A microstructure-based procedure to simulate the effect of wetting-drying cycles on the soil water retention curve

Andrew Vidler[1*], *Olivier* Buzzi[1], and *Stephen* Fityus[1]

[1]Priority Research Centre for Geotechnical Science and Engineering, University of Newcastle, Callaghan, NSW, Australia

Abstract. Analysing unsaturated soil response often requires the soil-water-retention-curve (SWRC). The SWRC depends upon the soil microstructure, which evolves with hydromechanical loading such as in-situ exposure to wetting-drying cycles. If in-situ response is of interest and studied in the laboratory, it is essential specimens have a structure representative of in-situ conditions. Simulating wetting-drying cycles in the laboratory is possible albeit time-consuming and a faster alternative procedure would be preferred, which is the focus of this paper. Mixtures of two soils were prepared in the laboratory by either: exposure to three simulated wetting-drying cycles, or one of two compaction approaches. The microstructure and drying-path SWRC of the specimens prepared with each method were measured. Most of the compacted specimens achieved similar pore size distributions to the cycled samples though the outcomes in terms of achieving a target SWRC, which was the objective of the study, are mixed. The SWRCs of most compacted samples had similar gravimetric water contents yet significantly higher saturation degree at every suction measured. This is explained by the compacted samples containing less macro pores than cycled samples. The compaction procedure, designed to produce specimens having a SWRC similar to that of cycled materials, seems promising but needs modification.

1 Introduction

The soil water retention curve (SWRC) is essential information required to analyse the response of unsaturated soils. Research has shown that the SWRC is strongly correlated to the soil microstructure, which evolves with hydromechanical loading. This is particularly the case when a soil is subjected to wetting drying cycles which, under the right conditions, can trigger collapse. In engineering applications where the in-situ soil response is of interest, and is to be studied in the laboratory, it is essential to prepare specimens to a structure that is representative of in situ conditions. This can be achieved by subjecting specimens to a series of wetting drying cycles, although this is time consuming. Thus, this paper presents a preliminary study to investigate a faster procedure of soil conditioning, with an emphasis on microstructure, to prepare specimens that possess the same drying SWRC as specimens subjected to wetting and drying cycles.

Two soils were used to investigate such a procedure: a coal tailings and topsoil from a mine site that were being studied at the time by the authors. The topsoil and tailings investigated may be mixed together and surficially placed during mine rehabilitation. Thus, the microstructure and SWRC after wetting and drying cycles needs to be measured for the soils and several mixtures to assess the likelihood of successful plant growth on rehabilitated land. In this situation, finding a rapid approach to prepare specimens having a similar SWRC than those subjected to several wetting-drying cycles in situ, would be beneficial, to reduce preparation time. This paper explores a procedure based on microstructural considerations to achieve specific SWRC.

2 Materials

The soils used in this study were collected from a coal mine in the Permian coalfields of eastern Australia and are called A1 tailings and A2 topsoil. Mixtures of the soils were also tested with three mixtures created at increments of 25% by volume to make 5 materials in total (100:0, 75:25, 50:50, 25:75, 0:100 of A1:A2).

3 Methodology

3.1 Wetting drying cycles

To assess the validity of any faster preparation procedure, comparisons must be made to soils with a microstructure conditioned through wetting and drying cycles. Thus, soil specimens were conditioned in the laboratory by applying wetting-drying cycles to columns of soil. The initial (or placement) conditions were adopted as a void ratio (e) of 1.3 and a saturation degree of 25%. A soil column of 400 mm depth (assumed to be a likely depth of placement) was prepared in 90mm inner diameter PVC pipe, for each

* Corresponding author: andrew.vidler@uon.edu.au

material from Table 1. Wetting of the column was performed by pouring deionised water on the top surface, and drying was achieved by placing the soil columns inside a drying cabinet set to a relative humidity of 40%.

The first three to six cycles have the greatest impact on the volume change and structuring of a soil [1–3]. Because each drying step takes about a month to complete, the conditioning was limited to three wetting-drying cycles, after which, each column was wetted once more to facilitate sample retrieval. Samples were collected from the top and bottom of the column to assess variability within the column and are referred to as wet/dry cycled samples herein.

3.2 Compaction procedures

Compaction procedures were trialled as a faster sample preparation process, which involved compacting a loose soil mixture to the same void ratio as wet/dry cycled samples. Two different procedures were trialled, a wet compaction procedure and dry compaction procedure [4] The wet compaction procedure compacts a wet sample to the target void ratio and a saturation degree ≈ 1, whereas the dry compaction procedure compacts a dry sample to the target void ratio then achieves saturation by wetting at constant volume.

The soil used in the wet compaction procedure was first prepared to the target water content and passed through a 2.36mm sieve to break apart larger aggregates, although some agglomeration was unavoidable. After the soil had equilibrated in an airtight container for one day, the soil was quasi-statically compacted to the target void ratio within a stainless steel sample ring.

The soil used in the dry compaction procedure was an oven dried (110 °C) loose powder, compacted quasi-statically to the target void ratio within a stainless steel sample ring. The soil and ring were then wetted by submersion in deionised water for 24 hours while clamped between two porous plates, which allowed air to escape yet prevented material loss.

3.3 Measurement of suction, volume and water content, and pore size distribution

The drying path of the SWRCs were measured in a similar manner to what is described in [5], with the SWRCs constructed in terms of degree of saturation vs suction by combining the gravimetric SWRC and shrinkage curve. The pore size distribution (PSD) of the materials was measured by mercury intrusion porosimetry (MIP) similar to what is described in [4]. The mercury intrusion void ratio (e_{MIP}) at any entrance pore size was found by multiplying the specific intrusion (mL intruded mercury/g of sample) by the sample's specific density. The void ratio associated with micro voids and macro voids within a sample, herein referred to as e_{micro} and e_{macro}, respectively, was calculated as per [6] using the RFS criterion. This criterion assumes that the boundary pore size value between the micro and macro voids occurs at the peak in the PSD.

3.4 Estimation of water retention curve from pore size distribution

Given that this investigation explores the correlation between microstructure and water retention curve, it will be useful to construct a SWRC from the PSD measured with mercury intrusion, herein a capillary pressure based approach as proposed by [7] was used. It is relevant to specify that inferring a SWRC from a PSD relies on the assumption of no volume change during drying, which comes from the fact that a PSD is a snapshot of the soil structure at a given suction.

4 Results and discussion

4.1 Microstructure

A comparison of the PSDs from the soil column (top and bottom) after cycles, with the PSDs of compacted specimens, is shown in Figure 1. The boundary value between micro and macro pores was identified for each sample's PSD in Figure 1 (using the RFS criterion, represented by the arrow), which allows calculation of e_{macro} from the cumulative PSDs for the wet/dry cycled and compacted samples (the cumulative PSDs can be seen in [4]). The boundary values adopted are detailed in Table 1 along with other microstructural parameters such as e_{MIP}, e_{macro}/e. Table 1 also highlights that the wet compaction procedure could not achieve the same void ratio as the wet/dry cycled specimens; this occurred due to excessive agglomeration prior to compaction when preparing the soil to the target water content.

Figure 1 shows the PSDs for wet-compacted samples are somewhat similar to the PSDs of the wet/dry cycled samples: wet/dry cycled and compacted specimens have a similar entrance diameter at the peak but compacted specimens tend to have a much narrower peak than their wet/dry cycled counterparts. This was somewhat expected as the compacted samples have a lower void ratio than their wet/dry cycled sample counterparts. A narrower peak indicates there are a greater proportion of dominant sized pores and fewer pores of greater or lesser size, this can be seen in Figure 1 for the 0%, 50%, 75% and 100% A2 topsoil mixtures, which have fewer larger pores. The lower proportion of greater sized pores is supported by the lower e_{macro}/e values in Table 1 for the compacted samples of 100% and 75% A2 topsoil mixtures, which had the most significant differences from the PSD of the wet/dry cycled samples. The compaction process seems to work best for the mixtures with 0%, 25% and 50% A2 topsoil, with a poorer match between PSDs achieved for 75% and 100% A2 topsoil. This is the reason why an alternative compaction process (dry compaction) was explored for the 100% A2 topsoil mixture.

Table 1. Values of void ratio (e), e_{MIP}, boundary pore size that defines the transition from macro to micro pore sizes, e_{macro}, e_{micro} and e_{macro}/e_{micro} determined for each soil mixture sample. Samples include those exposed to wetting and drying cycles from either the top or bottom of a soil column (Cycled (top) or Cycled (btm) respectively), and wet-compacted and dry-compacted samples.

A2 topsoil content	Soil sample type	e	e_{MIP}	Boundary pore size (μm)	e_{macro}	e_{macro}/e
0%	Cycled (top)	1.16	1.14	1.4	0.55	0.47
	Cycled (btm)	1.08	1.08	2.2	0.42	0.39
	Wet-compacted	0.95	1.02	1.2	0.47	0.49
25%	Cycled (top)	0.94	0.96	1.1	0.48	0.51
	Cycled (btm)	1.03	0.95	1.1	0.46	0.45
	Wet-compacted	0.87	0.90	1.3	0.44	0.51
50%	Cycled (top)	0.96	0.94	1.1	0.48	0.50
	Cycled (btm)	0.95	0.91	1.1	0.48	0.51
	Wet-compacted	0.83	0.86	1.2	0.40	0.48
75%	Cycled (top)	0.82	0.79	1.1	0.42	0.51
	Cycled (btm)	0.83	0.87	1.8	0.48	0.58
	Wet-compacted	0.73	0.74	1.4	0.25	0.34
100%	Cycled (top)	0.77	0.78	2.0	0.34	0.44
	Cycled (btm)	0.82	0.83	2.0	0.39	0.48
	Wet-compacted	0.65	0.64	3.0	0.2	0.31
	Dry-compacted	0.67	0.64	2.2	0.17	0.25

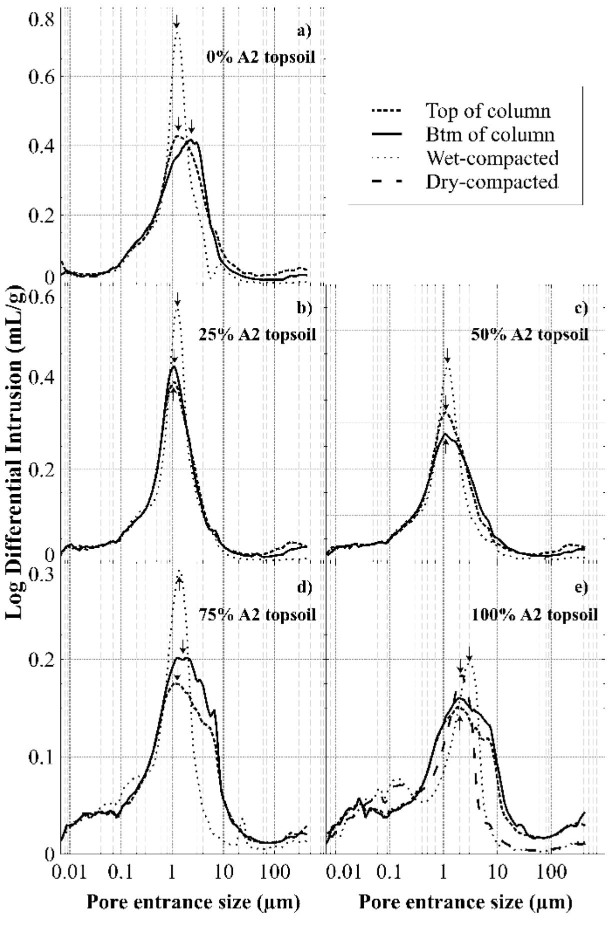

Fig 1. Pore size distributions of wet/dry cycled soils from the top and bottom (Btm) of the column, wet-compacted samples and dry-compacted samples. Each subfigure relates to a soil mixture: a) 0% A2 topsoil, b) 25% A2 topsoil, c) 50% A2 topsoil, d) 75% A2 topsoil, and e) 100% A2 topsoil. The arrows indicate the boundary value separating macro and micro pores determined with the RFS criterion [6].

The PSD of the sample that underwent the dry compaction process is similar to the PSDs achieved via the wet compaction process, with the dry-compacted sample having slightly smaller dominant pore entrance size. This is likely due to the fact that the material was wetted after the dry compaction in order to measure the drying branch of the retention curve, which reduces the difference between dry and wet compaction.

In conclusion, the microstructure of the compacted specimens is fairly close to that of the wet/dry cycled specimens, but some small differences do exist that have repercussions on the retention curves. For example, compacted samples have a lower proportion of larger pores than most wet/dry cycled samples (see Figure 1), which suggests that the retention curves of compacted samples are likely to display a higher saturation degree for all suction values, compared to their wet/dry cycled counterparts.

4.2 Water retention

To assess how the soil deforms upon drying, the shrinkage curves in terms of void ratio and suction are shown in Figure 2, for both the wet/dry cycled and compacted samples (wet-compacted and dry-compacted). Most of the shrinkage curves have a relatively consistent gradient, and the majority of the wet/dry cycled and compacted samples are parallel to one another, for the same soil mixture. Although, some of the compacted samples have a somewhat bi-linear behaviour. The gradients of the shrinkage curves increase as the soil mixture's topsoil content reduces. When comparing compacted and wet/dry cycled samples, the figure clearly shows that most compacted samples have a lower void ratio at any suction.

The SWRCs of wet/dry cycled and compacted samples, in terms of gravimetric water content and suction, are shown in Figure 3. The retention curves for wet/dry cycled and compacted samples generally maintain a consistent gradient. Four out of five compacted samples have a SWRC that is very close to that of their wet/dry cycled counterparts. It is only for 100% A2 topsoil that the difference is quite pronounced. These results indicate that a compaction soil structuring procedure could be used to achieve a similar SWRC to

 https://doi.org/10.1051/e3sconf/202338225002

soil exposed to several wetting and drying cycles, at least when the SWRCs are in terms of gravimetric water content.

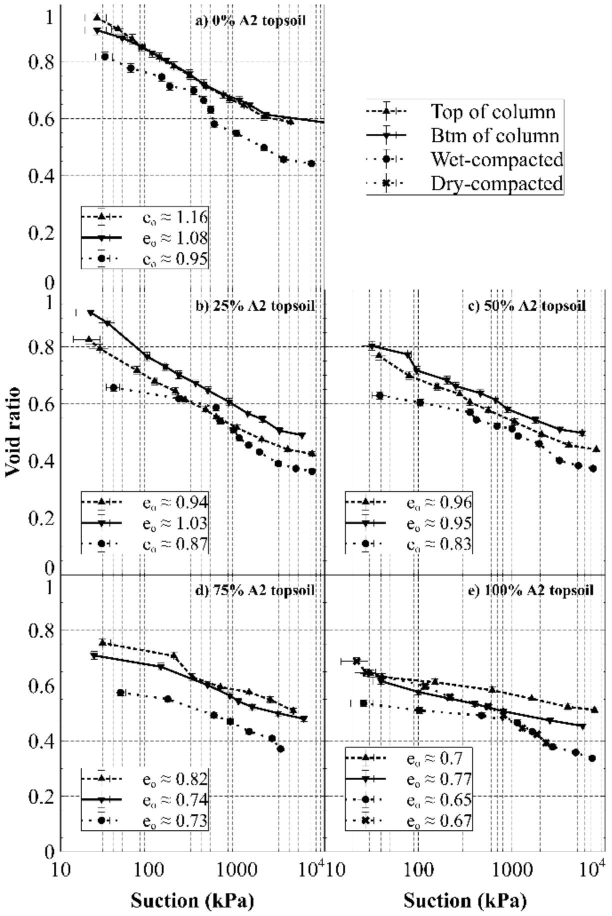

Fig 2. Shrinkage curves in terms of void ratio and suction for the wet/dry cycled and compacted samples. Each subfigure relates to: a) 100% A2 topsoil, b) 75% A2 topsoil, c) 50% A2 topsoil, d) 25% A2 topsoil, and e) 0% A2 topsoil. The initial void ratio before any drying (e_o) is shown for each sample.

Figure 4 shows the retention curves, in terms of saturation degree vs suction, for all wet/dry cycled and compacted samples. The compacted samples tend to display a higher saturation degree than wet/dry cycled samples across all suction values, because of their microstructure (fewer larger pores and lower e_{macro} for most soil mixtures, see Table 1 and Figure 1), a lower initial void ratio (as per Table 1) because of experimental difficulties and the fact that most compacted samples have a lower void ratio at any suction during drying (see shrinkage curves in Figure 2).

The retention curves of the compacted materials tend to be more convex than those of the wet/dry cycled materials, which is likely to be a combined effect of differences in deformability and microstructure. The difference in stress history between cycled specimens and compacted specimens is likely to play a role here, but it is currently not accounted for in the approach.

The retention curve of the compacted 25% A2 topsoil sample is the only one to fall very close to its wet/dry cycled counterpart, which can be explained by a greater similarity in microstructure (see Figure 1).

A better control on the void ratio, would result in the SWRCs being closer together but the contribution of the void ratio is believed to be less than that of microstructure. For example, for the 100% A2 topsoil, the dry-compacted sample has similar values of void ratio than that of the top of the column up to about 600kPa of suction (see Figure 2), but the two retention curves are quite different.

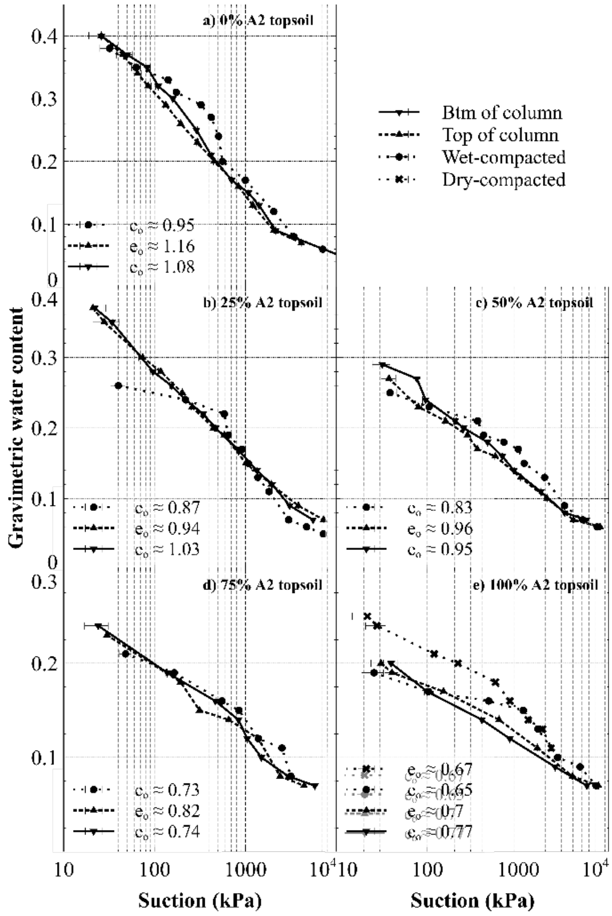

Fig 3. Drying path of water retention curves in terms of gravimetric water content and suction for the wet/dry cycled and compacted samples. a) 100% A2 topsoil, b) 75% A2 topsoil, c) 50% A2 topsoil, d) 25% A2 topsoil, and e) 0% A2 topsoil. The initial void ratio before any drying (e_o) is shown for each sample.

The results shown in Figure 4 are promising and suggest that the compacted soil structuring procedure could be fine-tuned to achieve a greater similarity between the wet/dry cycled and compacted samples SWRCs (in volumetric terms). But before making suggestions on how the compaction soil structuring process should be improved, the correlation between changes in microstructure and changes in retention curves is further explored. In the following, the PSD of 100% A2 topsoil was hypothetically modified and converted into retention curves (as per the procedure in Section 3.4) to evaluate how changing the microstructure affects the retention curves of the material.

Figure 5 shows three proposed hypothetical PSD alterations: an increase in peak height while maintaining the position of the peak (blue PSD), a shift of the peak towards larger pores (red PSD), and a combination of both (green PSD). Note that, given that most of these hypothetical modifications require an increase in initial void ratio, it is apparent the dry-compacted procedure is relevant; achieving a higher initial void ratio with the wet-compacted procedure is likely to be difficult given the severe agglomeration associated with the high water contents required. Thus, the following discussion, and the PSDs in Figure 5, relate to the dry-compacted samples.

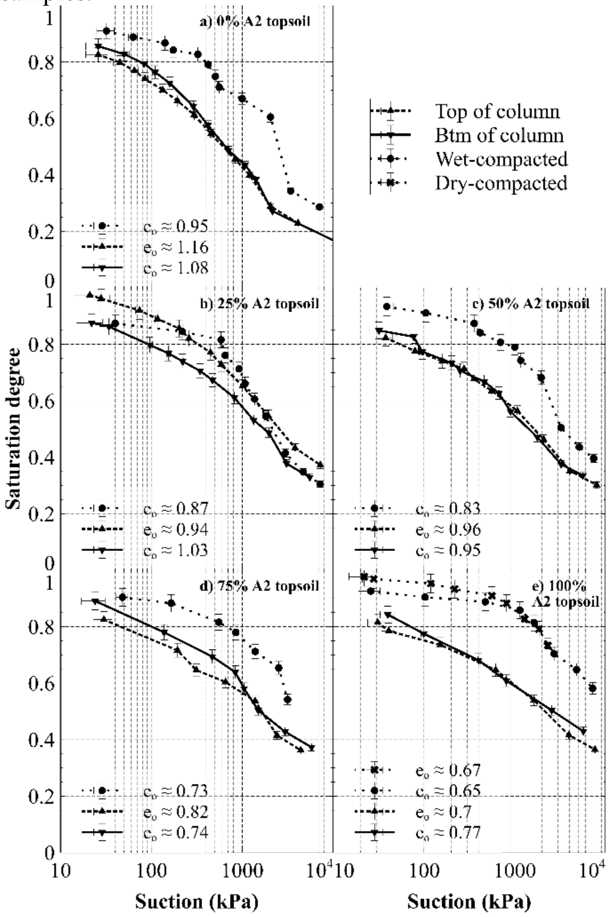

Fig 4. Drying path of water retention curves expressed in terms of saturation degree and suction for the wet/dry cycled and compacted samples; a) 100% A2 topsoil, b) 75% A2 topsoil, c) 50% A2 topsoil, d) 25% A2 topsoil, and e) 0% A2 topsoil. The initial void ratio before any drying (e_o) is shown for each sample.

The SWRCs constructed from the PSD data of the measured and hypothetical samples are shown in Figure 6 in terms of saturation degree and suction. When comparing the SWRCs of the wet/dry cycled and compacted samples in Figure 4, the wet/dry cycled samples have a lower saturation degree at every suction. Thus, the change in SWRC shape required for a greater similarity between wet/dry cycled and compacted samples is a reduction in saturation degree at every suction for the compacted samples. This is clearly achievable by introducing larger pores as shown by Figure 6 where a PSD shifted towards a larger dominant pore size (red lines) results in a reduction of saturation degree at every suction, when compared to the SWRC constructed from the measured PSD (solid lines).

The PSD with a shifted dominant pore size (red lines in Figure 6) causes a greater reduction in saturation degree and volumetric water content, when compared to the PSD with a greater proportion of dominant sized pores (blue line in Figure 6), despite the latter PSD having a larger e_{MIP}. The hypothetical PSD combining a shift and an increase in peak height has an effect on the water retention behaviour that is effectively an average of blue and red lines shown in Figure 6.

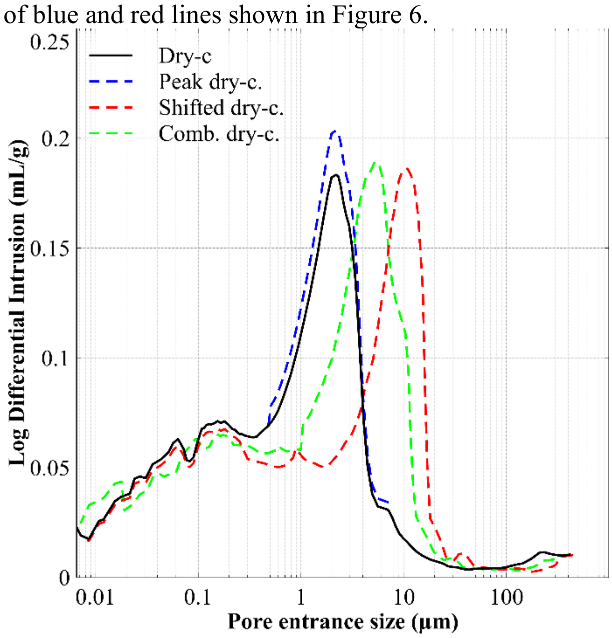

Fig 5. Measured and hypothetical differential pore size distributions for 100% A2 topsoil. The black line corresponds to the measured PSD of the dry-compacted sample, blue is the hypothetical PSD with an increased peak height, red is the hypothetical PSD with a shift of the peak to larger pores, and green is the hypothetical PSD combining the effects of the blue and red PSDs.

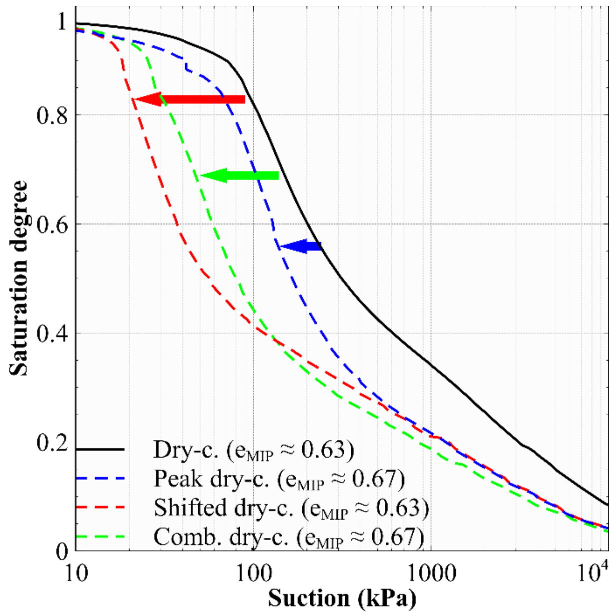

Fig 6. Water retention curves constructed from the PSDs in Figure 5 in terms of saturation degree for A2 100% topsoil. The arrows highlight the change in retention behaviour due to the hypothetical change in the PSD of the related colour.

Given all of the results and discussion so far on the compacted procedure investigated herein, the procedure appears suitable to rapidly prepare samples with similar gravimetric SWRCs to samples prepared by wet/dry cycles. However, it is clear that the compaction soil structuring procedure used is not adequate at conditioning samples to achieve similar volumetric SWRCs to the wet/dry cycled samples. The compacted procedure could be modified for improved results, namely by increasing the initial void ratio or cultivating a larger dominant entrance pore size by some manner, with the dry-compacted procedure likely to be necessary for these changes. Note that it is essential for this procedure to be applied to know the target microstructure and retention curve, so the need to cycle some specimens is not totally eliminated, but it can be reduced.

5 Conclusion

A more rapid soil conditioning procedure using compaction was investigated as an alternative to the procedure replicating wetting and drying cycles in soil columns, which requires a lengthy testing period of three months or more for a 400mm high soil column. The compaction procedure consists of compacting, in a quasi-static manner, a soil to a target void ratio and assessing its microstructure. The loose sample material is prepared at a selected moisture content. When compared to the wet/dry cycled samples obtained from the soil columns, the compaction procedure produced samples with relatively similar pore size distributions (PSDs) and SWRCs in terms of gravimetric water content. However, significant differences were observed on the shrinkage curves and the SWRCs expressed in terms of saturation degree. This was primarily caused by:

- the compacted samples having a smaller proportion of larger pores than the wet/dry cycled samples, as determined through comparison of PSDs;
- the void ratio of the compacted samples being lower than the wet/dry cycled samples at every suction, as determined by comparison of shrinkage curves;
- and the inability of wet-compacted samples to be prepared to the target void ratios.

Although promising, the compaction procedure investigated did not quite produce specimens that could completely replace specimens subjected to natural wetting and drying cycles, and should be modified. To that end, constant volume SWRCs constructed from PSDs of real and hypothetical compacted samples showed that if a slightly higher initial void ratio can be achieved, it may significantly alter the SWRCs in terms of saturation degree, and in a favourable manner. Thus, future research is recommended to improve the compaction soil conditioning procedure and consider the possible effect of stress history.

References

1. E. Pousada, *Deformabilidad de las arcillas expansivas bajo succión controlada*, (1984).
2. C.-S. Tang, N. An, A.-M. Tang, B. Shi, and Y.-J. Cui, *Effect of wetting-drying cycles on soil desiccation cracking behaviour*, in proceedings of the 3rd European Conference on Unsaturated Soils, (2016)
3. S. Tripathy and K. S. Subba Rao, Geotech. Geol. Eng., **27**, 89-103 (2009)
4. A. M. Vidler, *Water retention properties of engineered soils for mine rehabilitation*, (2022)
5. A. M. Vidler, O. Buzzi, and S. Fityus, Appl. Sci., **11**, (2021)
6. S. Yuan, X. Liu, E. Romero, P. Delage, and O. Buzzi, Geotech. Lett., **10**, (2020)
7. E. Romero, A. Gens, and A. Lloret, Eng. Geol., **54**, (1999)