Using X-ray microtomography to identify physical changes in green roof substrates as a result of ageing

Simon De-Ville, Manoj Menon, Virginia Stovin
Department of Civil & Structural Engineering, University of Sheffield
sde-ville1@sheffield.ac.uk, m.menon@sheffield.ac.uk, v.stovin@sheffield.ac.uk

Primary Supervisor: Dr. **V. Stovin** – e-mail: v.stovin@sheffield.ac.uk
Secondary Supervisor: Dr. **M. Menon** – e-mail: m.menon@sheffield.ac.uk

ABSTRACT. Green roofs are complex engineered structures that can provide significant benefits to biodiversity, the thermal performance of buildings and stormwater management, amongst others. As such, there are guidelines that dictate the composition and properties of green roof substrates to ensure that these benefits can be realised. However, a green roof's position exposes it to several natural processes that may alter the properties of the substrate beyond their allowed limits. There is currently little understanding of the presence and magnitude of changes to substrate properties as a result of influencing processes over time. This paper uses techniques not used before in a green roof context to non-invasively explore the internal structure of two green roof substrates in both aged and virgin forms. Using X-ray microtomography and image processing techniques, particle size distributions and porosity values are determined for selected 2D planes. It is found that the X-ray microtomography technique is a good method to non-destructively assess the properties of green roof substrates. The particle size distribution and porosity of the two substrates was found to be different between the aged and virgin samples. However, the uncertainties surrounding substrate heterogeneity mean these quantitative changes in properties should be considered to be indicative rather than absolute.

KEYWORDS. Green Roof; Substrate; X-Ray Microtomography; Temporal Changes; Porosity.

INTRODUCTION

There are two main active elements of a green roof, the vegetation and the substrate. Both of these elements are subject to a number of processes that have the potential to alter their characterised physical properties over time. On the surface the most visible of these processes is plant growth, and this is relatively straightforward to quantify. However, the subsequent root growth beneath the surface is more difficult to evaluate, as it is not readily visible in its intact form. The substrate may also be subject to organic matter turnover, consolidation and chemical alteration from polluted rainwaters, all of which have the potential to alter the substrates properties. Yet, similarly, observations of such changes are difficult to undertake without destructive sampling.

There is currently a lack of research within the field of green roof ageing [1]. However, existing research has found that the levels of organic matter within a green roof can change with time, and both increases [2] and decreases [3] have been identified. Getter and Rowe [2], who briefly discuss changes in the properties of a mature substrate, found an increase in pore space values from 41 to 82% alongside a 294% increase in water holding capacity. All of these studies used destructive testing means to determine the substrate properties and so the green roofs were decommissioned in these cases.

Therefore, there is clearly a need to further explore green roof ageing in a way that allows for continued green roof operation to maximise green roof lifespan. X-Ray microtomography (XMT) is an X-Ray imaging technique that allows for the non-destructive characterisation of material properties. Images with high resolutions can be obtained and analysed to show the spatial arrangement of solid particles and pore spaces in a soil-like matrix [4]. XMT is an established technique within the soil science field, where the main application has been for the characterisation of soil physical properties [5]. Other studies have used XMT to examine: plant roots and their interactions with the soils; earthworm burrows; soil insects; and other soil microorganisms. However, there has been no use of XMT to image green roof substrates and assess any property changes as a result of ageing.

Hence, this study has the following objectives:

- to determine the usefulness of non-invasive X-ray microtomography (XMT) in evaluating changes to properties of green roof substrates as a result of ageing;
- to qualitatively describe any observed changes in substrate properties and the impacts upon the substrate's ability to meet its design criteria.

METHODOLOGY

Sample Collection and Preparation

Four substrate cores were prepared for non-invasive analysis. The core holders were 68 mm in height with an internal diameter of 46 mm, these sizes were restricted by the loading gauge of the XMT machine. The core holders were constructed from *Poly(methyl methacrylate)* (PMMA, commercially known as *Perspex*). A non-metallic material is required for the XMT imaging process in order to prevent poor image quality.

Two distinct types of substrate were used to compare the potential changes in properties. One of the substrates is Brick based and was used extensively as part of the 'Marie Curie Green Roof Project' and is referred to as Marie Curie Substrate (MCS). In addition to the crushed brick component, MCS also contains bark and coir (combined 15% by weight). The second substrate mix is based on Light Expanded Clay Aggregate (LECA) (80% by weight) and also includes compost (20% by weight). Both substrates have been characterised previously, LECA by Poë *et al.* [6] and the mineral component of MCS by Yio *et al.* [7].

From each type of substrate, an aged and a virgin core was created. The virgin cores (MCS_V and $LECA_V$) were formed from material that was part of the same batch as that used in two active green roof test beds, the same beds from which the aged cores were taken. The aged MCS core (MCS_A) was taken from the Mappin Test Bed (a full description of the roof configuration can be found in Kasmin *et al.* [8]). The aged LECA core ($LECA_A$) was taken from one of the Hadfield Green Roof Test Beds (a full description of the roof configuration can be found in Beretta *et al.* [9]). Both of the aged substrate cores were also vegetated with mixed *Sedum spp.* vegetation.

X-Ray Microtomography Image Capture and Analysis

For this study the cores were imaged using a *General Electric v|tome|x M* CT scanner at the University of Nottingham's Hounsfield Facility. Each core was scanned at a resolution of 30 μm.

Image analysis was undertaken using the open-source image editor ImageJ [10]. The scan data from each core was divided into three sections each of 740 slices: lower; middle and upper (This was due to computer RAM limitations). A single slice from the centre of each section was taken forward for further analysis, Fig. 1 illustrates the location in the vertical plane where the slices were taken.

Porosity and particle size distribution were both identified using the particle analyser tool in ImageJ. The particle analyser tool identifies individual particles within an image by first locating particle edges, then outlining the remaining particle using the wand tool of ImageJ, the selection is then filled and the area and Feret diameter of this shape is determined. The Feret diameter is the distance between two parallel tangents on opposite sides of the identified particle, and provides an indication of 3D particle diameters when projected onto a 2D plane. These particle diameters were used to construct particle size distributions. Porosity values were determined from the particle areas. The area of the circular core less the particle area indicates a total void area. Filling of intra-pores, the pore spaces within aggregate pieces, using binary image processing, allows for a closed pore area to be determined.

RESULTS AND DISCUSSION

Visual Observations

Fig. 2 shows the physical differences between the compositions of the two substrate mixes, with LECA having a much less dense particle matrix compared to MCS. Closer examination of Fig. 1 and 2 show the aged cores have considerably greater variation in their particle distributions with depth, compared to the virgin pair. The upper regions of both the MCS_A and $LECA_A$ have an increased number of smaller particles. The softer levels of grey within the image (Fig. 2) correspond with areas of organic matter, and show root masses along with entrained organic content. The central region of $LECA_A$ includes some identifiable roots and other organic matter. The central region of MCS_A shows no sign of root activity, which when looking at Fig. 1 is not unexpected due to its denser particle matrix. This increased packing may have prevented the breakthrough of roots to lower levels within the substrate. In the lower region of both substrates there is little evidence of a build up of fines; something that may have been expected. This could potentially be because the analysed horizontal slice is not at the very bottom of the core. Alternatively, the core depth of 68 mm is shallower than the original substrate depth of 80 mm and so the very bottom layer has not been captured as part of the scan.

Characterised Observations

The particle size distributions (PSD) in Fig. 3 show that for MCS_V the PSD is relatively uniform throughout the entire depth. This is to be expected in a newly constructed core. MCS_A has an increased variation between the upper and middle/lower layers compared to the virgin MCS_V. The shift in the upper section PSD indicates that there are more small particles than in either of the other two sections. This is possibly a result of root growth and weathering processes that have caused the larger aggregate pieces to degrade into smaller ones, alongside atmospheric particle deposition and organic matter turnover.

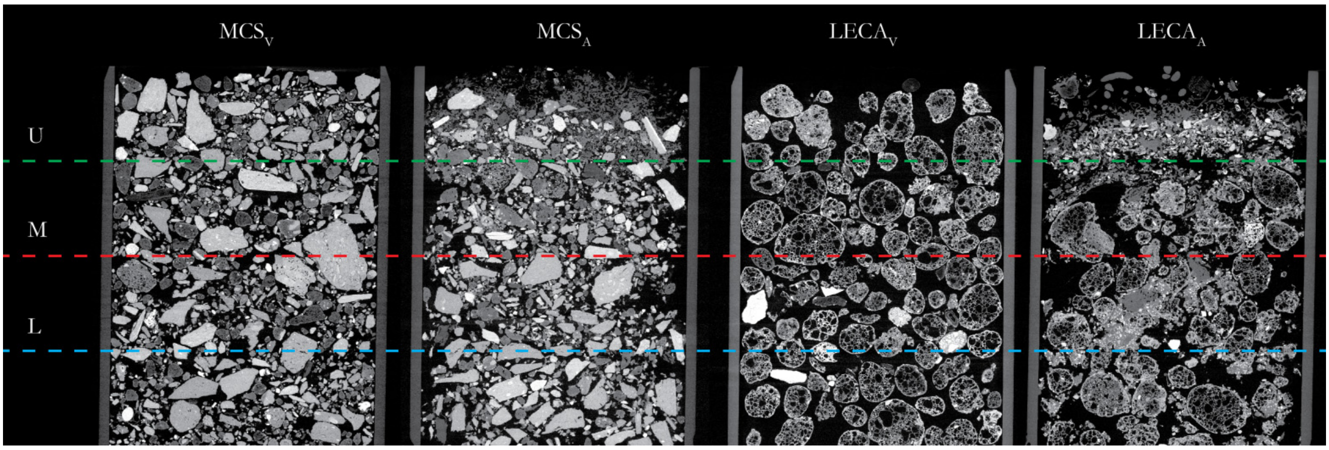

Figure 1: Reconstructed XMT slices in the vertical plane of the four substrate cores. The green line represents the centre of the upper third of the sample (U), the red line represents the centre of the middle third of the sample (M) and the blue line represents the centre of the lower third of the sample (L). Horizontal plane slices at these points can be seen in Fig. 2.

The virgin $LECA_V$ exhibits a large difference in the PSD of its upper and middle layers compared to the lower layer. The increased number of smaller particles in the lower layer would suggest that the core has undergone a degree of granular convection, with the smaller particles making their way to the bottom of the core. $LECA_A$ has a PSD that is more similar to MCS_A, than to $LECA_V$. The upper layer sees a large shift in the PSD from the virgin to aged cores, with $LECA_A$ having considerably more small particles in the upper layer than in either the middle or lower layer. As seen for MCS_A, this could again be a result of aggregate degradation due to root growth and/or weathering.

Both the virgin MCS_V and $LECA_V$ have a more uniform distribution of open, closed and total porosity with depth when compared to their aged counterparts (Fig. 4). The slight differences in porosity between the layers of MCS_V and $LECA_V$ are to be expected, and are more than likely a facet of the heterogeneous nature of the substrate mixes. MCS_A displays considerable variation in porosity across the three layers. In the upper layer overall total porosity is only slightly reduced compared to MCS_V. However, there is a large increase in closed porosity and a subsequent decrease in open porosity. This is likely a result of the shift in the particle size distribution, associated with smaller particles are smaller pores, which can more easily become separated from the wider pore matrix. Alternatively the presence of roots and stems could be misidentified closed pores (as these display as pore-like holes in XMT images), which may be influencing the overall porosity values.

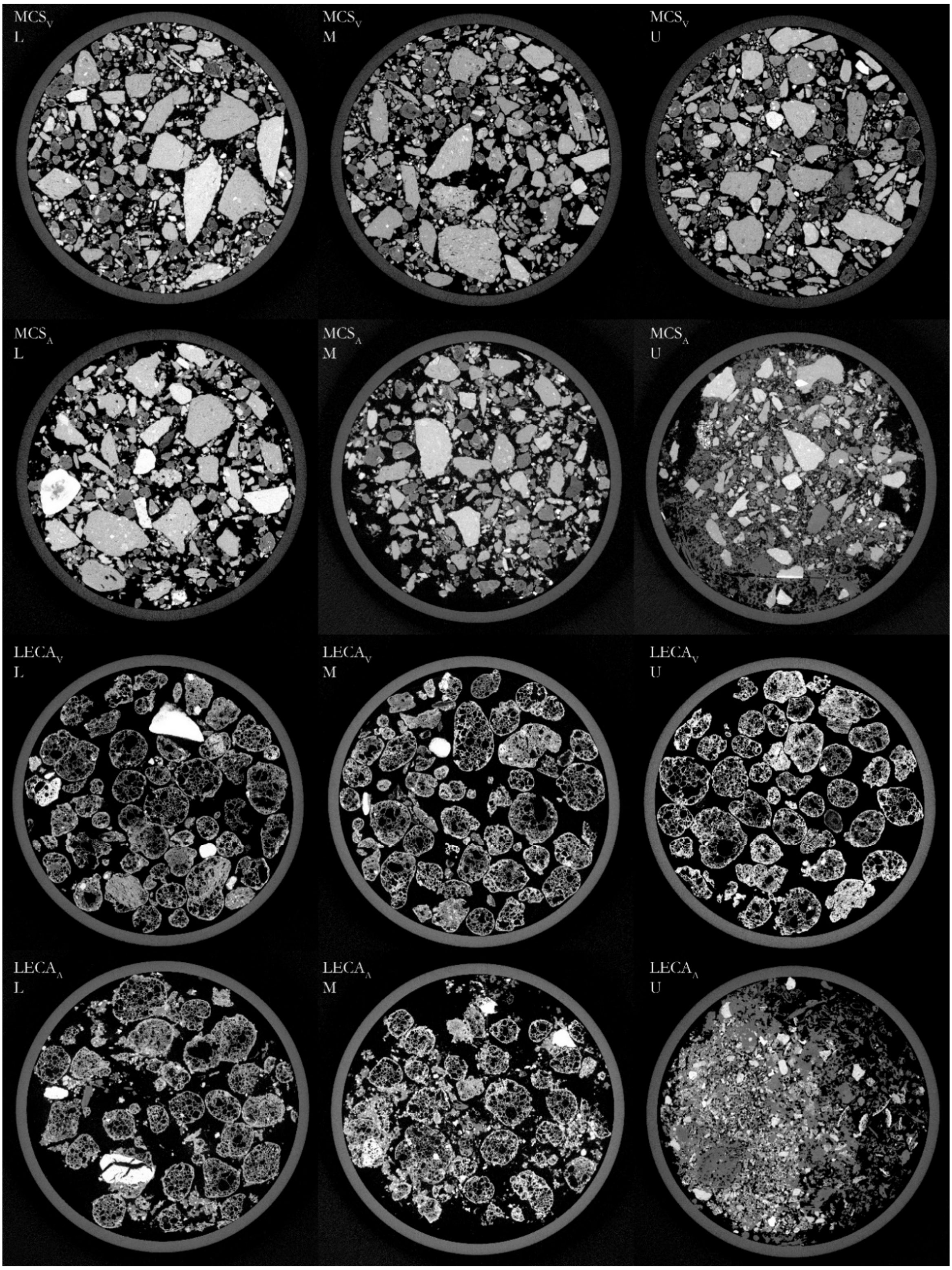

Figure 2: Reconstructed XMT slices (horizontal plane) from the lower, middle and upper layers (as illustrated in Fig. 1) of the four substrate cores.

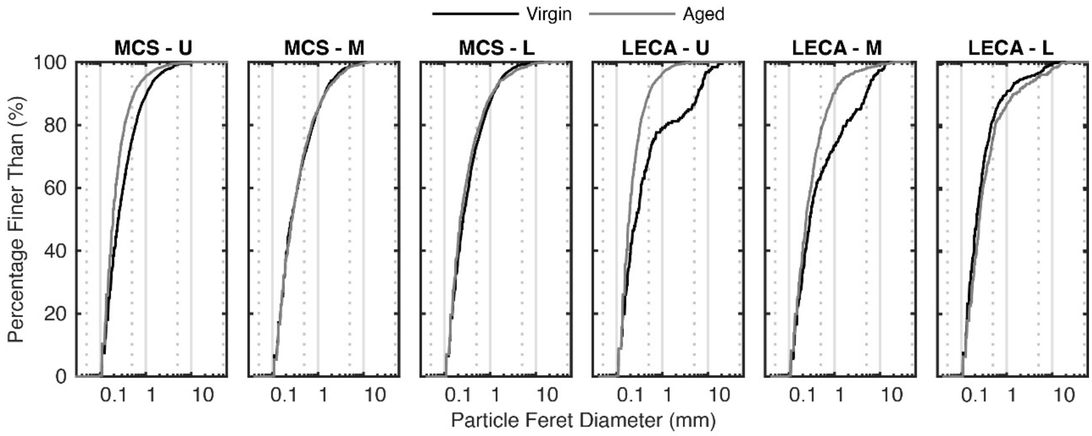

Figure 3: Particle size distributions as computed from the XMT slices of Fig. 2.

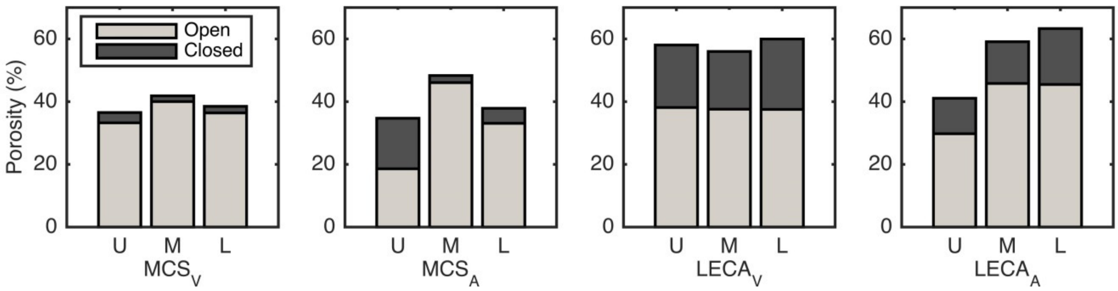

Figure 4: Calculated open and closed porosity of the four substrate cores.

$LECA_A$ has a reduced total porosity compared to that of $LECA_V$ for the upper layer. This is largely due to material from the Sedum planting, something that is not present in the $LECA_V$. The lower two layers of $LECA_A$ retain a similar total porosity to that of $LECA_V$. However, there is a reduction in the ratio of closed to open pore space. This indicates that the previously closed internal pore networks of the LECA particles have broken open, potentially as a result of root action, and have now become connected to the wider open pore network.

Implications of Altered Properties

The change in properties, i.e. the shift in PSD and altered porosity, for the aged substrate cores compared with the virgin cores, could have detrimental impacts on their abilities to meet their initial design criteria. A reduced porosity will reduce the air and water holding capacities of the substrate. Plants need an adequate air supply to their roots in order to survive, if the porosity continues to fall oxygen levels in the soil could become so low as to prevent sustained vegetative cover. Not only would a die-off of vegetation lead to a reduction in the bio-diversity benefits of a green roof, it would also impact on hydrological, acoustic and thermal performance. The shift in PSD to more small particles may result in clogging of green roof filter sheets if these fines leach through to the lower layers, preventing free-draining conditions causing water volumes to build up within the roof system. Additionally, the smaller lighter particles will be more susceptible to wind erosion and scouring.

CONCLUSIONS

The non-invasive nature of XMT makes it an ideal tool for the examination of green roof substrate properties in a non-destructive fashion. This permits the preservation of the core and allows for further tests (e.g. permeability tests, hydraulic conductivity tests) to be conducted on an intact sample, something that could not be undertaken using existing destructive methods.

This study provides evidence that the properties of green roof substrates do change as a result of ageing. It can be seen that ageing processes lead to a reduced porosity and smaller particle sizes in the upper layers of the green roof substrate. However, because the aged and virgin cores are different samples of a heterogeneous substrate, the properties of the virgin core analysed here cannot be assumed to correspond exactly with the original properties of the aged sample. Hence, the quantitative changes identified here should be considered indicative rather than absolute.

Further Research

To eliminate the uncertainty seen between aged and virgin samples of the substrate, new green roof microcosms will be developed. These microcosms will be imaged using XMT at regular intervals to determine the changes in physical substrate properties over time. In conjunction a full 3D image analysis will be undertaken. This will provide a more complete picture of key properties throughout the entire microcosm, compared to a 2D slice analysis.

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REFERENCES

[1] Li, Y., Babcock Jr, R., Green roof hydrologic performance and modeling: a review, Wat. Sci. Tech., (2013) 1–12.
[2] Getter, K.L., Rowe, D.B., Andresen, J. a., Quantifying the effect of slope on extensive green roof stormwater retention, Ecol. Eng., 31 (2007) 225–231.
[3] Emilsson, T., Rolf, K., Comparison of establishment methods for extensive green roofs in southern Sweden, Urban Forestry & Urban Greening, 3 (2005) 103–111
[4] Menon, M., Yuan, Q., Jia, X., Dougill, J., Hoon, S.R., Thomas, D., Williams, R., Assessment of physical and hydro-logical properties of biological soil crusts using X-ray microtomography and modeling, J Hydrol, 397 (2011) 47–54.
[5] Taina, I.A., Heck, R.J., Elliot, T.R., Application of X-ray computed tomography to soil science: A literature review, Canadian Journal of Soil Science, 88 (2008) 1–19.
[6] Poë, S., Stovin, V., Beretta, C., Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration, J Hydrol., 523 (2015) 356–367.
[7] Yio, M.H.N., Stovin, V., Werdin, J., Vesuviano, G., Experimental analysis of green roof substrate detention characteristics, Wat. Sci. Tech., 68 (2013) 1477–86.
[8] Kasmin, H., Stovin, V., Hathway, E.A., Towards a generic rainfall- runoff model for green roofs, Wat. Sci. Tech., 62 (2010) 898–905.
[9] Berretta, C, Poë, S, Stovin, V., Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics, J Hydrol, 511 (2014) 374–386.
[10] Schneider, C.A., Rasband, W.S., Eliceiri, K.W. NIH Image to ImageJ: 25 years of image analysis, Nature Methods, 9 (2012) 671-675.