Sample size choices for XRCT scanning of highly unsaturated soil mixtures

Jonathan C. Smith and Charles E. Augarde^a

School of Engineering and Computing Sciences, Durham University, South Road, Durham, UK

Abstract. Highly unsaturated soil mixtures (clay, sand and gravel) are used as building materials in many parts of the world, and there is increasing interest in understanding their mechanical and hydraulic behaviour. In the laboratory, x-ray computed tomography (XRCT) is becoming more widely used to investigate the microstructures of soils, however a crucial issue for such investigations is the choice of sample size, especially concerning the scanning of soil mixtures where there will be a range of particle and void sizes. In this paper we present a discussion (centred around a new set of XRCT scans) on sample sizing for scanning of samples comprising soil mixtures, where a balance has to be made between realistic representation of the soil components and the desire for high resolution scanning. We also comment on the appropriateness of differing sample sizes in comparison to sample sizes used for other geotechnical testing. Void size distributions for the samples are presented and from these some hypotheses are made as to the roles of inter- and intra-aggregate voids in the mechanical behaviour of highly unsaturated soils.

1 Introduction

Soil-based construction materials (SBCMs) are receiving increasing interest due to their potential green credentials, in comparison to conventional construction materials bound with cement. *Rammed earth* and *adobe* are two popular forms of SBCM found in both heritage structures and modern buildings [1]. It is only recently however that these materials have been recognised as manufactured, highly unsaturated soils, and a number of groups around the world are now applying unsaturated soil mechanics principles to attempt an improved understanding of the mechanical behaviour of these materials [2].

SBCMs, and rammed earth in particular, are mixtures of soil fractions from clay to gravel and therefore present issues when considering sampling and testing. Investigations of the mechanical behaviour of rammed earth in uniaxial compression show that reducing sample size, and consequently having to remove the largest fractions from the mixture prior to manufacture, considerably alters the measured strength and stiffness properties [3]. X-ray computed tomography (XRCT) scanning is becoming a popular tool for geotechnical investigations, however there is a large variation in the size of samples scanned with a growing trend towards small, non-standard samples with diameters less than 12mm (to obtain higher resolutions).

In this paper we investigate the internal structure of a selected SBCM using three cylindrical sample sizes scanned using XRCT before and after loading. Comments are made on the macrostructures of the samples based on the XRCT results with the aim of

establishing the roles of the different constituents within the mixtures.

2 Internal structure of soil based construction materials

While there has been considerable research into the internal structure of simple unsaturated soils, using MIP for instance, there is very little work completed for soils containing a mixture of particle sizes, from clay to gravel, as found in SBCMs.

Beckett et al. [4] used XRCT to observe the changes to the macrostructure of rammed earth following compressive loading and observed how compaction during manufacture affects the macrostructure within individual layers of rammed earth. Due to limitations on sample size, only the inter-aggregate soil matrix, formed of clay and sand particles, was investigated. The results show that the interconnectivity and size of voids significantly increases following loading and that the effect of cracking is greater within poorly compacted material. This study also shows that single layer specimens have a highly heterogeneous macrostructure whilst double layer specimens are largely homogeneous, and the macrostructure of a compacted layer is not affected by the compaction of additional material above it. This rare example provides a valuable insight into the macrostructure of a SBCM, however the analysis was only performed in 2D, preventing void volumes being determined, and the lack of gravel particles within the mix is likely to have significantly altered the void structure.

^a Corresponding author: Charles.augarde@dur.ac.uk

Hall et al. [5] also used XRCT to characterise the void geometry of cement-stabilized soils for earthen construction. However the addition of cement to the soil mixture will have fundamentally altered the material properties, since the cement will act as a chemical binder between the particles, and it is therefore difficult to apply results to the study of unstabilized SBCMs. This has prompted the experimental study described below.

3 Experimental programme

3.1 Sample size

Three cylindrical sample sizes, 12mm diameter x 24mm high, 38mm diameter x 76mm high and 100mm diameter x 200mm high, were used in this investigation (referred to hereafter as $\phi 12$, $\phi 38$ and $\phi 100$ respectively). The $\phi 12$ sample was chosen as it was the largest sample size for which a high resolution scan with a voxel size of less than $1\mu\text{m}$ could be easily obtained using the XRM410 scanner whilst the $\phi 38$ sample was close to the maximum sample size which could be easily placed and have its entire width scanned in a single XRCT image. The $\phi 100$ sample was used as it was close to the maximum diameter soil sample which could be scanned with the XRM410. From a material testing perspective the $\phi 38$ and $\phi 100$ samples are both standard geotechnical triaxial testing sizes, ensuring samples could be easily manufactured, and unconfined compression tests performed without the need for new testing equipment or techniques.

3.2 Materials

A single SBCM mix, 30*:60:10, was used throughout the investigation and chosen as it lay in the centre of the limits suggested in [6] and the SBCM mixes used in Smith's wider study [3]. The 30*:60:10 SBCM mix was manufactured by combining appropriate amounts of speswhite clay, sharp sand and pea gravel. Both the sharp sand and the pea gravel were oven dried at 105°C and then passed through 2mm and 10mm sieves respectively. The BS1377 Vibrating Hammer Test [7] was used to determine the optimum water content and target dry density for the SBCM mixture [8]. An OWC of 8.93% and dry density of 2060 kg/m^3 were obtained.

Five samples were manufactured for each of the $\phi 12$, $\phi 38$ and $\phi 100$ sample sizes. Prior to sample manufacture the soil mixture was sieved to 2mm for the $\phi 12$ samples and to 5mm for the $\phi 38$ samples, to prevent the larger particles interfering with the compaction and loading behaviour. The soil for the $\phi 100$ samples was not sieved in order to closely match an on-site soil mix, and had a maximum particle size of 10mm. The appropriate amount of water was added to each mixture to reach OWC and the mixture was left to equilibrate overnight. Since SBCMs are often compacted in layers within formwork, all three samples were also constructed from layers of compacted material.

The correct mass of wet soil mixture for an individual layer was added to the sample mould to ensure each sample layer would be at the target optimum dry density and was then statically compacted to achieve the required layer depth. Once the appropriate number of layers had been compacted the sample was pushed from the mould by hand, ensuring no disturbance was caused on the sides of the sample, and left to dry in a temperature monitored room at $22^\circ\text{C} \pm 2^\circ\text{C}$ until a stable mass was obtained (at between 0.8% and 1.2% water content), at which point no further water was lost to the atmospheric conditions. Three filter paper test samples, each using two cylinders (50mm diameter and 20mm high), were also prepared alongside each of three sample sizes and compacted to the same target density. These were left to dry under the same conditions as the $\phi 12$, $\phi 38$ and $\phi 100$ samples before being placed in a sealed jar to equilibrate for ten days. The filter paper test results provided total suction values for the three different mixtures.

Three samples from each batch of five manufactured samples, those closest to the batch mean dry mass, were selected for scanning and mechanical testing. Following testing it was found that all samples were within 1.8% of the target dry density. To differentiate between different samples within the triplet, each sample was assigned a suffix A, B or C. Once the samples reached their stable dry mass, top and bottom plastic caps were placed on the samples and the sample was sealed within a latex sheath using rubber O-rings. The caps and sheath prevented any further change in water content during scanning, compression testing and re-scanning, and provided a flat surface to which the compressive load could be applied and also enabled easy secure mounting of the samples inside the XRM410.

3.3 Experimentation

All samples were scanned using the XRM410 before and after unconfined compression, constant water content tests. Displacement rates of 0.03mm/min, 0.1mm/min and 0.25mm/min for the $\phi 12$, $\phi 38$ and $\phi 100$ samples respectively were chosen in accordance with [9] ensuring the strain rate did not exceed 2% per minute and failure occurred within 15 minutes. Each sample was tested to failure, observed by evidence of a load peak, after which compression was stopped and the load released.

Both the pre-loading and post-loading scans involved three specific scans: a large field of view scan, to capture as much of the sample as possible; and two small field of view scans at the maximum resolution achievable for the sample size, located either side of a compaction plane to capture any differences in material structure at the top and bottom of the layers.

The $\phi 12$ sample's large field of view scan captured the entire sample and the $\phi 38$ sample's large field of view scan captured the entire sample diameter but was limited by the square x-ray detector within the XRM410 to only half the sample height, centred on the middle of the sample. The large size of the $\phi 100$ sample prevented the entire diameter of the sample being seen and the scan settings were chosen to enable the scanning of as much of

the sample as possible, approximately 80mm centred on the interface between the bottom and middle compaction layers. The key XRCT scan parameters are given in detail in [3] as are the detailed methods used to post-process the data.

4 Results and discussion

4.1 Mechanical behaviour

Table 1 shows the compressive strengths obtained from the unconfined compression tests for all nine samples (three of each diameter). The $\phi 12C$ sample was found to be a clear outlier as when included the $\phi 12$ samples' failure stresses had a standard deviation of 0.29MPa, which was reduced to 0.05MPa when the $\phi 12C$ sample was disregarded.

The aspect ratio of all three cylindrical sample sizes was 2:1 ensuring that geometrical differences in shape did not affect the results obtained. However one significant difference in the manufacture of the $\phi 100$ samples was the use of three compaction layers rather than the two layers used to manufacture the $\phi 12$ and $\phi 38$ samples. This additional compaction layer was included to reduce the depth of each layer and thus the heterogeneity of the individual layers, however the three compaction layers will have introduced an additional layer interface and plane of weakness into the sample that may have resulted in the lower compressive strengths obtained.

The total suction values obtained from the filter paper tests for the $\phi 12$, $\phi 38$ and $\phi 100$ samples were 8.51 ± 0.37 MPa, 8.76 ± 0.07 MPa and 8.04 ± 0.25 MPa respectively. These are of the same magnitude as those measured in [2] for similar SBCMs and the difference can be attributed to the different clay material and mix composition used in this investigation.

The only remaining difference between the three

Table 1 : Strengths of samples scanned

Sample	UCS (MPa)		
	A	B	C
$\phi 12$	2.25	2.15	2.80
$\phi 38$	1.84	1.68	1.82
$\phi 100$	0.45	0.58	0.49

samples is the sieving of the largest particles from some of the mixes. The compressive strength of the samples increases following the removal of the gravel fraction. The effect of the removal of gravel fraction on the internal structure of the SBCMs and how this may alter the compressive strength of the samples is therefore examined in detail below.

At the low water contents found in SBCMs, water will only be present in the smallest voids between the clay and sand particles, and as adsorbed layers. The clay and sand fractions in all three sample sizes are unaltered, in terms of relative proportion (1 part clay to 2 parts sand) and mineralogy, which may explain the similarity in total suction values for all three sample sizes. As the

water is only present in the smallest voids within the sample when the SBCM has dried it will be those voids which most control the capillary and adsorptive suction terms and therefore the suction values measured will be largely unchanged by the removal of the gravel fraction. The decrease in compressive strength with the addition of gravel particles, despite similar measured total suction values, may therefore suggest that the gravel reduces the strength of the SBCM by introducing initial points of weakness, i.e. cracks and large voids, into the compacted clay-sand mixture.

Void size distributions were successfully obtained for all large field of view (LFoV) XRCT scans performed, and the small field of view scans for the $\phi 12$ and $\phi 38$ samples. It was not possible to obtain void size distribution plots from the small field of view scans for the $\phi 100$ samples as the automated analysis employed was unable to identify individual voids within the sample. This was despite the source operating at the highest power settings, the maximum exposure time being used to obtain images and the pixel size being doubled in order to ensure sufficient x-rays were detected for an image to be captured. It suggests that the $\phi 100$ samples were too large for the small field of view scans to be performed. The void size distributions for the $\phi 12A$ sample are shown in Figure 1 and for the $\phi 38A$ sample in Figures 2. The $\phi 100$ large field of view void size distributions for all three samples are shown in Figure 3. All the figures show the void size distribution before and after compressive loading and, where necessary, the small field of view results for the bottom of compaction layer and top of compaction layer are differentiated using 'BoL' and 'ToL' respectively.

The void size distribution plots used here differ considerably in form to those commonly presented when void sizes are explored using MIP. A typical void size distribution from MIP data plots the volume of intruded mercury against the void entrance diameter and it is then it is assumed that a smaller void entrance diameter represents a smaller void volume. In contrast, the VSDs presented here plot on the y-axis the cumulative void volume of all voids smaller than and equal to a given void volume, shown on the x-axis, as a percentage of the total sample volume. These plots can therefore be interpreted in a similar way to particle size distribution plots which plot on the y-axis the cumulative mass of all particles which are smaller than a given particle diameter, shown on the x-axis, as a percentage of the total sample mass. The plotting and discussion of void volumes, rather than void entrance diameters, is possible since the post-processing of the XRCT scan data identifies the volume of each void within the sample directly. For MIP data either one or two peaks (for a monomodal void structure and a bimodal pore structure respectively) will be evident which coincide with the most abundant void entrance diameters within the sample and it is assumed that these peaks indicate that a particular void volume within the sample abounds. In the case of the XRCT-obtained VSDs the **gradient** of the curve at a particular void volume can be used as an indication of the number of voids of that volume within the sample, i.e. a steep region within the

curve shows there are a high number of voids of that volume and can be interpreted in a similar way as a peak in MIP data. A flat region within an XRCT-obtained void size distribution curve suggests there are no voids of the given volume within the sample.

4.2 Observations from the small field of view scan results

For all five samples in which small field of view scans were obtained it is clear that before unconfined compression, the regions scanned at the bottom of the compaction layer contained a smaller void fraction than the top of the compaction layer region. This builds upon the work described in [4] which shows that the material structure can vary through the depth of a layer, although the results presented in [4] suggest that only single-layer specimens display a highly heterogeneous material structure and double-layer compacted specimens achieve

Figure 1: VSD for $\phi 12A$ sample

a largely homogenous material. The results from the investigation described here however clearly show that double-layer samples can also exhibit material heterogeneity and, since the $\phi 12$ and $\phi 38$ samples used in this investigation followed the same preparation technique as used by [4], differences in manufacturing procedure cannot account for the material heterogeneity of the samples investigated here.

It is however possible that differences in XRCT scanning and post-processing could have resulted in the difference in void structure between the top and bottom of compacted layers being observed in this investigation which were not captured in the work presented in [4]. The XRCT scans described by [4] were performed at a pixel size of $11\mu\text{m}$ and a minimum pore area of 3×3 pixels which limited the minimum void area identified within the scans to $33\mu\text{m}^2$. Only one in every ten slices was analysed in the vertical plane limiting the overall volumetric resolution to approximately $330\mu\text{m}^3$. In the XRCT scans performed here however the highest resolution of the small field of view scans is $20\mu\text{m}^3$ and it is therefore suggested that the differences in the image-analysis technique employed, and the improved final resolution, had a considerable part to play in the

Figure 2: VSD for $\phi 38A$ sample

observation of heterogeneity in the material structure of the samples used in this investigation.

The $\phi 12$ and $\phi 38$ sample small field of view scans, performed at the smallest voxel sizes possible for the sample size, provide an insight into the smallest observable voids within the SBCM samples using XRCT scanning. The steep gradient of the curve below $10^6\mu\text{m}^3$ in the void size distribution curves of the $\phi 12$ samples, and the flat line visible for voids above this void volume, indicates that the voids within the $\phi 12$ samples are predominately less than $10^6\mu\text{m}^3$ in volume. The void size distribution curves for the $\phi 38$ sample however show two clear regions where voids exist (the steep parts of the curve below $10^6\mu\text{m}^3$ and between $10^7\mu\text{m}^3$ and $10^9\mu\text{m}^3$), separated by a plateau between $10^6\mu\text{m}^3$ and $10^7\mu\text{m}^3$ and followed by a flat line visible for voids above $10^9\mu\text{m}^3$. This suggests therefore that the $\phi 38$ samples contain voids smaller than $10^6\mu\text{m}^3$ and a second group of voids ranging in volume between $10^7\mu\text{m}^3$ and $10^9\mu\text{m}^3$.

Because all the scans were analysed using the same image processing techniques the lack of voids in the small field of view $\phi 12$ scans is not due to image processing, since voids with volumes larger than $10^6\mu\text{m}^3$ can be seen in other void size distributions, and can be taken as a true representation of the material structure. The lower limit of the set of voids smaller than $10^6\mu\text{m}^3$ however cannot be determined, despite the apparent flattening of the void size distribution curves at

Figure 3: VSD for $\phi 100$ samples

$2 \times 10^2 \mu\text{m}^3$, as the resolution of the small field of view scans is limited to $20 \mu\text{m}^3$. The visible plateau between $10^6 \mu\text{m}^3$ and $10^7 \mu\text{m}^3$, for all twelve small field of view $\phi 38$ scans, are not all perfectly flat or between identical void volumes which suggests the observed plateau is not a result of the image processing but from the SBCM structure and minimal voids between these volumes exist within the $\phi 38$ scans.

The $\phi 12$ samples can be considered as the soil matrix material found in SBCMs, as they contained only clay and sand fractions, and the small field of view scans were centred on regions within a layer. The voids smaller than $10^6 \mu\text{m}^3$, identified in both the $\phi 12$ and $\phi 38$ samples, are therefore likely to be the intra-aggregate voids found within the assemblages of clay and sand forming the binder matrix within the broader SBCM structure.

The addition of the 2-5mm gravel particles has clearly introduced a second range of void sizes, between $10^7 \mu\text{m}^3$ and $10^9 \mu\text{m}^3$, in the internal structure of the $\phi 38$ samples. It is suggested that these voids are inter-aggregate voids which have formed between the larger aggregates now present within the mixture. Double structure models have been well-documented in unsaturated soils however predominantly focus on clay-sand mixtures in which intra-aggregate voids have been identified between clay particles, and are therefore far smaller than the resolution of the XRCT scans performed in this investigation. As such the two sets of void volumes identified in this chapter in the $\phi 38$ samples, below $10^6 \mu\text{m}^3$ and between $10^7 \mu\text{m}^3$ and $10^9 \mu\text{m}^3$, are all still part of the SBCM macrostructure and a series of intra-elemental voids will also exist, undetectable using current XRCT techniques, between small groups of clay particles, i.e. the SBCM microstructure.

The lack of small field of view scans for the $\phi 100$ samples means it is not possible to observe this double void size macrostructure, or the changes that occur within it, however it is suggested that a similar void size distribution to the $\phi 38$ samples would be observed, whereby small voids, less than $10^6 \mu\text{m}^3$, exist within the intra-aggregate matrix and the inter-aggregate voids are then observed between $10^7 \mu\text{m}^3$ and $10^9 \mu\text{m}^3$ forming around the gravel particles.

4.3 Observations from the large field of view scan results

The large field of view scans, performed at a considerably larger voxel size, are unable to capture any voids smaller than $8 \times 10^4 \mu\text{m}^3$ within the sample and do not capture many voids smaller than $10^5 \mu\text{m}^3$. This can both explain why the majority of the small field of view scans show more voids within the sample and why the double void macrostructure is not observed in the $\phi 38$ and $\phi 100$ large field of view scans. This however does not prevent the large field of view results providing valuable insights.

The increasing void size distribution curve above $10^6 \mu\text{m}^3$, for the $\phi 12$ samples' large field of view scans, indicates that between 2% and 3% of the total sample

volume are voids with volumes greater than $10^6 \mu\text{m}^3$. This is in contrast to the small field of view scans which show no voids larger than $10^6 \mu\text{m}^3$ in volume. The $\phi 12$ samples were manufactured using two layers of SBCM causing the transition between the two compaction layers to occur at 50% sample depth. It is therefore suggested that larger voids identified within the large field of view scans are located within the sample at the interface between the two layers but not within the clay-sand matrix formed inside an individual layer which is scanned in the small field of view scans. Interestingly there is a much smaller increase in the large voids detected within the $\phi 12$ large field of view scans than in the smaller voids within the clay/sand binder matrix and this suggests that, at least for the $\phi 12$ samples in which only binder material is present, failure occurs within the binder and not at a layer interface.

The $\phi 38$ and $\phi 100$ large field of view scans show the largest change in void volume following compressive loading in the largest voids and this suggests that the change in internal structure during loading predominately occurs in the large voids and pre-existing flaws within the SBCM. The $\phi 100$ samples show a smaller increase in voids following the unconfined compression tests than the $\phi 38$ samples. It is however possible that the lack of evolution in the $\phi 100$ samples' macrostructure is due to the scanning of only one region within the $\phi 100$ samples. A limitation of only scanning one region around the bottom compaction layer interface means that significant macrostructure changes could have occurred around the upper compaction layer interface which would not have been captured during the XRCT scans and, if no major structural changes occurred at the bottom compaction layer interface, only a minimal increase in voids would be observed. In the $\phi 38$ samples however, since only one compaction layer interface was present within the sample which was at the centre of the region scanned using XRCT, any macrostructural changes which occurred during compression testing of the $\phi 38$ samples should have been captured.

In addition, both the $\phi 38$ and $\phi 100$ samples show a variation in the increase in void volume across the set of three samples. The reasons for this are not clear however some variation may have been introduced during the transferring of the samples from the unconfined compression testing apparatus to the XRCT scanner which could have affected the sample structure. The inability to scan the samples during the unconfined compression testing is therefore clearly a shortcoming of this study and being able to apply load to the samples within the XRCT scanner may have helped reduce the variability in the post-failure loading conditions.

It is therefore difficult to draw firm comparisons between the changes in the largest voids within the $\phi 38$ and $\phi 100$ samples, as variability may have been introduced during the transfer of samples to the scanner and not all the macrostructural changes will have been captured within the $\phi 100$ samples. However all six samples, the three $\phi 38$ samples and three $\phi 100$ samples, do show the same trend that the change in void volume increases with void size and this therefore suggests that

these large voids are most altered during compressive loading of SBCMs.

4.4 Links between material structure and compressive strength

The void size distribution results obtained show that a double void size macrostructure exists within the SBCM samples because of the inter-aggregate voids linked to the presence of large gravel particles and intra-aggregate voids which exist within the clay-sand binder matrix. Current unsaturated soils theory also suggests that a range of smaller voids exists between clay particles, which are too small to be detected XRCT techniques, and these inter-elemental voids form a third range of voids within the internal structure of SBCMs.

Based on these findings Figure 4 illustrates a proposed internal structure of SBCM samples, using both the results from the small field of view $\phi 38$ samples to describe the intra-aggregate and inter-aggregate voids and the assumed existence of inter-elemental voids between the clay particles which remained undetected in this investigation. This double void size macrostructure coupled with the third range of smaller inter-elemental voids is key to explaining the compressive strength results obtained and can also help form a basic understanding of the fundamental roles of each constituent material within the SBCM mix.

The similar total suction values obtained for all three sample sizes and the similarity in the void size distributions in the voids smaller than $10^6 \mu\text{m}^3$ for the $\phi 12$ and $\phi 38$ samples suggest that it is within the clay-sand matrix that suction is developed within the SBCM. Since suction is a key source of strength it is clear that changing the clay type used affects the suction developed and hence affects the compressive strength. Studying the intra-aggregate voids below $10^6 \mu\text{m}^3$ in different clays will undoubtedly provide an interesting insight into the role of clay within SBCMs. However the results from this investigation also show that, despite similar total suctions being developed within the samples and similar void sizes existing below $10^6 \mu\text{m}^3$, the clay is not the only factor influencing compressive strength.

The reduction in compressive strength as larger particles are introduced to the SBCM mixture and the largest change in void sizes being observed in the inter-aggregate voids $> 10^7 \mu\text{m}^3$ suggest that the gravel fraction within the SBCM has a large influence on the compressive strength. The $\phi 12$ samples show that failure of the clay-sand binder matrix occurs within voids smaller than $10^6 \mu\text{m}^3$ at approximately 1.55MPa and it is possible to assume that the clay-sand matrix within the larger samples would also fail in a similar way at a similar compressive strength. The introduction of the gravel particles to the SBCM, and the resultant presence of inter-aggregate voids within the structure, however results in a reduced strength and it is suggested that this is because the larger voids introduce points of weakness from which cracks can propagate.

The triple-structure of voids suggested here has not been identified before in SBCMs. Unfortunately the trend

Figure 4: Speculative structure of SBCMs

towards XRCT investigations focussing on idealised, narrowly graded materials and the relative infancy of investigating the internal structure of SBCMs means there exists no dataset to which these results can be compared. It is hoped therefore that these findings will provoke an interesting discussion.

5 Conclusions

This paper concerns testing of manufactured unsaturated soils, both for strength and more significantly for internal structure. Some speculations on the internal structure of these complex soil mixtures are presented. The authors acknowledge the assistance provided by the Durham XRCT Facility, which was funded in part by the UK EPSRC (EP/K036084/1 & EP/K024698/1).

References

1. P.A. Jaquin, C.E. Augarde, *Earth Building: History, science & conservation* (IHS BRE Press: Bracknell, 2012)
2. P.A. Jaquin, C.E. Augarde, D.G. Toll, D. Gallipoli *Geotechnique*, **59**(5):487–490 (2009)
3. J.C. Smith, *Examining Soil Based Construction Materials through X-Ray Computed Tomography*, PhD Thesis, Durham University, 2015
4. C.T.S. Beckett, M.R. Hall, C.E. Augarde, *Acta Geotechnica*, **8**(4):423–438 (2013)
5. M. Hall, S. Mooney, P. Sturrock, P. Matelloni, S. Rigby, *Acta Geotechnica*, **8**(1):67–79 (2013)
6. H. Houben, H. Guillaud, *Earth construction: a comprehensive guide* (ITDG Publishing, London, 1989)
7. British-Standards, EN ISO 14688, 2002.
8. J.C. Smith, C.E. Augarde, ECS Tech. Rpt, Engineering and Computing Sciences, Durham University, ECS-TR 2013/04, 2013.
9. British-Standards, BS1377-4:1990