified with a waterproof tag that refers to its construction site, its borehole and its depth. Each borehole shall be located (in horizontal and vertical directions) with reference to some established and permanent coordinate system. The coring date and all indications useful for the test and its interpretation should be indicated in the sampling report such as the climatic conditions and the groundwater level observed during coring operations. The coring direction (horizontal or vertical) must also be specified. In case of subdivided samples, reference must be made to the original sample.

In addition, colour photographs of cleaned samples, filled sample boxes and accessible soil strata may be directly performed after coring.

For additional information on the sampling methods, the reader can consult EN 12504-1 or ASTM D 2113 - 83 especially for diamond core drilling.

In the case of DSM structures, the sampling is generally performed with a water based drilling technique; hence, it is not possible to determine the water content of the samples.

3. TRANSPORTATION

In the case of DSM material, drying/freezing of samples may affect the mechanical properties. Hence, samples must be protected in order to minimize moisture loss. For that reason, samples shall be transported in sealed containers equipped with padding material preventing any moisture loss and sample cracks due to shocks or vibrations. These containers should be designed in such a way to withstand rough transportation conditions and must be clearly marked. If necessary, special shipping and/or laboratory handling instructions are associated with the sample box.

Specific information concerning transportation is given in:

- ASTM D 4220 - 89 for soil samples,
- and ASTM D 5079 – 90 for rock core samples.

4. PRESERVING/STORAGE

During the whole period between delivery and testing of DSM samples, they are stored in an acclimatized chamber with a relative humidity larger than 95% and a temperature equal to 20 ± 2°C, as indicated in EN 12390-2: 2009.

Table 1: Timeline of the DSM samples: procedures followed within the framework of the BBRI 'Soil Mix' project

Sampling	**Transportation**	**Preserving/Storage**	**Handling/Preparation of test specimens/Test and report**	
In situ	In situ	In laboratory	In laboratory	
EN 14679: 2005 Execution of special geotechnical works – Deep mixing **EN ISO 22475-1: 2007** Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 1: Technical principles for execution **ASTM D 420 – 93** Standard Guide to Site characterization for Engineering, Design, and Construction Purposes				
EN 12504-1: 2009 Testing concrete in structures - Part 1: Cored specimens - Taking, examining and testing in compression **ASTM D 2113 - 83** Diamond Core Drilling for Site Investigation	**ASTM D 4220 - 89** Standard Practices for Preserving and Transporting Soil Samples **ASTM D 5079 - 90** Standard Practices for Preserving and Transporting Rock Core Samples	**EN 12390-2: 2009** Testing hardened concrete - Part 2: Making and curing specimens for strength tests **ASTM D 1632 - 87** Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory	Visual analysis and quantification of soft soil inclusions	**Section 5.2** of the present paper, after **Ganne et al. (2011 and 2012)**
			Handling procedure for the preparation of DSM test specimens	**Section 5.3** of the present paper
			Density	**EN 12390-7: 2009** Testing hardened concrete - Part 7: Density of hardened concrete
			Unconfined compressive strength, UCS	**EN 12390-3: 2009** Testing hardened concrete - Part 3: Compressive strength of test specimens
			Modulus of elasticity, E	**NBN B 15-203: 1990** Concrete testing - Statical module of elasticity with compression **ISO/FDIS 1920-10: 2010** Testing of concrete - Part 10: Determination of static modulus of elasticity in compression
			Tensile splitting strength, T	**EN 12390-6: 2010** Testing hardened concrete - Part 6: Tensile splitting strength of test specimens
			Ultrasonic pulse velocity, V_p	**ASTM C 597 - 09** Standard Test Method for Pulse Velocity Through Concrete **EN 12504-4: 2004** Testing concrete in structures - Part 4: Determination of ultrasonic pulse velocity
			Porosity	**NBN B 15-215: 1989** Concrete testing - Absorption of water by immersion
			Hydraulic conductivity	**DIN 18130-1: 1998** Laboratory tests for determining the coefficient of permeability of soil

5. HANDLING/PREPARATION OF TEST SPECIMENS

5.1. Identification

Once a technically qualified person receives the sample boxes, the cataloging and specimen identification operations start. First, a catalogsheet is established with the following information: the construction site, the contractor's name, the material type and the number of boxes and samples. The type of test may already be mentioned with the required sample age for the test realization. A reference should be made to the sampling report associated with the sample boxes.
The samples are then removed from their box for a first visual analysis and in order to determine the type of test(s). Each sample is identified with a unique identification mark allowing traceability to its original coring and depth. A colour photograph that includes the name of the construction site, the sample identification and a reference scale is performed (see Fig. 1).

Figure 1: Identification of core sample

5.2. Visual analysis and consideration of soil inclusions

Due to the specific procedure of deep mixing, soft soil inclusions in the DSM material are inevitable. Nevertheless, the volume of soil inclusions in DSM structure is an important factor to quantify as it has an influence on the material strength, its stiffness and its permeability. Hence, within the framework of the BBRI 'Soil Mix' project, two methodologies to quantify soil inclusions have been developed (Ganne et al., 2011 and 2012).

5.2.1. Description of the methodologies

In the present test procedure, the inclusions are considered as soft soil inclusions. In order to quantify the volume of soil inclusions, DSM material from in situ executed DSM columns and panels have been observed.
Soil inclusions can be described based:
- on drilled cores, as illustrated in Fig. 1,
- on entire sections of DSM columns/panels, as illustrated in Fig. 2.

The two methodologies quantifying the amount of soil inclusions are the surface percentage (A) and a simplified procedure: the line percentage (B).

<u>Methodology (A):</u>
The calculation of the surface percentage of soil inclusions involves six successive steps:
1. DSM columns or panels are executed in situ by standard DSM procedure
2. The test columns/panels are (partly) excavated, as illustrated in Fig. 3
3. The column/panel is then sawed to create a statistically representative 'fresh' saw-cut section (see Fig. 4).
4. The saw-cut surface, as presented in Fig. 2a, is photographically digitized to recompose one digital mosaic photo. The pixel resolution is about 0.3 mm.
5. Using commercially available image processing techniques (IPT), soft soil inclusions, as highlighted in Fig. 2b, are assigned in black on the digital mosaic photo. As the soft soil inclusions are not always observable, manual verifications are performed on the saw-cut surface.
6. The determination of the surface percentage of soil inclusions consists in the calculation of the amount of assigned (black) inclusions and the total surface of the saw-cut using IPT.

Alternatively, the saw-cut section of a core sample can also be used.

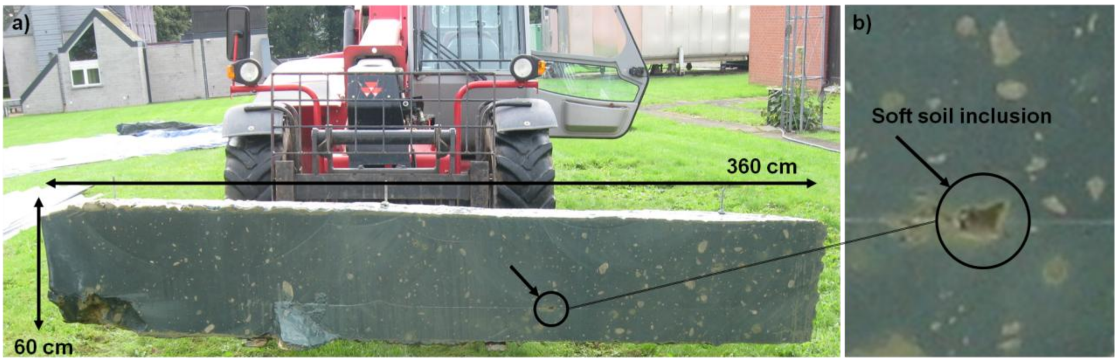


Figure 2: a) Saw-cut section of a CSM panel, b) enlargement of a soft soil inclusion

Figure 3: Excavation of an in situ executed CSM panel (Lameire Funderingstechnieken n. v.)

Figure 4: Sawing of a CSM panel

<u>Methodology (B):</u>

The line percentage methodology is a simplified procedure that is fairly easy to apply for drilled cores. As illustrated in Fig. 5a, four lines are drawn, distributed equidistantly around the core diameter and the cumulative length of soil inclusions along the lines is manually measured (see Fig. 5b). The line percentage is calculated as the proportion of this cumulative length to the total lines length.

This methodology is applied to complete core lengths as they are received and before sawing, in order to avoid loss of information with regard to soft soil inclusion due to further treatment of the samples.

Methodology (B) can also be applied to an entire section of DSM columns/panels considering parallel lines drawn on the saw-cut surface. Then, line and surface percentages of soft soil inclusions can be compared.

a) **b)**

Figure 5: Application of the methodology (B) for a drilled core

Both methodologies are based on the Delesse principle (after Weibel, 1980): the observed line and surface percentages of inclusions in a representative volume of material can be considered as unbiased estimations of the volume percentage of inclusions in the material, assuming a chaotic distribution of the inclusions into the block. Figure 6 illustrates the Delesse principle for inclusions in a cubic block of side l. In Fig. 6b, η(y) is the percentage of inclusion in the *y* direction. Each column corresponds to the percentage of inclusion for a slice of material with a width dy. $\overline{\eta}$ is the average percentage in the *y* direction.

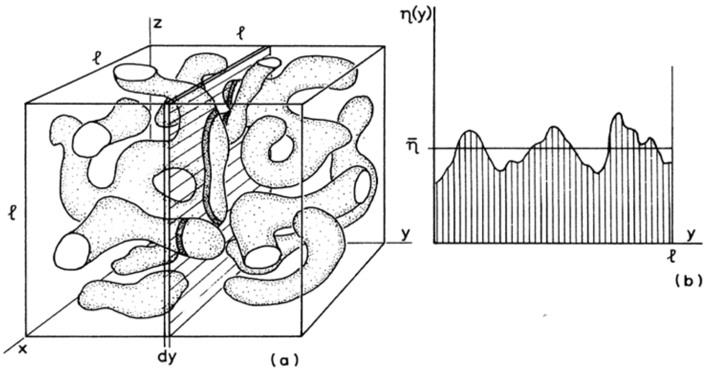


Figure 6: The principle of Delesse, after Weibel (1980)

After completion of the mechanical test, the surface or line percentage can be correlated to the test result (UCS, T and E). Nevertheless, if it is found after testing, based on a visual observation, that large soft soil inclusions become only visibly after testing, as there are not visible on the outer surface. The operator should indicate this information in the remarks section of the test report.

5.3. Handling/Preparation of the test specimens – procedure description

5.3.1. Size of the test specimens

After visual analysis, each core sample must be sawed and treated to comply with its test type. Table 2 describes requirements for the size of the test specimen.

Table 2: Requirements for the specimen size for the tests performed within the framework of the BBRI 'Soil Mix' project

Density	According to **EN 12390-7: 2009**, "*The minimum volume of a specimen shall be 0.785 l*". This condition is encountered with 100 mm diameter samples with height to diameter ratio, H/D, close to 1.
UCS	The height to diameter ratio is 1. This choice was based on the necessity to collect a maximum of cores and was made in order to compare the UCS test results on cylindrical cores with cube strength, as indicated in **EN 12390-3: 2009** and especially in **EN 12504-1:2009**.
Modulus of elasticity	According to **NBN B 15-203: 1990**, the height to diameter ratio is 2, which is in line with the indications of the **ISO/FDIS 1920-10: 2010**: "*The length to diameter ratio of the test specimens shall be between L/d = 2 to 4 and 2 is recommended*".
Tensile splitting strength	Samples with height to diameter ratio close to 1 have been tested in order to use similar size ratio as for UCS test. As reported in **NBN EN 12390-6: 2010** for concrete samples: "*the effect of cylinder size on measured tensile strength was not found to be significant, possibly due to the variability of the data*". Such variability is also observed for DSM material.
Ultrasonic pulse velocity	As indicated in **ASTM C597-09**: "*The least dimension of the test object must exceed the wavelength of the ultrasonic vibrations*". Considering the natural frequency of the transducers used for the test, 160 kHz, and the range of pulse velocities recorded for DSM material, varying between 2000 and 3600 m/s, the specimen size was always comfortably larger than the wavelength: H/λ is close to 6.
Porosity	In accordance with the **NBN B 15-215: 1989**, the volume of the tested specimens, with H/D close to 1, was larger than 800 cm³.
Hydraulic conductivity	The permeability of the DSM specimens was determined with the help of the **DIN 18130-1: 1998**. This latter gives requirement for cohesive and coarse-grained soils: "*The cross-sectional area of the specimen, A, shall be not less than 10 cm² for cohesive soil, and not less than 20 cm² for coarse-grained soil, unless the test equipment requires the use of larger specimens*". In the present study, the test specimens had cross-sectional area close to 80 cm².

5.3.2. Handling procedure description

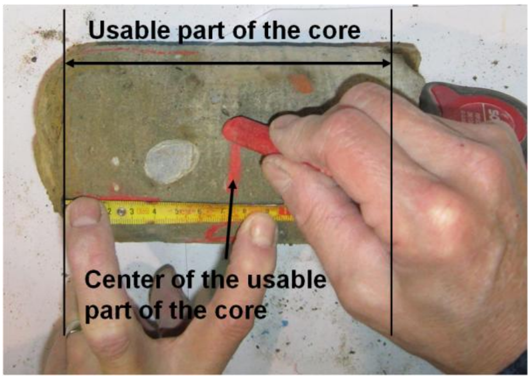
At this stage of the test process, the way the operator handles the core sample is significant for the test result. Within the framework of the BBRI 'Soil Mix' project, the same handling procedure was followed for every DSM sample. Figures 7 to 9 describe the handling and the marking of test specimens by the operator for different situations.

First, the operator determines the usable part of the DSM sample. In most cases, the sample edges are particularly damaged (due to the drilling operations) and are not representative for the DSM material. The center of the workable part is indicated on the core (see Fig. 7a).

Afterwards, the operator defines the dimensions of the test specimen(s) in the usable area in such a way to use a maximal part of the DSM sample and to avoid subjective positioning of the test specimen(s) due to the presence of local soft soil inclusion(s) at the extremities of the core. To ensure this objective selection, the same quantity of DSM material is rejected at both extremities of the usable part of the core. In Fig. 7b and 7c, the sawing lines are drawn on the DSM core. Figure 7d illustrates the full marking of the core.

Each test specimen, defined according to this procedure, must be once again identified and recorded.

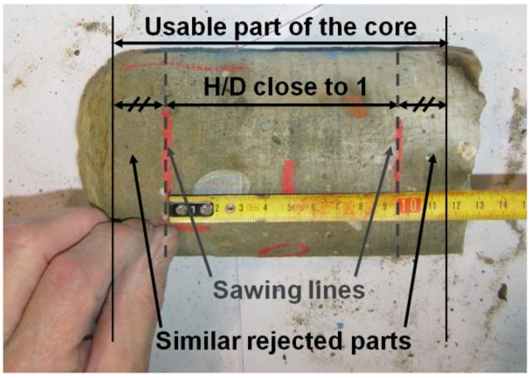
After the marking, the test specimens are generally sawed or possibly ground. The intended load-bearing surfaces could be prepared by grinding or by capping, as indicated in the Annex A of EN 12390-3.



a) Definition of the usable part of the sample

b) Drawing of the first sawing line

c) Drawing of the second sawing line



d) Full marking of the DSM core

Figure 7: Preparation of a DSM test specimen intended for UCS test (H/D ratio close to 1)

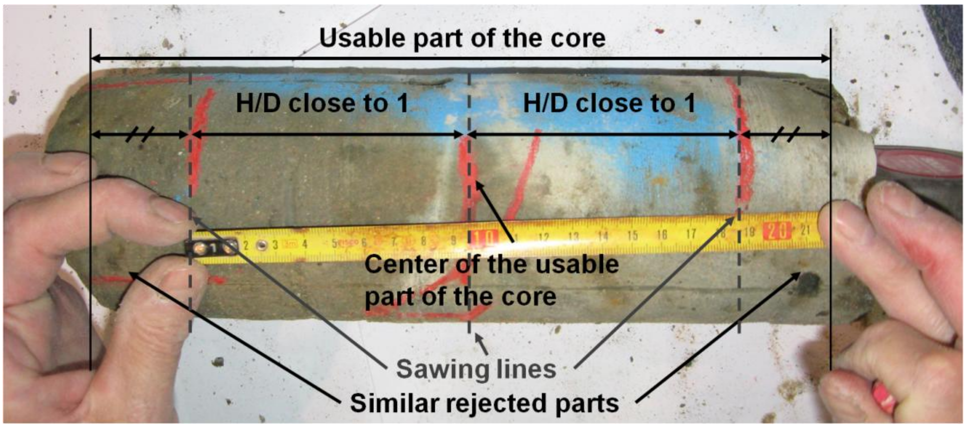


Figure 8: Preparation of two DSM test specimens, both intended for UCS tests

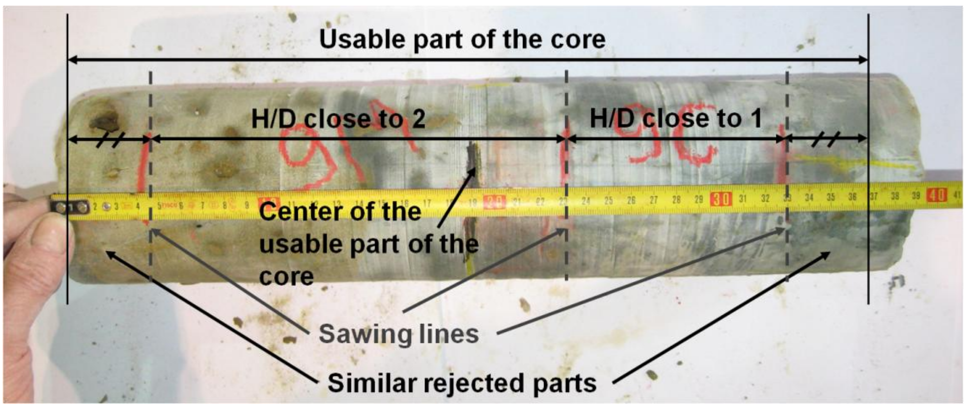


Figure 9: Preparation of two DSM test specimens for the determination of the modulus of elasticity (sample 9M) and the UCS (9C)

6. TEST AND REPORT

6.1. Test procedures

Within the framework of the BBRI 'Soil Mix' project, several tests have been conducted to characterize the DSM material:
- unconfined compressive strength,
- tensile splitting strength,
- modulus of elasticity,
- ultrasonic pulse velocity,
- adherence with steel reinforcement.

These tests have been performed on the basis of the standards for concrete and soils referred in Table 1. Nevertheless, there are specificities related to the nature of the DSM material. The details of the test procedures are defined in Denies et al. (2012b).

6.2. Test report

The content of the test report depends on the type of tests. Nevertheless, several elements should always be included:
- date and time of the test;
- identification of the test specimen;
- percentage of soft soil inclusions measured with methodology (A) and/or (B);
- conditions of the specimen on receipt and the date of delivery;
- storage conditions since receipt;
- age of the specimen at the time of the test;
- dimensions of the test specimen (height, diameter and H/D ratio);
- specimen mass;
- density of the specimen;
- surface condition of the specimen at the time of the test,
- indications on adjustment by grinding and/or capping (if it has been applied to the specimen);
- maximum load at failure (kN) – in case of UCS and tensile splitting strength tests and for the determination of the modulus of elasticity;
- strength based on the maximum load (MPa).

If it is the purpose to obtain more detailed information with regard to the failure pattern, the loading of the DSM sample must be performed with a constant rate of deformation and not with a constant rate of load as usually recommended in the standards to determine the UCS value of concrete. In that case, the test report shall also be documented with pictures of the failure pattern of the sample, as illustrated in Fig. 10. It is to note that the failure pattern also depends on the specimen size and on the ratio H/D.

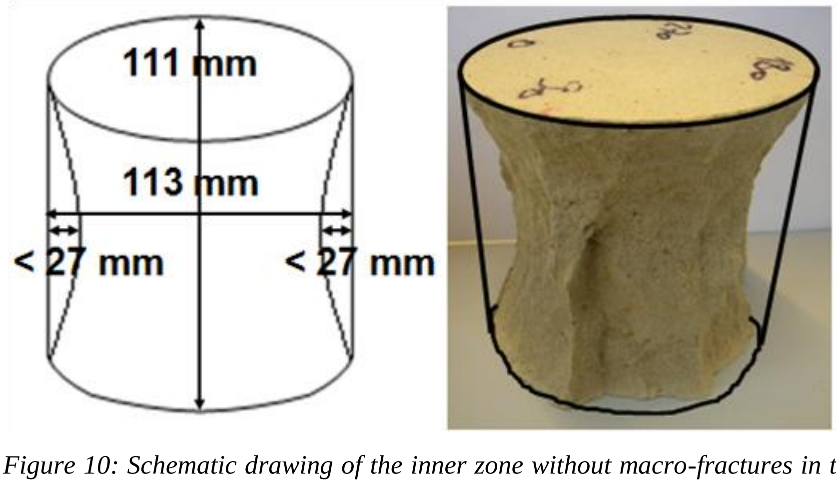


Figure 10: Schematic drawing of the inner zone without macro-fractures in the DSM samples (L/D ratio close to 1)

The final purpose of the laboratory tests on core samples is to characterize the in situ executed DSM material. Hence, whatever the considered stage in the timeline of the sample, **traceability is the key to a successful test campaign**. Indeed, in the test report, the results associated with a particular sample should be correlated to its original borehole location and depth and hence, to the parameters and date of execution of a specific SMW element.

7. CONCLUSIONS

In recent years, SMW have increasingly been used – in Belgium and in several other countries – for the retaining of soil and water in the case of excavations. Unfortunately, up till now, guidance rules and recommendations concerning the realization of SMW with a soil and/or water retaining function have been lacking in spite of the fast increasing number of applications (Denies et al., 2012a). As part of QA/QC development and European standardization, basic rules are required with regard to design, execution and control of these different DSM execution processes. For the purpose of developing such standard, several tests to characterize DSM material, executed in situ by standard DSM procedure, have been performed (Denies et al., 2012b).

The European standard for the execution of deep mixing (EN 14679: 2005) gives some indications with regard to the laboratory testing on DSM core samples, but no specific requirements are provided for the preparation of the test specimens and the details of the different test procedures (for the determination of the UCS, the modulus of elasticity and the permeability) are not described. For that reason, within the framework of the BBRI 'Soil Mix' project, procedures for the sampling, the transportation, the storage, the handling and the preparation of the DSM test specimens have been proposed on the basis of several standards for soil and concrete materials (see Table 1).

With the present paper the authors hope to contribute to the development and the establishment of test procedures in the continuity of the content of the European standard EN 14679 (2005) for deep mixing. In addition, for the purpose of controlling the uniformity and homogeneity of DSM material, two methodologies to quantify the volume of soft soil inclusions have also been developed.

8. ACKNOWLEDGEMENTS

The authors wish to thank members of the BBRI for their technical assistance and experience in the development of the handling and test procedures, especially, Bernard André, Rosario Bonsangue, Christian Mertens and Christian Verbeke. This research program is financially supported by the Agency for Innovation by Science and Technology of the Flemish Region IWT (BBRI, 2009-2013).

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