SOIL MIX walls as retaining structures – critical analysis of the material design parameters

P. Ganne, N. Huybrechts
Belgian Building Research Institute, Division of Geotechnics, Brussels, Belgium

F. De Cock
Geotechnical Expert Office Geo.be, Belgium

B. Lameire
Belgian Association of Foundation Contractors ABEF, Belgium

J. Maertens
KULeuven, Jan Maertens & partners, Belgium

ABSTRACT:
The application of soil mix technology in Belgium is sharply increasing. Next to soil improvement applications, soil mix walls are extensively used for excavation support. The compressive strength and elastic modulus of the soil mix material are essential parameters in the design of these retaining structures. This paper describes a procedure for the estimation and measuring of the compressive strength and the elastic modulus of soil mix material. These procedures are based and validated on a large population of laboratory test results on in situ cored soil mix material, realized in Belgian soils. Furthermore, a procedure to define the 5% fractile characteristic value of the compressive strength of soil mix material is proposed and validated.

1. INTRODUCTION

Since several decennia, the (deep) soil mix technique is known as a ground improvement technique (Probaha, 1998). Therefore, the ground is in situ mechanically mixed while a binder, based on cement and lime (Probaha et al., 1998), is injected. The results of national and European research programs have been published in multiple interesting reports (such as Eurosoilstab, 2002), while also the European standard for the execution of deep mixing “Execution of special geotechnical works – Deep Mixing” (EN 14679) was published in 2005. Most of these research projects focussed on the global stabilisation of soft cohesive soils such as peat, clay, gyttja, silt, …

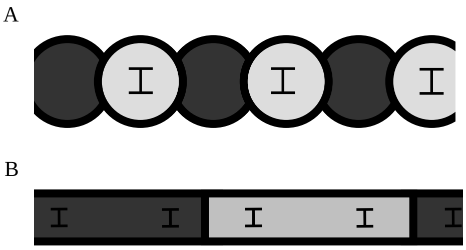

Figure 1. Schematic plan view of the secant execution of (A) cylindrical soil mix columns and (B) rectangular soil mix panels.

More recently, soil mix is increasingly used for the retaining of soil and water in the case of excavations as a more economical alternative for concrete secant pile walls and even for king post walls (i.e. soldier pile walls). The soil mix cylindrical columns or rectangular panels are placed next to each other, in a secant way. By overlapping the different soil mix elements (Rutherford et al., 2007), a continuous soil mix wall is realised (Figure 1 and 2). Steel H or I-beams are inserted into the soil mix before curing to resist the shear forces and bending moments in the retaining wall. The maximum installation depth of the soil mix walls lies – so far – in the order of 20 m. The main structural difference between these soil mix walls and the more traditional secant pile walls is the constitutive wall material which consists of a mixture of soil and cement in stead of traditional concrete.

Figure 2. Photo of a soil mix wall with a ground and water retaining function (CVR).

So far, three main types of soil mix systems are used in Belgium: CVR C-mix®, TSM and CSM. The characterization of the resulting soil mix material is a difficult issue. This paper firstly describes the different types of soil mix systems, whereupon the determination of the compressive strength and of the elastic modulus of the soil mix material is discussed.

2. SOIL MIX SYSTEMS IN BELGIUM

The CVR C-mix®, the TSM and the CSM are the three most used types of soil mix systems in Belgium. All three are wet soil mixing systems.

2.1. CVR C-mix®

The CVR C-mix® is performed with an adapted bored pile rig and a special designed shaft and mixing tool. This tool rotates around a vertical axis at about 100 rpm and hence, cuts the soil mechanically. Simultaneously, the water\binder mixture (water\binder ratio between 0.6 and 0.8), is injected at low pressure (< 5 bar). The injected quantity of binder amounts mostly to 350 and 450 kg binder/m³, depending on the soil conditions. The binder partly (between 0% and 30%) returns to the surface. This is called 'spoil return'.

The resulting soil mix elements are cylindrical columns. The diameter of the soil mix columns is the diameter of the mixing tool, of which the nominal diameter varies between 0.43 and 1.03 m. When the soil mix is used as a retaining structure, the production rate is about 160 m² of soil mix wall per day.

In order to increase the production rate, a CVR Twinmix® and a CVR Triple C-MIX® is used. A twinmix has two mixing tools, mixing two overlapping cylindrical columns (total wall length of 0.8 to 1.2 m) at the same time. The daily return increases till 210 m². A CVR Triple C-mix® has three mixing tools in line, with an overall wall length of 1.5 to 1.8 m. The production rate increases to 300 m² per day.

2.2. Tubular Soil Mix (TSM)

The TSM technique uses a mechanical and a hydraulical way of mixing. Apart from the rotating (around the vertical axis) mixing tool, the soil is cut by the high pressure injection (till 500 bar) of the water\binder mixture. The water\binder ratio of the mixture can be chosen between 0.6 and 1.2. The injected quantity of water\binder mixture amounts mostly to 200 and 450 kg binder/m³, depending on the soil conditions. Part of the binder (between 0% and 30%) returns to the surface as spoil return.

The resulting soil mix elements are cylindrical columns with a diameter between 0.38 and 0.73 m. The production rate is about 80 m² of soil mix wall per day.

Again, a twin and a triple version exist. The total wall length of the two (three) cylindrical columns of a twin (triple), varies between 0.8 and 1.4 m (1.2 and 2.1 m). In this way, the production rate is increased till about 180 (twin) and 250 m² (triple) of soil mix wall per day.

2.3. Cutter Soil Mix (CSM)

A CSM device is commercially available. It makes use of two cutting wheels that rotate independently about a horizontal axis, cutting the soil. At the same time, the water\binder mixture is injected at low pressure (< 5 bar). The water\binder ratio can be chosen between 0.6 and 1.2. The injected quantity of binder amounts mostly to 200 and 400 kg binder/m³, depending on the soil conditions. Part of the binder (between 0% and 30%) returns to the surface as spoil return.

The resulting soil mix elements are rectangular panels. In Belgium, these panels have a length of 2.4 m and a thickness of 0.55 m, though cutter devices with other dimensions are internationally available. The production rate is about 100 m² to 250 m² per day.

2.4. Advantages of soil mix walls as retaining structures

The use of soil mix as ground and/or water retaining structures has some specific advantages.

No important vibrations are caused by the execution of soil mix. As the stress relaxation of the soil is limited, soil mix can be executed nearby existing constructions.

Contrary to concreted secant pile walls, the execution of the soil mix walls does not suffer from delayed supply (e.g. due to traffic jams) of the fresh concrete.

Another interesting advantage, compared to jet-grouting is the limited amount of spoil return.

3. TEST PROGRAMME

Cores of soil mix have been drilled horizontally on 23 different job sites in Belgium, with different soil conditions and with different types of soil mix systems. All in all, 950 unconfined compressive tests and 100 determinations of the elastic modulus have been performed on these cores. Also wet grab samples and laboratory samples have been analysed.

3.1. Execution of unconfined compressive tests

The laboratory test to determine the unconfined compressive strength (UCS) is performed by a MFL 250 kN loading machine. The loading rate amounts to 2.5 kN/s. The samples have a diameter between 85 mm and 115 mm. The accuracy of the diameter of the cores is 0.3 mm. The height to diameter ratio is 1 (EN 206). All test samples with soil inclusions > 1/6 of the diameter are rejected, on condition that no more than 15% of the test samples from one particular site are rejected. This possibility to reject test samples results from the reflexion that a soil inclusion of 20 mm or less will not influence the behaviour of a soil mix structure, conversely, a soil inclusion of 20 mm in a test sample of 100 mm diameter will influence the result of the test significantly. Of course, this condition is only suitable if one assumes that in the soil mix structure, no soil inclusions larger than 1/6 of its width occur.

3.2. Execution of elastic modulus tests

The laboratory test to determine the elastic modulus is unconfined performed (MFL 250 kN) on in situ cored test samples with a diameter between 85 mm and 115 mm. The accuracy of the diameter of the cores is 0.3 mm. The height to diameter ratio is 2. For the tests of the elastic modulus, cores with a visual better quality are selected, in order to preserve a uniaxial behaviour of the tested samples. The elastic modulus is determined on a secant way by a cyclic loading between 10% and 30% of the estimated UCS of the test samples. The loading rate amounts to 2.5 kN/s. The sample deformations during these loading cycles are measured by three couples of demec points. Once the mean difference of the measured deformation, caused by each cyclic loading, is smaller than 1.10^{-5} Strains (NBN-B15-203), the secant elastic modulus is calculated. Thereafter, the loading is continued to determine the UCS.

3.3. Comparison of cored and wet grab samples

Further on in paragraphs 4 and 5, only laboratory tests using drilled cores are considered. This has been decided after a comparative study of the UCS of cored as well as wet grab samples. Indeed, at two job sites, also wet grab sampling has been performed. In the first half hour after the mixing of the soil with the binder, a specially designed cylindrical wet grab sampling tool is pushed in the fresh soil mix element. This sampler stays closed until it reaches the depth of 2 ± 0.2 m. At this moment, the sampler opens over a height of 0.2 m. After the soil mix material fills the sampler, it is locked and pulled up. The material is preserved in a cylindrical mould (diameter = 113 mm; height = 220 mm) in an acclimatised room (humidity > 98%; temperature = 20 ± 2°C). Two weeks later, the same soil mix elements are cored at the same location (at 2.0 ± 0.2 m depth). The cores and the wet grab samples are tested on the same day (curing time = 14 days). This procedure is applied twice on a job site in Ghent (CSM in tertiary sand) and twice on a job site in Louvain (CSM in tertiary sand). The differences between the mean UCS of drilled cores and of wet grab samples varies between -10% and +35% (Table 1). These differences can not be explained by the variation of the test results only (Larsson, 2005). Probably, also the curing conditions have a significant influence.

Table 1. Comparison between the UCS results at 14 days on cored and wet grab samples (# is the number of test samples, μ is the mean UCS and σ is the standard deviation of the UCS tests).

	Drilled cores	Wet grab
Site - element	UCS [MPa]	UCS [MPa]
Ghent Element I	μ = 2.37 σ = 0.36 # = 5	μ = 2.61 σ = 0.23 # = 4
Ghent Element II	μ = 1.60 σ = 0.25 # = 5	μ = 1.85 σ = 0.10 # = 4
Louvain Element I	μ = 3.98 σ = 0.78 # = 4	μ = 3.68 σ = 0.21 # = 4
Louvain Element II	μ = 4.99 σ = 0.71 # = 5	μ = 3.64 σ = 0.45 # = 4

3.4. UCS in top of wall

It has also been observed on different sites that the soil mix UCS over the first meter is strongly influenced by the execution procedure at the start and the stop of an element (e.g. infiltration of rinsing water). As an example, Figure 3 shows that on the site of Bruges (CSM in quaternary sand), the UCS of samples over the first meter is only about 60% of the mean UCS at larger depth. Consequently, the top of the wall is not representative for the dieper part. Therefore, paragraphs 4 and 5 consider only laboratory tests on samples, cored deeper than the first 1 m below surface.

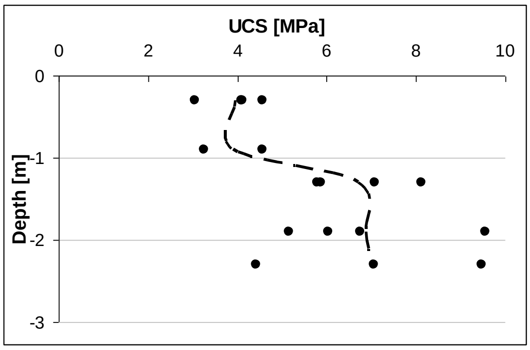

Figure 3. UCS results of samples, cored at different depths (site Bruges: CSM in quaternary sand).

3.5. Influence of the curing time on the UCS of soil mix test samples

The UCS of a soil mix sample depends among others on the curing time. In this article, the curing time of the tested soil mix samples varies between 14 days and 180 days. Therefore, laboratory mixed samples are used to determine the influence of the curing time.

The mixing of the soil and the binder is performed in laboratory using a specific procedure:

- mixing the water and the cement during two and a half minute (in a Zyklos mixing apparatus,
- the dried soil is introduced during one minute,
- continuing the mixing during two and a half minute,
- moulding the soil mix in cylindrical moulds (diameter = 113 mm; height = 220 mm).

For homogeneity reasons, each set of 24 test samples is realized during the same mixing. After 3, 7, 14, 28, 56 and 91 days, the UCS of 4 samples are determined. Using the average of the UCS of 4 samples as a function of time, the following formula is fitted:

$$f_{cm}(t) = \beta_{cc}(t)\ f_{cm} \tag{1}$$

where $f_{cm}(t)$ is the evolution of the UCS with time [MPa]; f_{cm} the 28 days UCS [MPa] and

$$\beta_{cc}(t) = \exp(s(1-\sqrt{\frac{28}{t}})) \tag{2}$$

where t is the curing time [days] and s the fitted parameter (EN 1992-1-1).

Depending on the soil conditions, the type of binder, the amount of binder and the amount of water, the influence of the curing time is tested in 11 different conditions. According to the soil conditions in Belgium, the applied water and cement content and the type of binder (see paragraph 2), the fitted parameter s varies between 0.96 to 0.99 (cement used by CSM) and between 1.28 and 1.71 (cement used by CVR C-mix®).

4. RESULTS OF UCS AND ELASTIC MODULUS OF CORE SAMPLES

950 UCS tests and 100 test of elastic modulus are performed on samples, cored at 23 different job sites in Belgium. The soil is mixed with the water\binder mixture by the soil mix systems and the typical execution parameters, used in Belgium (see paragraph 2). It is obviouss that the UCS and the elastic modulus are influenced by these execution parameters, the soil conditions and so forth.

4.1. Influence of the soil conditions on the UCS of soil mix samples

In order to focus on the influence of the soil conditions, the UCS results in this paragraph are corrected to a curing time of 28 days (based on paragraph 3.4).

To determine the influence of its nature, the soils are classified as (A) quaternary or tertiary sand, (B) silt or (C) alluvial clay. Figure 4 to 6 show the histograms of the UCS test results of the soil mix samples, corrected to a curing time of 28 days, according to the nature of the soil. It is clear that the UCS of soil mix from sands is generally higher than the UCS of soil mix from clays. 80% of the soil mix samples has a UCS at 28 days higher than 4.5 MPa (sand), 3.0 MPa (silt) and 1.7 MPa (clay). It is also noticed that a large variability of the UCS is present, with no regards to the nature of the soil.

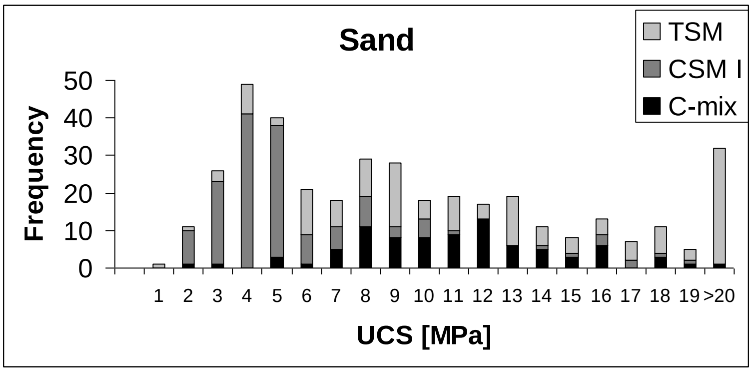

Figure 4. Histogram of UCS [MPa] of cored samples of soil mix material, mixed in quaternary and tertiary sand by a TSM, CSM or CVR C-mix®. The test results are corrected to a curing time of 28 days.

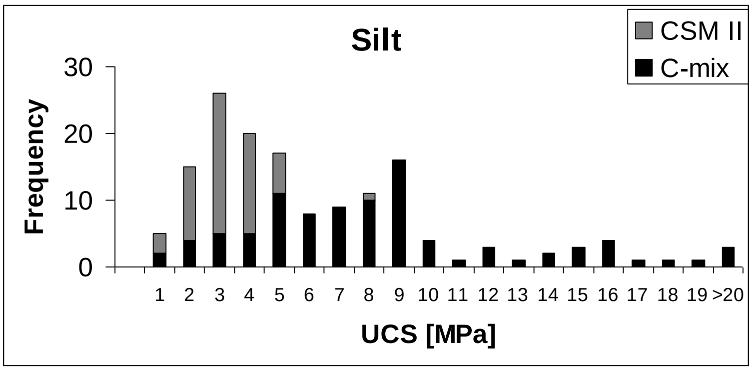

Figure 5. Histogram of UCS [MPa] of cored samples of soil mix material, mixed in silt soils by a CSM or CVR C-mix®. The test results are corrected to a curing time of 28 days.

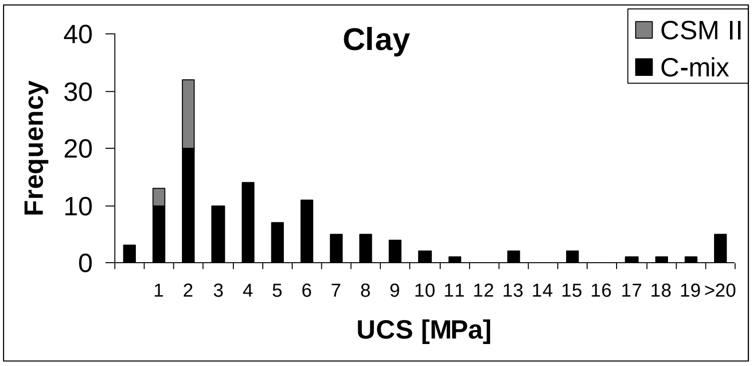

Figure 6. Histogram of UCS [MPa] of cored samples of soil mix material, mixed in alluvial clay soils by a CSM or CVR C-mix®. The test results are corrected to a curing time of 28 days.

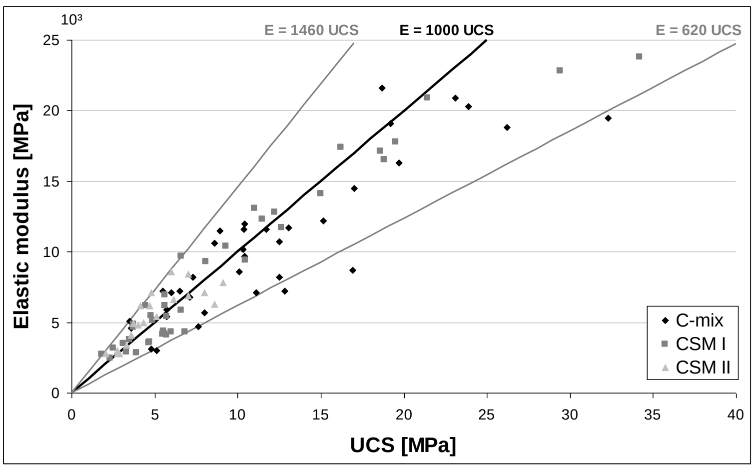

Figure 7. Elastic modulus [MPa] as a function of the UCS [MPa] of soil mix material in different types of soil.

4.2. Elastic modulus of soil mix material

The secant elasticity modulus has been determined on 100 cored soil mix samples. After the cyclic loading for the determination of the elastic modulus, the test is pursued until failure to define the UCS (as described in paragraph 3). These samples are cored in soil mix walls, executed on 17 sites, with various soil conditions and various execution parameters (paragraph 2). The curing time of the tested soil mix samples varies between 14 days and 180 days. Since the aim of this paragraph is to determine the correlation between the elastic modulus and the UCS of the soil mix material in general, the test results in this paragraph are not corrected for the curing time.

Figure 7 shows the elastic modulus as a function of the UCS of the tested soil mix material, without distincting for the soil type. A linear relation between the elastic modulus and the UCS is fitted. Doing so, the best estimated value of the elastic modulus of the soil mix material is roughly:

$$E = 1000\,UCS \tag{3}$$

where E is the secant elastic modulus [MPa] and UCS the unconfined compressive strength [MPa] of the soil mix material. A lower 5% fractile estimation of the elastic modulus of the soil mix material is:

$$E = 620\,UCS \tag{4}$$

A higher 5% fractile estimation of the elastic modulus of the soil mix material is:

$$E = 1460\,UCS \tag{5}$$

These estimations are only valid for the range 2 MPa < UCS < 30 MPa.

5. DETERMINATION OF CHARACTERISTIC VALUE OF THE UCS

The UCS (tested as in paragraph 3) is used as a quality control for the in situ soil mix material. The aim is to estimate a 5% fractile characteristic value of the UCS that may be considered in the design. The conventional method to estimate a characteristic value, is to assume a Gaussian population of the test results. In this case, the 5 % fractile characteristic value is estimated as (neglecting student t - correction):

$$X_{k,0.05} = \overline{X} - 1.64\,\sigma \tag{6}$$

where $X_{k,0.05}$ is the estimated 5% fractile characteristic value, $\overline{X}$ the mean value and σ the standard deviation of the population of the test results.

This method is considered in Belgium to give by far too pessimistic results for populations of UCS of soil mix material. This is demonstrated in Table 2, which compares the 5% fractile lowest test result (as determined on the test population), with $X_{k,0.05}$ (Eq. 6). For example, the UCS results of samples from Ghent KII (TSM in tertiary sand) show a $X_{k,0.05}$ of -0.7 MPa. Remark that a negative characteristic UCS value has no physical sense. Though, the 5% fractile lowest test result of the population amounts to 6.3 MPa. This substantial difference is caused by the non-symmetrical and non-Gaussian distribution of the UCS test results (Figure 8). Furthermore, the UCS results above 25 MPa causes an important increase of the standard deviation and, hence, a decrease of the $X_{k,0.05}$.

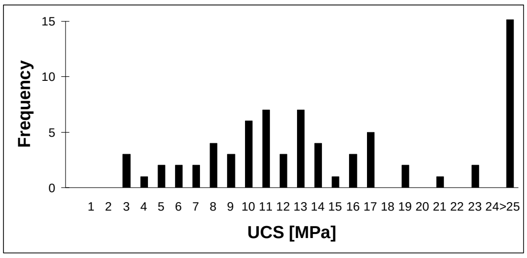

Figure 8. Histogram of the UCS test results of soil mix samples, cored at the site Ghent KII (TSM in tertiary sand).

The estimation of the characteristic value, assuming a log-normal distribution, gives a more realistic estimation. For example in the case of Ghent KII, the estimated characteristic value, assuming a log-normal distribution, amounts to 5.0 MPa. This value is to be compared to the 5% fractile lowest test result (as determined on the test population: 6.3 MPa). The 20% underestimation of the characteristic value of the UCS is due to the non-perfect log-normal distribution of the test results. Figure 9 shows the histogram of the base-10 logarithm of the test results of the UCS on soil mix cores from Ghent KII. This graph suggests that the population of the test results consists of two subpopulations (a population around 1.1 (thus 13 MPa) and one around 1.5 (thus 32 MPa)).

Table 2. Comparison of 5% characteristic value of the test results of the UCS on soil mix material, determined assuming a Gaussian distribution and assuming a log-normal distribution. Per site, the UCS tests are executed on samples, cored on the same depth (± 0.2 m) with about the same curing time. Samples from different sites may be cored at miscellaneous depths or may have different curing time

Site	Soil mix system	Soil	Mean value of UCS test results [MPa]	Standard deviation of UCS test results [MPa]	Coefficient of variation [%]	Number of tested samples [-]	5% fractile characteristic UCS value [MPa] (testpopu-lation)	5% fractile characteristic UCS value [MPa] (Gaussian)	5% fractile characteristic UCS value [MPa] (log-normal)
Bruges	CSM	Quaternary sand	6.3	1.6	25.4	39	4.1	3.8	4.0
Seabruges	CSM	Quaternary sand	6.5	0.8	12.3	38	4.8	5.3	5.3
Ghent KI	TSM	Tertiary sand	9.8	4.6	46.9	60	3.6	2.3	3.6
Ghetnt KII	TSM	Tertiary sand	17.2	10.9	63.4	52	6.3	-0.7	5.0
Antwerp	CVR C-mix®	Quaternary sand	11.9	4.1	34.5	50	6.5	5.2	6.4
Lommel	CVR C-mix®	Quaternary sand	18.6	3.9	21.0	39	11.6	12.2	12.4
Tongeren	CSM	Silt	5.3	1.6	30.2	33	2.8	2.7	2.7
Sint-Lievens Houtem	CVR C-mix®	Silt	10.8	4.9	45.4	31	4.8	2.7	4.5
Limelette	CVR C-mix®	Silt	14.8	5.4	36.5	38	7.4	6.0	7.8
Anderlecht	CVR C-mix®	Silt	8.0	5.8	72.5	64	2.0	-1.6	1.9
Ghent	CVR C-mix®	Alluvial clay	8.6	7.0	81.4	41	1.5	-2.8	1.6
Borgloon	CVR C-mix®	Alluvial clay	5.7	3.1	54.4	26	1.0	0.6	1.4
Knokke	CVR C-mix®	Clay	7.3	7.2	98.6	25	0.5	-4.5	0.9
Erembode-gem	CVR C-mix®	Alluvial clay	8.0	4.6	57.5	25	2.3	0.4	2.4

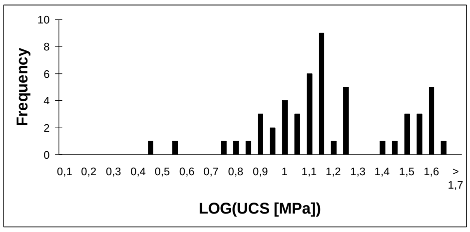

Figure 9. Histogram of the base-10 logarithm of the UCS test results of soil mix samples, cored at the site Ghent KII (TSM in tertiary sand).

In general (Table 2), the estimation of the characteristic value, assuming a log-normal distribution, is more realistic than the estimation, based on the Gaussian approach. Remark that the characteristic value of the UCS of soil mix material, is obtained by testing samples of about 100 mm in length and of about 100 mm in diameter. Further research will be performed to analyse the "size" dependency of this characteristic value that may be considered in the wall design criteria.

6. CONCLUSIONS

The application of the soil mix technology for the realisation of soil and water retaining structures is sharply increasing in Belgium, as in other parts of the world.

Using the soil mix technology for retaining structures, the quality in general, the UCS and the elastic modulus of the soil mix material should be estimated in advance. For this purpose Figures 4 to 7 can be used in Belgian-like soils (if the execution parameters are similar). After the mixing, laboratory tests of in situ cored soil mix material are to be executed to confirm the estimated parameters. Therefore, a procedure to determine the characteristic UCS of soil mix material is proposed and validated. This research is financially supported by the Belgian Normalisation Institute (NBN; BBRI, 2009 – 2010).

The question of an adapted methodology for the mechanical calculation of the soil mix structures taking into account the heterogeneities and soil-inclusion, remains unanswered. End 2009, the BBRI has started a research project about the calculation methodology of soil mix material, focussing on :

1. the compressive strength of soil mix structures considering the influence of soil inclusions,
2. the adherence between the soil mix material and the steel reinforcement elements,
3. the durability of soil mix material,
4. the permeability.

The aim is to obtain a calculation methodology for the soil mix structure, accounting for the presence of the heterogeneities and soil-inclusions, the scale effects and the time-effects such as curing time and creep. This new research project is performed in collaboration with the Catholic University of Leuven and the Belgian Association of Foundation Contractors (ABEF) and is financially supported by the Agency for Innovation by Science and Technology of the Flemish region (IWT; BBRI 2009-2013).

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