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On Dry Deep Mixing of natural clay across scales

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ABSTRACT: Dry deep mixing (DDM) is widely used for ground improvement of soft soils. Although the method has proven to substantially improve the engineering properties, DDM results in variable strength and stiffness properties that are heterogeneous in space. Characterising and controlling this variability is crucial to optimise the performance of lime-cement stabilised soil. In contrast to previous studies and guidelines in engineering practice for DDM that focus on stability, this work investigates the stiffness response, which is a more pertinent parameter for SLS performance. Only limited research exists on the spatial variability of DDM clays, with few prior studies assessing the spatial variability in both strength and stiffness. The same scale of fluctuation for both strength and stiffness is commonly used for natural soils; however, it has not yet been demonstrated for clays improved with DDM. This paper contributes to the state-of-the-art with an integrated approach for characterising strength and stiffness variability at both laboratory and field scales. Stiffness variability is assessed in the laboratory through an innovative image-based method. The distinct methodologies yield diverse estimates of variability, providing valuable insights into the inherent challenges of characterising variability in deep dry mixed natural clays.

KEYWORDS: Dry deep mixing, variability.

1 INTRODUCTION

In Nordic countries where the occurrence of soft sensitive clays is prevalent, Dry Deep Mixing (DDM) has been commonly employed as a ground improvement technique to support infrastructure development by enhancing connectivity and facilitating growth. Although there are established standards for mixing techniques (EuroSoilStab, 2002), factors such as proportion and type of binders added (Åhnberg, 2006), mixing equipment (Larsson, 2006) and in-situ soil conditions (Freitag et al., 1961) contribute to heterogeneity in mechanical properties across the length and breadth of the area improved.

To optimise binder usage and ensure reliable design, it is important to study soil–binder interactions at the laboratory scale. While field mixing conditions cannot be fully replicated in the lab (Paniagua et al., 2022), evaluating variability in lab-mixed samples remains essential. Understanding variability across both laboratory and field scales is key to improving predictive models and ensuring consistent field performance.

This study investigates the variability in strength and stiffness of dry-mixed clays across different time scales and mixing conditions: short-term laboratory-mixed samples (14 and 28 days) and long-term field-mixed samples (1 year). The analysis focuses on both element-level and intra-elemental variability to capture the effects of mixing scale and curing duration. The methods used to study the elemental and intra-elemental variability include a combination of standard testing methods, such as Unconfined Compression Strength (UCS) and Consolidated Isotropic Drained compression (CIDc) tests, and non-standard innovative techniques, such as X-ray Computed Tomography (XCT) and Digital Image Correlation (DIC) and miniature Cone Penetration Tests (mCPT).

SAMPLE PREPARATION

1.1 *Lab mixed samples (14 and 28 days)*

The natural clay used in this study was sourced from the Kärra test site in Gothenburg. A binder mix with CEM I cement and unslaked lime, mixed in a 50:50 ratio, and the total binder content was maintained at 80 kg/m³. The mix was prepared by gradually mixing the binders into the clay using mechanical mixers until a homogenous mixture was achieved. The binder was added in three equal portions, with a total mixing time of approximately four minutes. The lime-cement mixed clay was then carefully compacted using a brass rod to minimise air pockets. The sample tubes were immersed under water and kept under a static load of 20 kPa throughout the curing process.

1.2 *Field mixed samples (1 year old)*

Field mixed lime-cement mixed clays excavated from Centralen area of Gothenburg were used in this study. These samples were cured for 1 year in the field, and the excavated block sample was then trimmed to the required dimensions for laboratory tests. The binder content in the excavated block samples was 40 kg/m³; however, since these blocks included areas where two columns intersected, the actual binder content is expected to be higher than 40 kg/m³.

2 METHODS

To comprehensively evaluate the variability in strength and stiffness of the composite clays, a variety of testing approaches were employed. These methods were designed to capture both element-level and intra-elemental differences across different curing durations.

To determine the element-level variability in strength and stiffness in lab-mixed samples with a curing period of 14 and 28 days, they were tested using standard Unconfined Compression Strength tests and Consolidated Isotropic Drained compression (CIDc) tests. These tests aimed to assess the variability in peak strength and initial stiffness. Additionally, the intra-elemental variability in the strength of lab-mixed samples was examined using a miniature Cone Penetration test apparatus developed in the lab at Chalmers. Figure 1 shows an overview of the methods used to determine the variability in lab-mixed samples.

For the field-mixed (1 year) samples, the element-level variability in strength and stiffness was determined using standard UCS. The intra-elemental variability in the strength of lab-mixed samples was studied using two state-of-the-art image-based techniques. In the first method, X-ray Computed Tomography (XCT) scans were analyzed to determine the three-dimensional variability in grey-scale intensities, reflecting material non-homogeneity arising from regions of well-cemented areas and unmixed clay pockets. In the second method, a Digital Image Correlation (DIC) setup was integrated with a standard Unconfined Compressive Strength (UCS) test to examine stiffness variability across the sample face, caused by heterogeneity during mixing. Figure 2 provides an overview of the techniques used to assess variability in the laboratory-mixed samples.

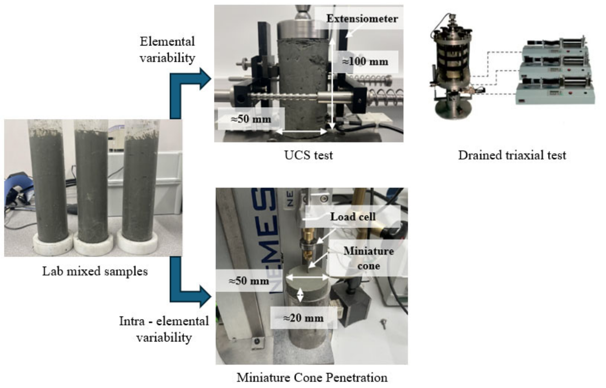

Figure 1. Methods used to study elemental and intra-elemental variability in lab-mixed samples (14-28 days)

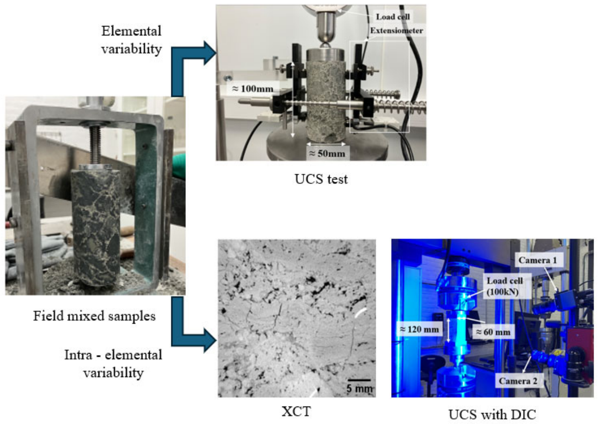

Figure 2. Methods used to study elemental and intra-elemental variability in field-mixed samples (1 year)

2.1 *Unconfined Compressive Strength (UCS) test*

The UCS tests were performed on cylindrical samples of dimensions ≈ 100 mm x 50 mm (H x D) using a GDS loading system equipped with a 10kN load cell to monitor the axial load on cylindrical samples. The samples were equipped with a pair of extensometers, each with a precision of 1 µm, to measure local strains at the midsection of the specimen. The resulting unconfined compressive strength, q_u, and the local stiffness E_{local}, were determined from these tests.

2.2 *Consolidated Isotropic Drained compression (CIDc) test*

CIDc tests were conducted using a Bishop and Wesley triaxial cell integrated with a GDS system for precise control and data acquisition. These tests were performed on cylindrical samples with dimensions approximately ≈ 100 mm x 50 mm (H x D). Samples were saturated by applying a back pressure of 50 kPa for over 18 hours, achieving Skempton b-values of around 0.6, which is typical for stiff clays (Black and Lee, 1973). Each sample was instrumented with local strain transducers having a gauge length of approximately 45 mm to enable accurate strain measurement. Following saturation, the sample was subjected to isotropic consolidation under an effective stress of 50 kPa and confining stress of 100 kPa. The samples were then sheared under drained conditions at a constant rate of 0.01%/min up to 10% axial strain. As a result, the initial stiffness E from the initial part of the stress-strain plots were determined.

2.3 *Miniature Cone Penetration Test (mCPT)*

The mCPT test apparatus included an actuator using parts of a modified Nemesys mid-pressure syringe pump. A stainless-steel needle with a diameter of $B = 2$ mm and a cone tip at an angle of 60 ° was used as the miniature cone. The tests were performed at a rate of 1 mm/s, and the corresponding force response was measured using a load cell with a capacity of 100 N at a penetration of 4 mm. The resulting penetration resistance q_c was calculated as F/A_c, where F represents the force response at a 4 mm penetration depth and A_c represents the area of the cone. The test was performed on 4 points on each side of the sample (a total of 8 measurements). The spacing of the points on the face of the sample were selected based on scaling laws for CPT tests on soil (Garnier et al., 2007), where S was set to = 16.7 mm, yielding $S/B \approx 9$, an intermediate value between typical CPT ratios for clays ($S/B = 5$) and coarse-grained soils ($S/B = 10$) (Figure 3).

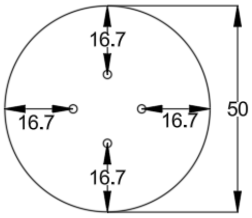

Figure 3. Spacing of points on the face of the sample (all dimensions in mm).

2.4 *X-ray Computed Tomography (XCT)*

Three-dimensional scans of the cylindrical samples, with dimensions ≈ 100 mm x 50 mm (H x D), were acquired using the RX Solutions EasyTom150 X-ray tomograph at the 4D Imaging Lab, Lund University. The XCT image data obtained were pre-processed to reduce noise and capture spatial variability in X-ray attenuation using autocorrelation. The data were binned ($2 \times 2 \times 2$ pixels per voxel) and cropped to 550×550 pixels (60 µm/pixel). From approximately 3,500 slices for each sample, the central 1,000 (~60 mm) were used for analysis.

To estimate the Scale of Fluctuation (SOF), spatial variations in grey-scale intensity from 2D and 3D image data of lime-cement clay samples were analysed. Using the python package SPAM (Stamati et al., 2020), directional covariances were computed and normalised by the overall variance to derive experimental correlation profiles. These were then fitted with a theoretical model to evaluate SOF along each principal axis based on image intensity patterns.

2.5 *Digital Image Correlation (DIC) with UCS*

DIC was performed on cubic samples of dimensions ≈ 100 mm x 50 mm (H x D). A GOM DIC stereoscopic two-camera setup was used to capture images at a rate of 6 frames per second of loading with a resolution of 3000. The loading system of 100kN capacity was used. Images were recorded at every stage of loading, enabling continuous tracking of displacement and deformation. The strain field in the elastic region was then computed using SPAM Python package's DIC script (Stamati et al., 2020). The strain field data was used to calculate the average strain across slices of 30-pixel thickness along the length of the sample. Based on these average strain values, the stiffness distribution was determined, assuming that the applied force was uniform across all slices due to symmetry. The SOF of the stiffness distribution across the vertical face of the sample was thus determined.

2.6 *Test plan*

The test plan for the study is as seen in Table 1.

Table 1. Test plan.

	Test	No. of samples tested
Lab-mixed	UCS	*3 (14 days), 3(28 days)*
	Triaxial	*3 (14 days), 3(28 days)*
	mCPT	3 (14 days), 3(28 days)
Field-mixed	UCS	*6 (1 year)*
	XCT	*6 (1 year)*
	DIC	2 *(1 year)*

3 RESULTS

3.1 *Variability in lab-mixed samples*

From observations during preparation, more air pockets were found near the top of the plastic tube due to less effective compaction as layers were added as seen in Figure 4. Better compaction at the bottom resulted in denser material, leading to variability in strength and stiffness between elements as well as within an element.

Figure 4. Observation of more air pockets and less compaction in the top half of sample tube (left) in comparison to the bottom half of sample tube (right).

Based on the results from the UCS test, the strength q_u at 14 days and samples extruded from different parts of the plastic tube ranged between 0.18 – 0.21 MPa at 14 days and between 0.23 – 0.28 MPa at 28 days. The local stiffness E_{local} ranged between 101-115 MPa at 14 days and at 28 days of curing, the stiffness increased to a range of 134-142 MPa. Figure 5 and Figure 6 depict the deviator stress vs average local axial strain plots. In both figures it is apparent that the samples extruded from the top part of the tube resulted in much stiffer samples although the strength measure by the UCS tests lie in a closer range. This could be an indication that the stiffness parameters are more sensitive to heterogeneity in the form of air pockets as compared to the strength behaviour. The stiffness of the samples ranged between 27- 63 MPa at 14 days curing while at 28 days the E ranged between 126-63 MPa.

On the other hand, intra-elemental measure of strength q_c determined from the mCPT test ranged between 3.16-3.64 at 14 days and in the range of 3.94-4.77 at 28 days of curing. The results of the tests performed with lab-mixed samples are listed in Table 2.

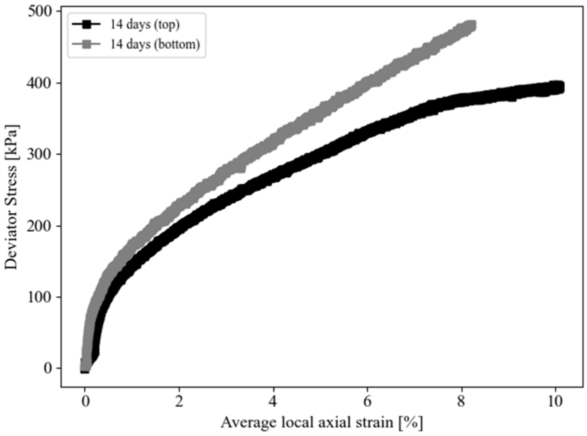

Figure 5. Deviator vs. Average local axial strain plot for 14-day samples extruded from bottom of the tube (gray) and top of the tube (black)

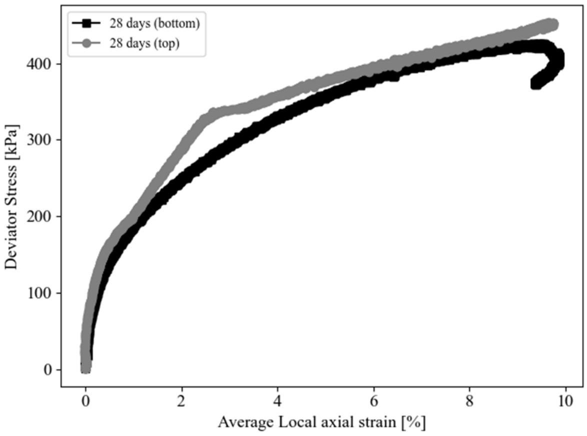

Figure 6. Deviator vs. Average local axial strain plot for 28-day samples extruded from bottom of the tube (gray) and top of the tube (black)

Table 2. Determined properties for lab-mixed samples.

Test	Property	Range [MPa]
UCS	q_u *(14 days)*	0.18 – 0.21
	q_u *(28 days)*	0.23 – 0.28
	E_{local} *(14 days)*	101 - 115
	E_{local} *(28 days)*	134 - 142
Triaxial	*E (14 days)*	27-63
	E (28 Days)	63-126
mCPT	q_c *(14 days)*	3.16 – 3.64
	q_c *(28 days)*	3.94 – 4.77

3.2 *Variability in field-mixed samples*

The field mixed samples showed a marbled pattern with areas of cemented clay with pockets of unmixed clay (0. XCT data, based on grey-level intensities which are directly related to the local density of the material, enabled the differentiation between cemented (denser) and uncemented (less dense) regions. By analysing the spatial variation of these intensities, it was possible to determine the Scale of Fluctuation (SOF), which represents the spatial length over which material properties are highly correlated. Since density variations are closely linked to differences in strength and stiffness, the SOF derived from XCT data could also represent the heterogeneity in mechanical properties within the sample, offering a non-destructive means to assess material uniformity. The resulting SOF was determined to be in the range of 0.96 – 1.99 mm.

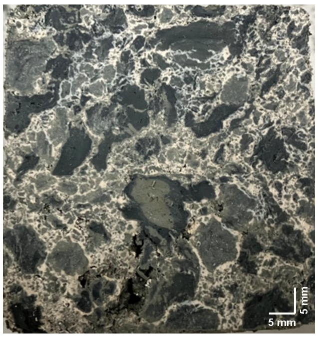

Figure 7. Field-mixed samples with marbled pattern with areas of cemented clay and unmixed clay pockets.

Based on the UCS tests performed on the field samples, the strength q_u ranged between 1.03 MPa to 2.56 MPa and the local stiffness measurements in the mid-section of the samples ranged between 589 – 3122 MPa.

Figure 8 represents the strain field determined. from the DIC and the corresponding calculated stiffness distribution along the length of the sample. Interestingly, the range of stiffness measured was similar to the range of local stiffness measured (grey box in Figure 8) which implies that the intra elemental behaviour of the sample due to occurring heterogeneity control the overall element level behaviour. The SOF for the distribution of stiffness across the length of the sample was determined to be in the range of 5.4-13 mm. The results from all the tests performed on field-mixed samples are seen in

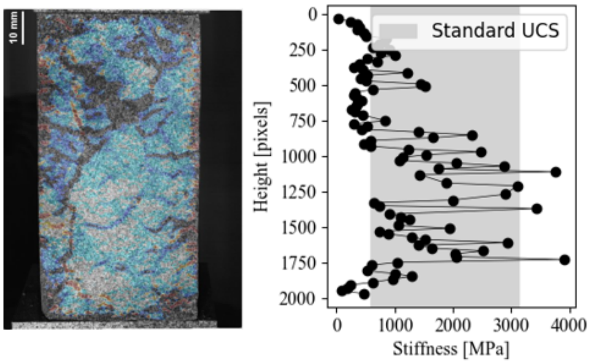

Figure 8. Strain field from DIC (left) and corresponding stiffness distribution (right)

Table 3. Determined properties of field-mixed samples.

Test	*Property*	*Range*
UCS	q_u *(14 days)* [MPa]	*1.03-2.56*
	E_{local}*(14 days)* [MPa]	*589-3122*
DIC	*SOF* [mm]	*5.4-13*
XCT	*SOF* [mm]	*0.96-1.99*

4 CONCLUSIONS

This study aids in quantifying the variability occurring in dry mixed clays across different spatial and temporal scales using samples of lab and field mixed lime-cement mixed clays. Although direct comparison between the two mixing processes was not feasible due to differing curing conditions and preparation methods, the findings highlight key sources of variability and provide a foundation for future scale effect studies exploring the influence of mixing environment, curing duration, and material heterogeneity on long-term performance.

5 ACKNOWLEDGEMENTS

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