The influence of soil suctions on the deformation characteristics of railway formation materials

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Abstract

Changing climatic conditions worldwide are causing changes in moisture conditions of railway formations and slopes, thereby either strengthening or weakening them. Current railway formation design methods do not take into account the changing moisture conditions over the predicted life of a railway formation. These changes in soil strength are due to the influence of soil suctions. The basic principles of unsaturated soil mechanics are well established in the field of geotechnics, and this study joins an international body of work that seeks to apply unsaturated soil theory to the field of railway and pavement formation materials.

This study comprised box testing of subgrade and subballast formation materials at different moisture contents to demonstrate the behaviour of these two materials relative to each other. The formation models were instrumented with tensiometers to monitor the effect of cyclic loading and loading frequency on material behaviour and soil suction under typical heavy haul loading (26 tonne/axle). The study also investigated the evolution of suctions present in railway formation materials as well as practical aspects relating to suction measurement under cyclic loading conditions.

Suctions were successfully measured in both the subgrade and subballast materials subjected to cyclic loading, demonstrating the different suction magnitudes generated by the materials under typical railway formation conditions. The well-drained subballast material was found to generate low magnitudes of suction over a large range of degrees of saturation (1 kPa – 15 kPa), while the less well-drained subgrade material was found to generate a greater range of suctions (1 kPa – 95 kPa) with a smaller variation in the degree of saturation.

The deformability of the subgrade material depended to a greater on the moisture state and soil suctions compared to the subballast material and showed a large variation in deformability as a function of its moisture state. At its wettest, the subgrade material experienced deformation exceeding the allowable failure limit, while the subgrade material deformed less than the subballast material at its driest. The subballast deformation was significantly affected by the loading frequency and less by its moisture state due to the low suctions present.

The findings of this study have practical implications for both in-situ and laboratory testing of railway formation materials and emphasized the importance of the moisture state of the formation during the railway service life.

Keywords: Matric suction; tensiometer; railway formation; SWRC; cyclic loading

1. Background

The design of railway formations has traditionally relied on empirical and catalogue design methods that prescribe a required formation (Li and Selig, 1998; Transnet, 2006; UIC, 1994). This formation structure may then be defined in terms of the number of layers required, their thicknesses and types of materials used. There is however no consideration given to the effect of in-situ conditions in these methods, particularly the effect of moisture content. Given the changing climatic conditions worldwide, it is important that the effect of moisture change over the life of a railway formation is considered.

When a soil is saturated, all the pores are filled with water. This leads to fairly predictable behaviour in terms of a well quantified effective stress. When the soil dries out, water leaves the pores, starting with the pores of largest diameter. The pore water then desaturates by leaving successively smaller pores as drying continues. These unsaturated soils have greater shear strength than their saturated counterparts. This is due to the increased contact stresses between particles in the presence of negative pore water pressure (soil suction - ψ). In the context of relatively well drained railway formation materials the increased contact stresses are caused by the surface tension of the water meniscus bridging between soil particles (Huat et al., 2012).

Studies that have been undertaken to apply soil suction theory to railway formation materials include quantifying the effect of soil suction and moisture state on resilient modulus (Azam et al., 2013; Cary and Zapata, 2011; Coronado et al., 2016; Han and Vanapalli, 2016; Otter et al.; 2016; Rorke, 2016), as well as modelling the effect of moisture conditions on the strength of the soil (Saad, 2013; Soliman and Shalaby, 2015; Mamou et al., 2017; Zhang et al., 2014). Laboratory studies investigated the response of soil suctions to cyclic loading (Cary and Zapata, 2016; Hosseini et al., 2017; Rorke, 2016).

The studies mentioned above entailed either numerical modelling or carefully instrumented small-scale laboratory tests. A need exists to bridge the gap between the successful laboratory testing of material and the implementation of suction instrumentation in-situ. Railway formations in the field present a much more hostile environment in which to carry out successful suction measurement compared to the laboratory. In order to be of value, laboratory suction studies should therefore model the conditions occurring in in situ granular formations during cyclic loading as closely as possible.

From Table 1, presenting typical suction ranges for various granular materials, it can be deduced that high suctions are possible in granular materials under very dry conditions. The suctions presented for recycled materials correspond with similarly graded virgin aggregates (Gupta et al., 2009). However, the suctions listed occur under extremely dry conditions and therefore it is important to investigate probable in-situ suction ranges of railway formation materials and their impact on formation deformability. Work by Cary and Zapata (2016) aimed to establish the systematic increase of matric suction in a railway subgrade material as cyclic loading takes place. The rate of the systematic increase of excess pore pressure in a sample subjected to cyclic loading was found to be a function of the loading rate, rest period and stress state of the soil, given the same initial matric suction for each sample.

Table 1: Range of suctions in granular material from literature

Material	Suction range (kPa)	Air-entry range (kPa)	Test method	Reference
Basalt aggregate	0 – 45	-	Filter paper	Walker (1997)
Sandstone aggregate	0 – 3500	-		

Recycled crushed concrete (RCA)	0 – 90	0 – 22	Hanging water column and Tempe cell	Rahardjo (2010) & Nokkaew et al. (2012)
Recycled asphalt pavement (RAP)	0 – 60	0 – 1.11		
RCA/recycled crushed masonry (RCM) blend 1	0 – 88	0 – 9	Filter paper and hanging water column	Azam et al. (2014)
RCA/RCM blend 1	0 – 240	0 - 18		
Virgin aggregate	0 – 19	0 – 8		

An investigation by Mamou et al. (2017) monitored the pore pressure change in unsaturated samples of subgrade materials while undergoing cyclic loading in a hollow cylinder apparatus under both undrained and drained conditions. The work by Mamou et al. (2017) was primarily concerned with the role of drainage conditions in the deformation behaviour of formation material undergoing cyclic loading and principal stress rotation. Previous work by Brown and Selig (1991) showed that a cyclic shear stress threshold exists below which a sample will remain stable under cyclic loading. Once this threshold is exceeded, the sample rapidly deforms. At this point, failure is deemed to have occurred. It is also at the point where the threshold is passed that the excess pore pressures will begin to increase under undrained conditions.

The goal of this study is to provide an understanding of the role of suctions relevant during cyclic loading of common railway formation materials and the deformation responses of these materials to suction change. This has implications for future railway design methods - methods that should consider changing climatic conditions.

2. Methodology

2.1. Test setup and material parameters

This study comprised box testing of subgrade (AB) and subballast (SB) formation materials at different moisture contents. These formation models were instrumented with tensiometers to monitor the effect of cyclic loading on soil suctions under typical heavy haul loading magnitudes (26 tonne/axle). The materials were subjected to the same cyclic heavy haul load magnitude and tested at different loading frequencies. The study investigated the suctions present in railway formation materials, as well as the application of suction instrumentation in railway conditions. Box testing was selected as a compromise between the measurement of suctions and deformations in the laboratory (e.g. using unsaturated cyclic triaxial testing), where conditions could be an over-simplification of reality, and the measurement of suctions in an operational railway formation, which is logistically challenging. The tests were carried out at increasing loading frequencies to simulate different operational speeds. The tests were all preceded by a 10-minute static loading phase. All testing phases, including the pre-test, were carried out at a 100 kPa load, with the cyclic phases cycling between 10 kPa and 100 kPa in a sinusoidal loading pattern, maintaining contact with the loading block throughout. Moisture contents for the tests were selected based on the range of degrees of saturation. Each formation was tested once at the optimum moisture content (OMC) and two more moisture contents. A range of moisture contents were selected for both the AB and SB materials while being mindful that cavitation may occur in tensiometers if suctions are too high. For this reason the range of SB material degree of saturation (0.32-0.96) was wider than the range for the AB material (0.60-0.87). Summary of testsTable 2 and Table 3 present the summary of tests and testing procedures respectively.

Table 2: Summary of tests

Material	Moisture content (%)	Degree of saturation	Test description
Subgrade (AB)	9	0.60	AB 9 % MC
	11	0.74	AB 11 % MC
	13	0.87	AB 13 % MC
Subballast (SB)	2	0.32	SB 2 % MC
	4	0.64	SB 4 % MC
	6	0.96	SB 6 % MC

Table 3: Summary of testing procedure for each test

Test stage	Frequency (Hz)	Cycles	Time (min)
Pre-test	Static – 100 kPa		10
Stage 1	0.25	2000	133
	Rest period		5
Stage 2	1	4000	67
	Rest period		5
Stage 3	2	4000	33
	Rest period		5
Stage 4	10	10000	17
	Rest period		5
	Total:	20000	260

The physical model used in the experiment consisted of a 500 mm x 500 mm strongbox with fully frictional sidewalls filled with compacted soil in 4 layers of 50 mm thick each. The total formation depth of 200 mm was chosen to correspond with a single layer of the 26 t/axle structural layer specification (Transnet, 2006). This model was instrumented to monitor pore pressures/suctions using tensiometers and surface deflection using 4 linear variable differential transformers (LVDTs). Figure 1 presents a schematic cross-section of the fully instrumented strongbox, while Figure 2 shows the test setup as used in a typical test.

The formation was constructed layer by layer from material that was pre-wetted to the targeted moisture content. These layers were compacted to 95% Mod AASHTO as per the South African railway formations specification (Transnet, 2006). A fitted plastic sheet with openings for instrumentation and the loading block was placed over the finished formation to reduce moisture loss through the surface.

A stiff loading block was fabricated by welding together I-beams to produce a 200 mm x 500 mm x 50 mm block that was used for all testing. Once loaded into the strongbox, a steel cylinder was placed on the loading block to provide spacing between the loading block and piston. Combined, the 200 mm loading block and steel cylinder weighed 39 kg and exerted a pressure of 7.7 kPa on the surface of the soil. This surcharge pressure was deemed acceptable as it was small in relation to the targeted cyclic stress of 100 kPa.

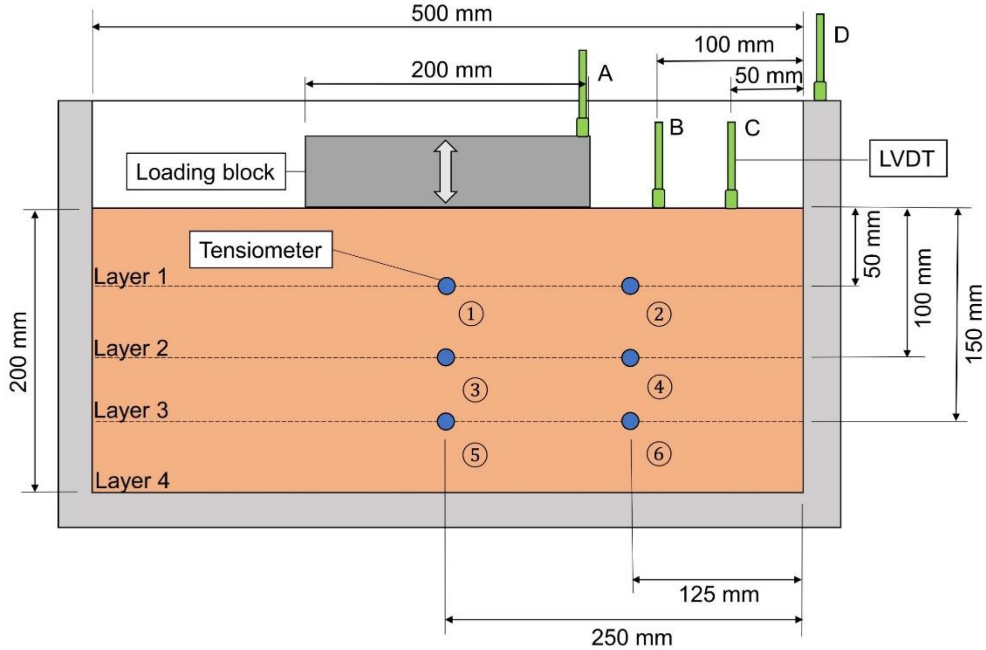

Figure 1: Schematic of the strongbox test setup

Figure 2: Layout of instrumentation and equipment for testing

A maximum applied cyclic stress of 100 kPa was selected to model the loading on the constructed strongbox formation, based on a study of a South African 26 tonne/axle formation (Gräbe et al., 2005). Gräbe et al. (2005) measured peak pressures that varied between 100 kPa and 120 kPa at the surface of the subballast layer during train loading using pressure plates at selected depths. For this study, a minimum load of 10 kPa was selected to allow the loading block and loading piston to remain in contact throughout testing. For the present study, the 4 individual axle loads from two adjacent bogies were grouped together as one sinusoidal load application. Loading frequencies were then calculated based on the passage of adjacent bogie load groups at specific targeted train speeds. These targeted train speeds are listed in Table 4.

Table 4: Targeted train speeds and equivalent loading frequencies

Targeted Speed (km/h)	Equivalent Loading Frequency (Hz)	Description
10	0.25	Heavily restricted speed
40	1	Restricted speed
80	2	Normal operating speed
>150	10	Accelerated formation testing

To characterise the soils used, samples of the subballast (SB) and subgrade (AB) materials were tested by a commercial geotechnical laboratory. The results of these tests are summarized in Table 5. Figure 3 presents the grading of both materials within the grading envelope recommended by Transnet (2006). Gradings were obtained using the hydrometer method to determine the finer portion of the grading curve in line with TMH1: Method A6 (NITRR, 1986). Subballast materials are designed to be stiff and free draining and therefore the SB material consisted of a high proportion of gravel and sand. The AB material was also granular, albeit with a higher proportion of fines when compared to the SB material.

Table 5: Material properties

Atterberg limits	**Material**	
	SB	**AB**
Liquid limit (%)	NP	31
Plastic limit (%)	NP	21
Plasticity index (%)	NP	10
Weighted PI (%)	NP	3.3
Linear shrinkage (%)	0	5
MDD, OMC & SG		
Maximum dry density (kg/m^3)	2136	2070
Optimum moisture content (%)	5.6	11.1
Specific gravity	2.73	2.66
Grading		
Gravel (%)	73	58
Sand (%)	22	24
Silt (%)	4	13
Clay (%)	1	5
Coefficient of curvature (C_c)	2.63	1.64
Coefficient of uniformity (C_u)	38	550
AASHTO Classification System	A -1 - a	A - 2 - 4
Unified Classification System	GW - GM	GC

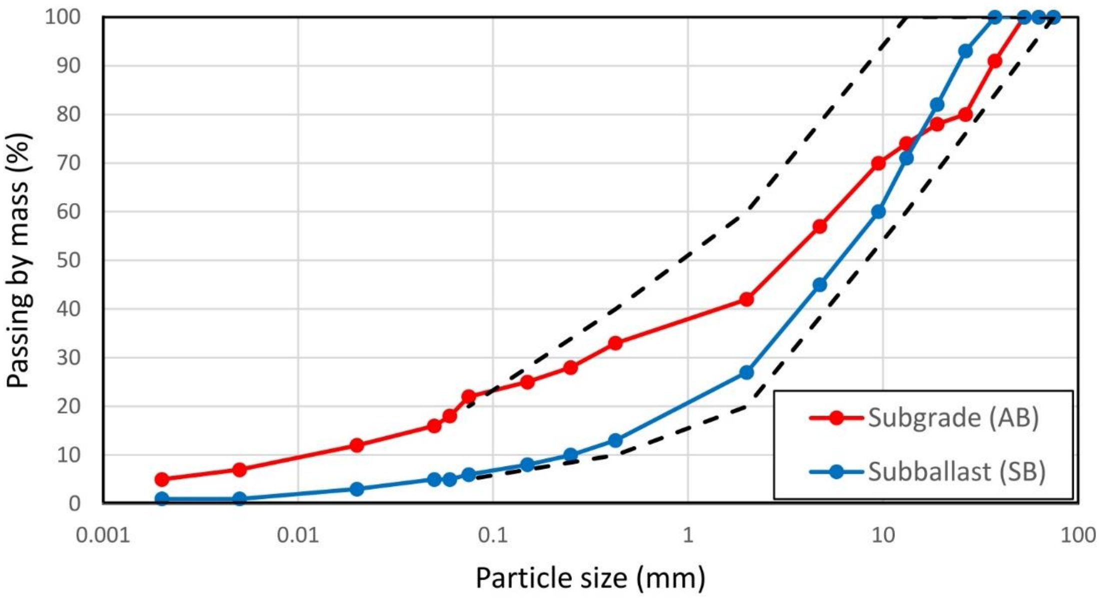

Figure 3: Particle size distribution of SB and AB materials in relation to the simplified allowable grading envelope of South African railway formations

2.2. Suction measurement

Tensiometers where built using MS54XX pressure sensors (Measurement Specialties, 2012) rated to a maximum positive pressure of 700 kPa and ceramic filters with an air entry value of 300 kPa. The construction, saturation and calibration of the tensiometers are described by Jacobsz (2018). Preliminary testing found interference in the tensiometer output caused by the stress imposed by the soil skeleton on the tensiometer casing. To mitigate this effect and ensure a tensiometer response which was representative of the matric suction in the soil, it was necessary to develop a tensiometer that could minimise the total stress effect. The result of this development was the modified shielded tensiometer presented in Figure 4. This design consisted of a typical tensiometer assembly (Jacobsz, 2018) with a high air entry ceramic and sensor which was set in a cylindrical aluminium case with waterproof epoxy following Toll et al. (2013). This assembly was then shielded by a steel tube, with a foam jacket being placed as a buffer between the steel tube and aluminium casing. The inclusion of the foam jacket created a buffer zone that prevented the stress experienced by the steel tube to affect the tensiometer assembly.

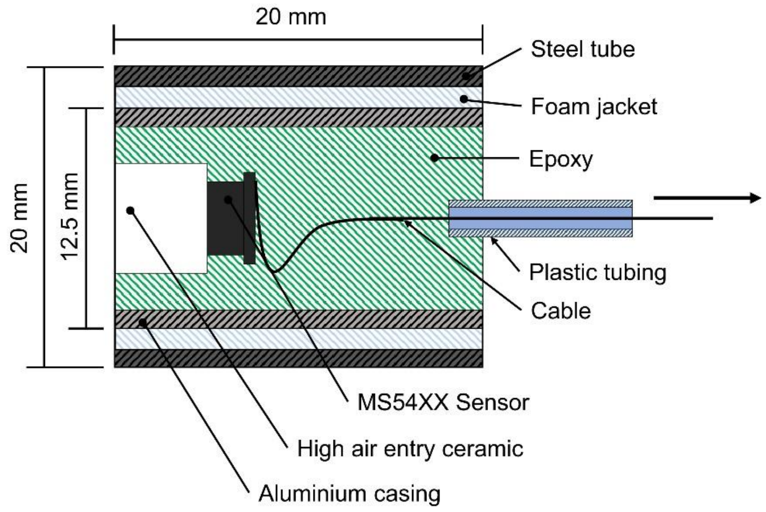

Figure 4: Cross-sectional schematic of modified shielded tensiometer

To establish the expected range of suctions in the materials, as well as relationships between matric suction and moisture content, tests were done to determine the soil-water retention curves (SWRCs) of both the SB and AB materials using the method of fitting a curve to suction data points plotted against moisture content or degree of saturation S_r as described by Fredlund and Xing (1994). This test was performed in 2 stages. In the first stage, tensiometers were used to continuously measure the suction change as the sample was dried out and moisture left the sample, causing the degree of saturation (S_r) to decrease. As the sample dried out, suctions began to increase, until the tensiometers cavitated. After cavitation, the tensiometers would cease providing representative suction values. This drying test therefore provided an incomplete SWRC as the tensiometer is incapable of recording suction data in the dry soil states. The second stage aimed to complete the high suction portion of the curve beyond the effective range of the tensiometers using the filter paper method to measure data points in the dry range. The filter paper tests were carried out using Whatman #42 filter paper and the calibration curve presented by Hamblin (1981).

The wetting curves of both the SB and AB materials were determined using data points obtained from the filter paper tests on samples wetted up from a completely dry state. The location of the wetting curve was then estimated using the *log-shift* method described in Fredlund et al. (2011). This method estimates the wetting curve of a soil by offsetting the drying curve by a percentage of a logarithmic cycle. Log-shift values of 25 %, 50 %, and 100 % are recommended for sandy, silty and clayey soils respectively. Drying curves were shifted with this method to best fit the existing wetting data obtained from the wetted filter paper tests to obtain the wetting curves. Log-shift values of 50 % for the AB material and 25 % for the SB material were found. These values are consistent with average values presented in Fredlund et al. (2011) for sand and silt materials respectively. The resultant SWRCs for the AB and SB materials are presented in Figure 5.

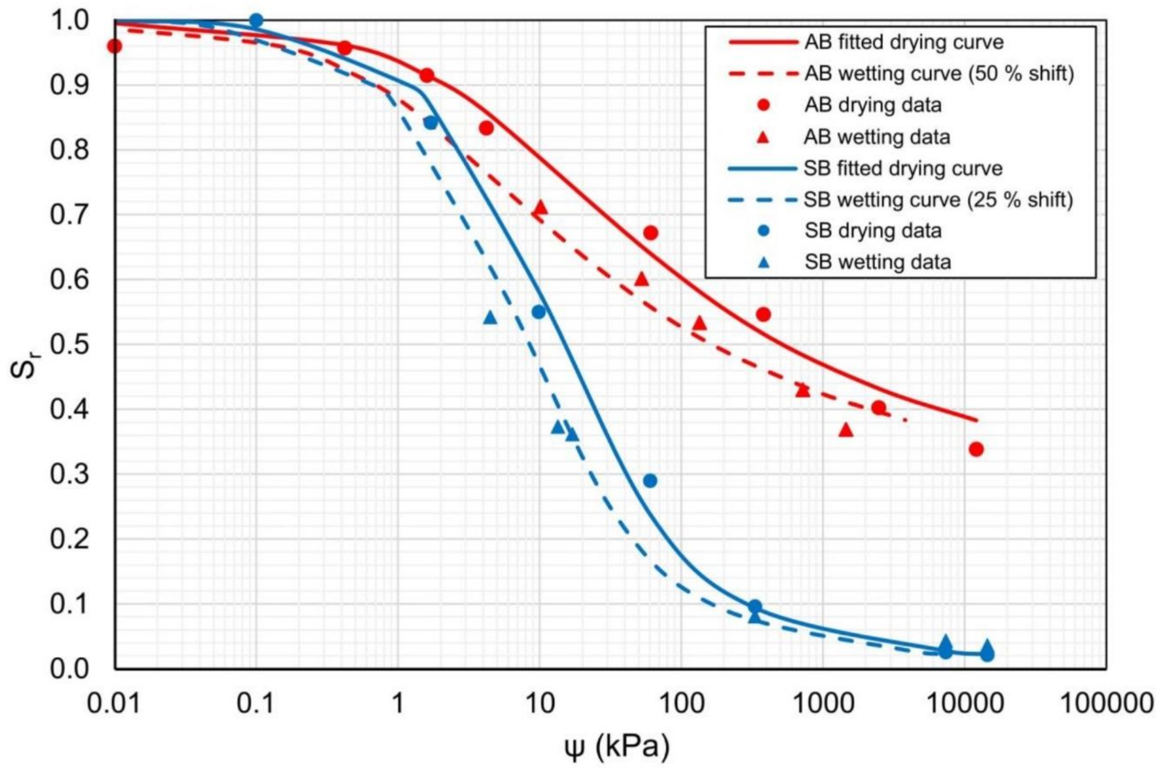

Figure 5: SWRCs of subgrade (AB) and subballast (SB) materials in terms of degree of saturation (S_r) and moisture content (MC)

3. Analysis and results

3.1. Soil suction magnitude and evolution

Suction measurements were taken with tensiometers during cyclic loading. The intention was to primarily use the tensiometers to investigate suction changes (if any) in the formation during testing at different moisture contents. These suction values would then be compared to the deformation associated with each moisture content to reach conclusions regarding the relative effect of suctions on the deformability of each material under cyclic loading.

In this section the term 'pore pressure' refers to positive and/or negative pressures, depending on the conditions. The term 'suction' then refers to the negative range of pore pressures only.

Figure 6 presents different examples of suction evolution during loading for the AB material. The tests included in the figure appear to be of different lengths due to the fact that some tests were allowed extra unloaded time to observe the effect of unloading on the suctions. While the AB 13 % MC and AB 11 % MC suctions showed little to no suction change over the test duration, the three AB 9 % MC suction plots show a large variation in final suction values. However, when plotted on the SWRC of the AB material presented in Figure 7, it becomes apparent that the final suction values are within the expected range of suction values for their respective moisture states. It is notable that the initial suctions of the AB 9 % MC material showed a large variation compared to the final suctions measured in that material. It is believed that initial conformance errors are the cause of this discrepancy, subsequent settlement stabilised measured suction values to realistic values.

Figure 7 presents a comparison of the post-test suction values obtained from the tensiometers and the measured SWRC of the AB material. These suction values show good agreement with the established SWRC and serves as a validation of the log-shift method described by Fredlund et al. (2011) to estimate the wetting curve from the drying curve. Despite the fact that the soil was prepared from a dried state to a targeted moisture content, the values do not plot on the wetting curve. The variation of plotted suctions between the drying and wetting curve imply that a movement of pore water may have occurred during the test and that the suction values measured occur on so-called scanning curves between the boundaries (Pham et al., 2005).

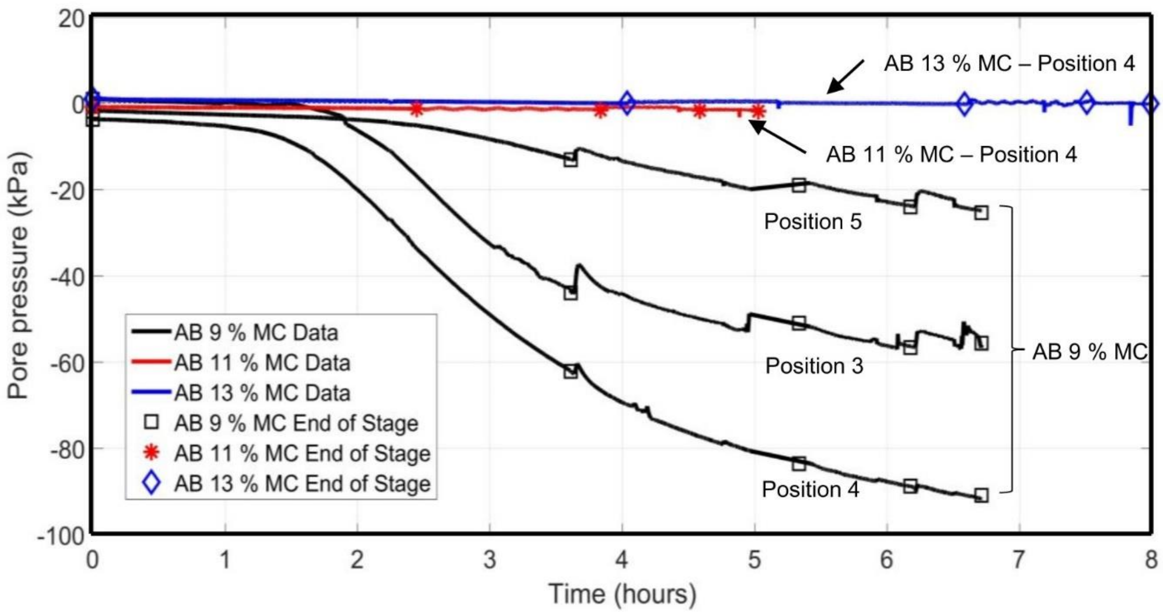

Figure 6: Evolution of soil suctions in subgrade material (AB) with increasing loading cycles

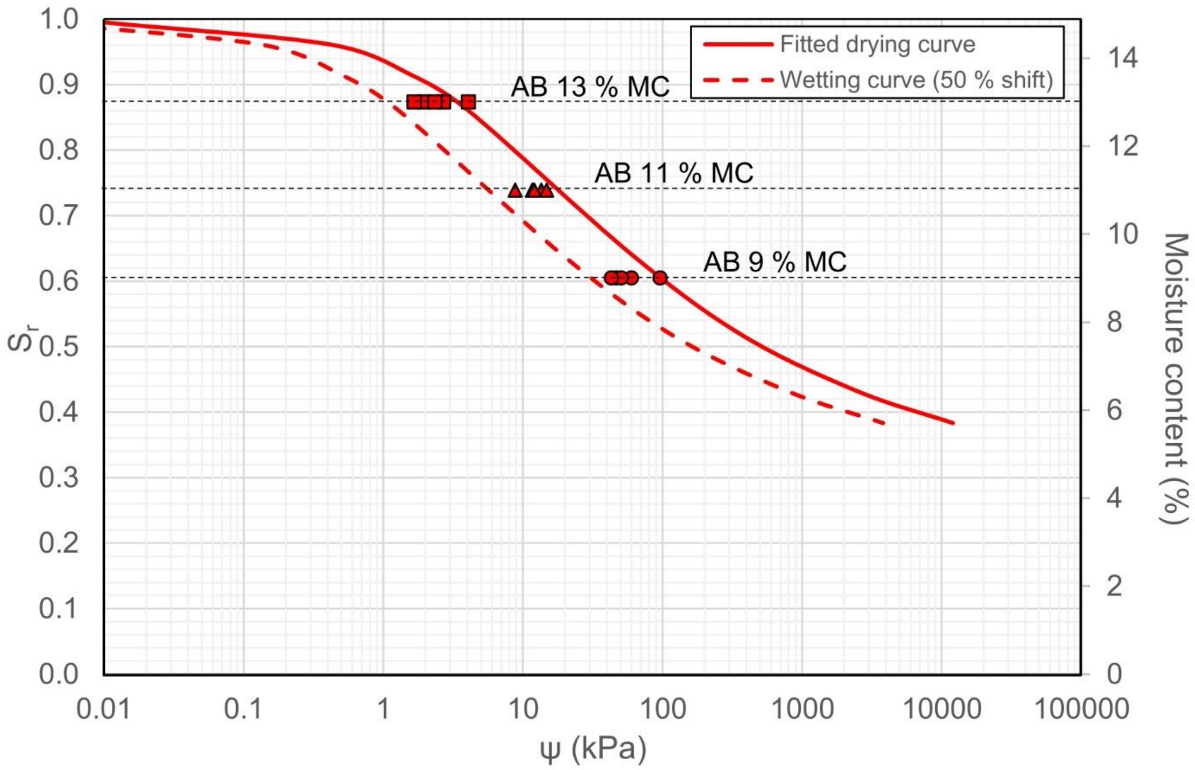

Figure 7: Comparison of measured suction values post-test with the SWRC of the subgrade material (AB)

The evolution of suctions in the SB material is presented in Figure 8 at the same scale as for the AB material above. The magnitude of the soil suctions were small and did not vary significantly during the test when compared to the AB material. Conversely, the suction values measured post-test in the SB material were lower than those predicted by the SWRC, as shown in Figure 9. The reason for this offset from the curve is not clear and may be due to the compression of the soil matrix, lowering the suction by increasing the soil water menisci radii as the particles are forced closer together. The offset is however exaggerated by the log-scale as the difference between the plotted values and those predicted by the SWRC are between 2 kPa and 15 kPa.

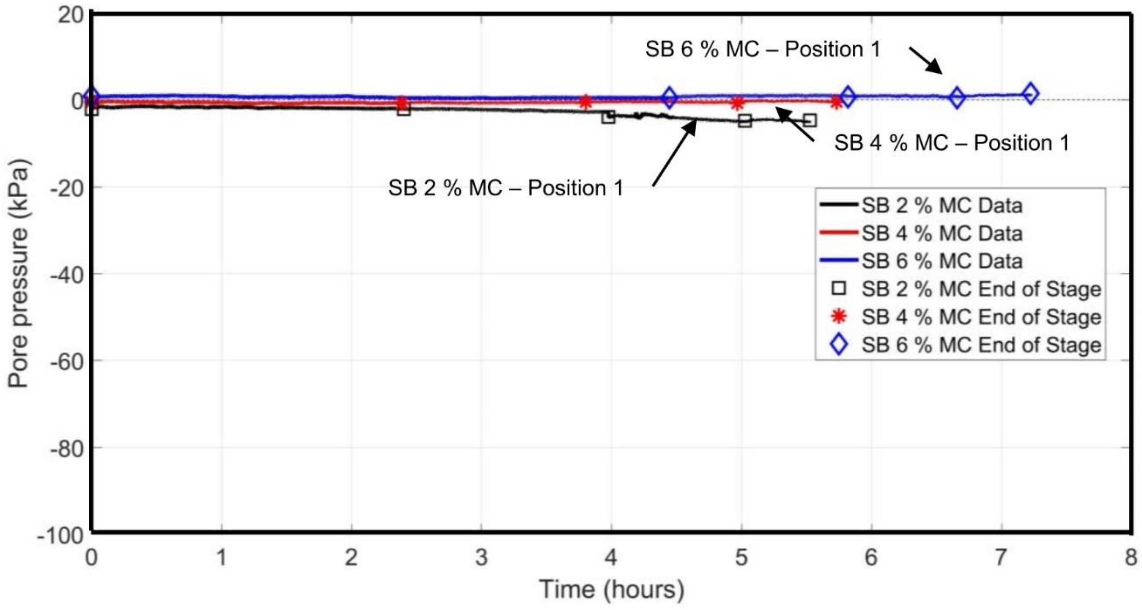

Figure 8: Evolution of soil suctions in subballast material (SB) with increasing load cycles

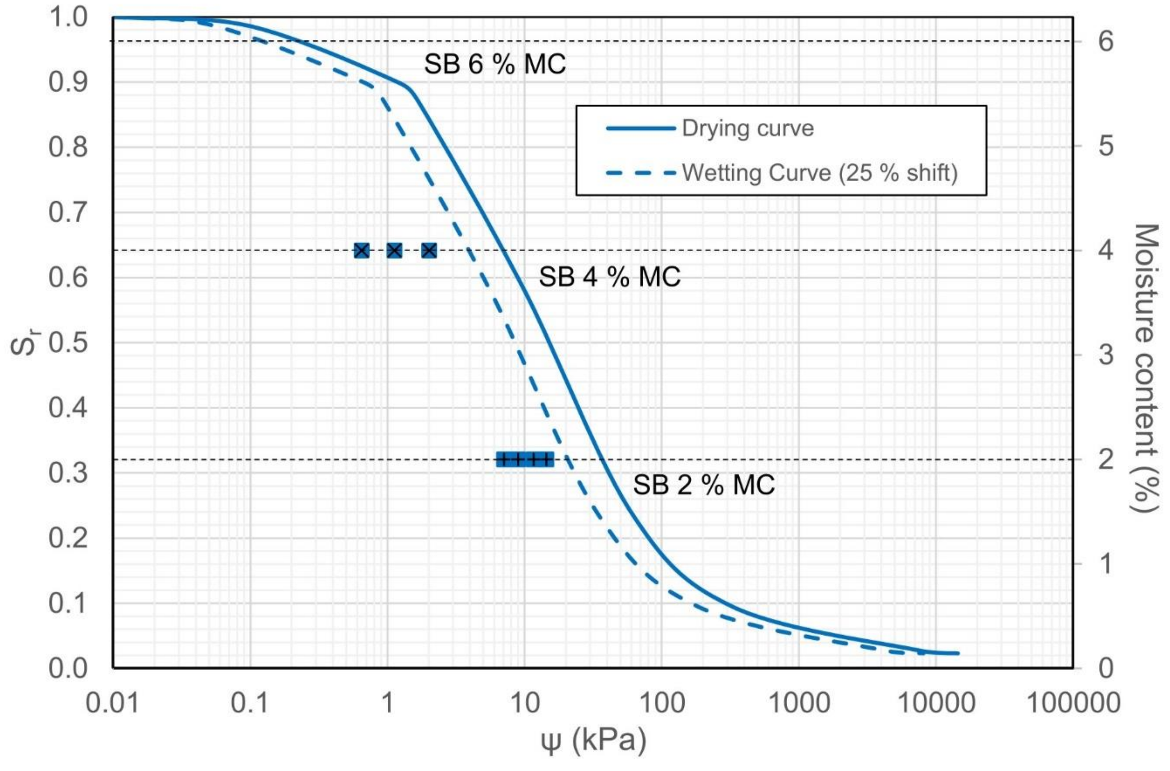

Figure 9: Comparison of measured suction values post-test with the SWRC of the subballast material (SB)

A direct comparison of the suctions is useful for visualising the different rates of change of suction in the 2 materials as a function of moisture content. Figure 10 presents typical trends in pore pressures present at the different degrees of saturation fitted by a power function. The figure shows the increase in suction associated with the decrease in the saturation of the materials. The suctions in the AB material is clearly more sensitive to changes in S_r compared to the SB material. The large difference in suctions in the AB material (1 kPa - 95 kPa) over a relatively small range of S_r values (0.61 - 0.88) is related to the difference in the total deformation observed in the AB material as described in the following section.

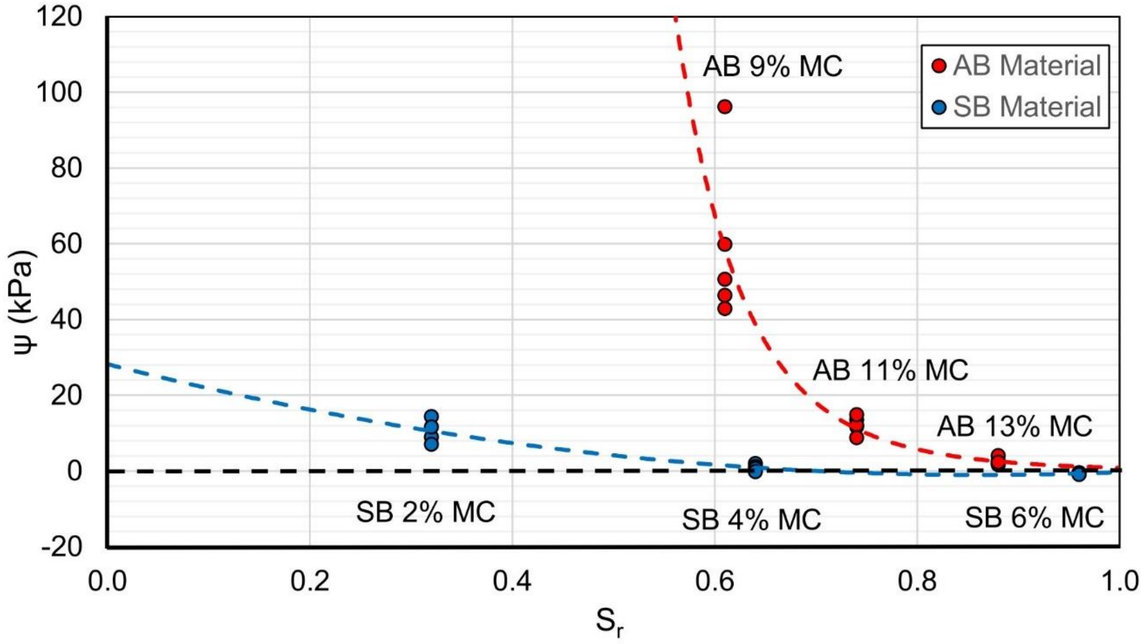

Figure 10: Summary of soil suctions in subgrade (AB) and subballast (SB) materials as a function of degree of saturation (S_r)

3.2. Deformation behaviour

This section explores the effect of loading frequency and moisture content on the deformation of the respective materials. To define a failure criterion, the recommendation by Li and Selig (1998) was used. This method states that formation failure has occurred once permanent deformation exceeds 2 % strain. Therefore, in the 200 mm deep formation used in this study, a permanent deformation of 4 mm corresponds to 2 % strain. The Li and Selig (1998) method and its associated failure criterion are applicable to subgrade materials for design purposes. It was however selected as a common failure criterion to permit the comparison of the relative deformability of the subballast and subgrade materials. The maximum loaded deformation of materials AB and SB at different moisture contents are presented in Figure 11 and Figure 12 as a function of cumulative load cycles. In the AB 13 % MC material, the 2 % strain limit was exceeded during the Stage 1 loading at 0.25 Hz. In both the AB 9 % MC and AB 11 % MC materials this failure criterion was not exceeded through all 4 loading stages.

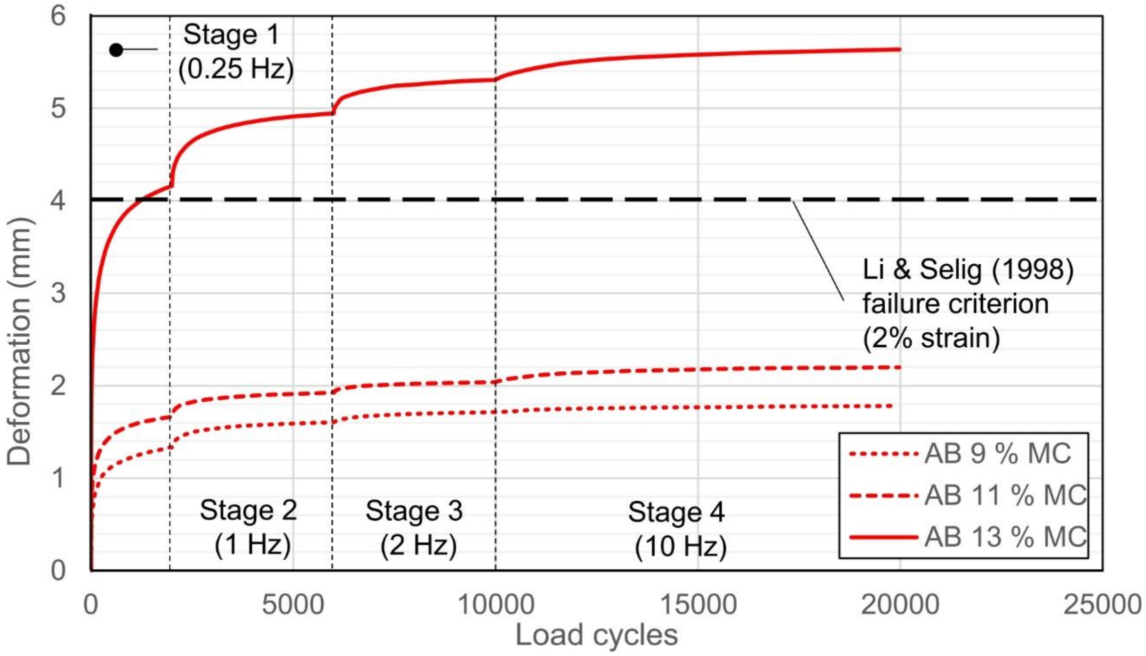

Figure 11: Subgrade (AB) material vertical deformation during testing

Figure 12 presents the permanent deformation of the SB material, as well as the adopted failure criterion of 4 mm. Firstly, it is notable that the deformation does not exceed 3 mm, and therefore is not considered to have failed. This was expected, as the SB material is designed to be stronger than the underlying AB material layer in order to dissipate loads from trains to the weaker underlying layers. Secondly, the SB material also shows slightly higher deformation at higher moisture contents.

It is clear from Figure 11 and Figure 12 that increases in moisture content and loading frequency are associated with an increase in the deformation of both materials.

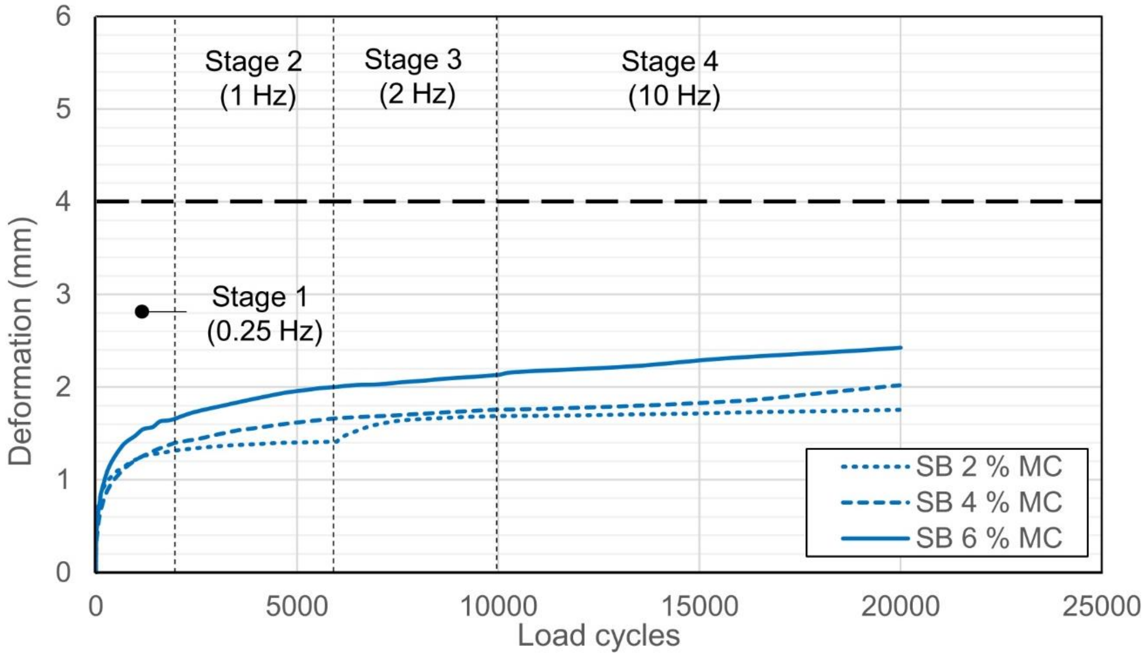

Figure 12: Subballast (SB) material vertical deformation during testing

To further demonstrate deformation trends during different loading stages, the deformations occurring in each loading stage were expressed as a percentage of the total deformation for that test. These are referred to as *deformation proportions*. This method allowed deformations in the different stages to be directly compared to each other. Figure 13 and Figure 14 present these deformation proportions per loading stage for the AB and SB materials respectively. Both the AB and SB materials show a diminishing contribution of each successive stage to the cumulative deformation. For both materials, the majority of the cumulative deformation occurred in the first stage (0.25 Hz). Stage 1 loading was responsible for 73 % - 78 % and 68 % - 70% of the cumulative deformation for materials AB and SB respectively. An unexpectedly high permanent deformation in SB 2% MC material occurred during Stage 3. It is believed that this might be the result of a combination of moisture state dependent deformation and vibratory compaction deformation due to the increase in the loading frequency.

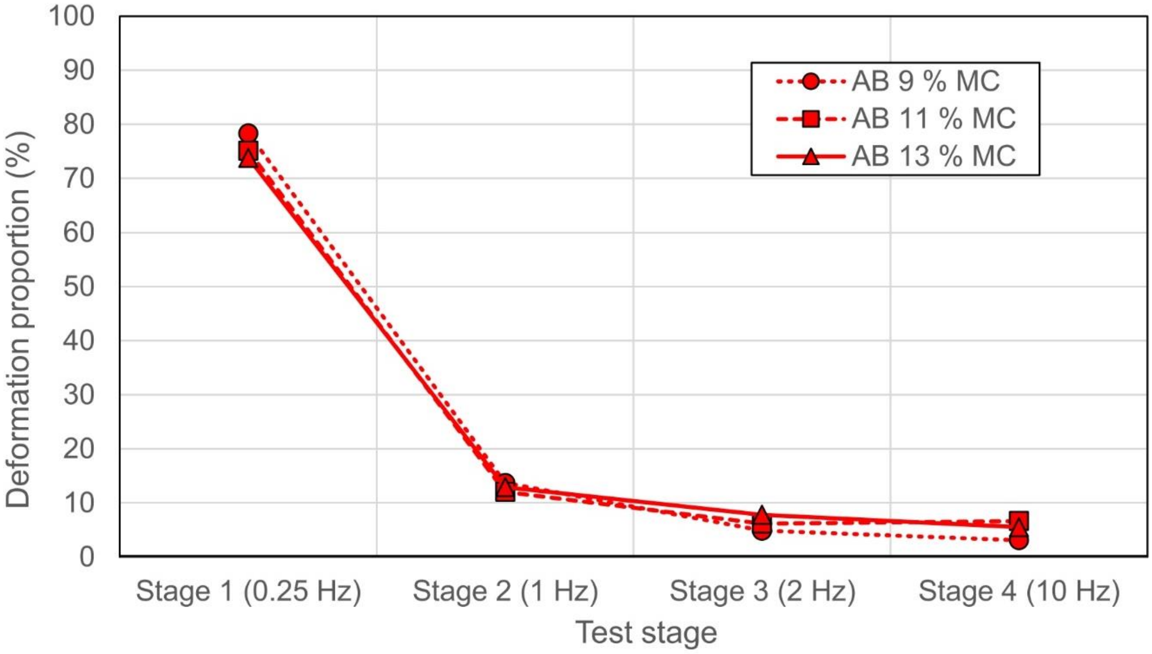

Figure 13: Distribution of deformation proportions across loading stages for subgrade (AB) material

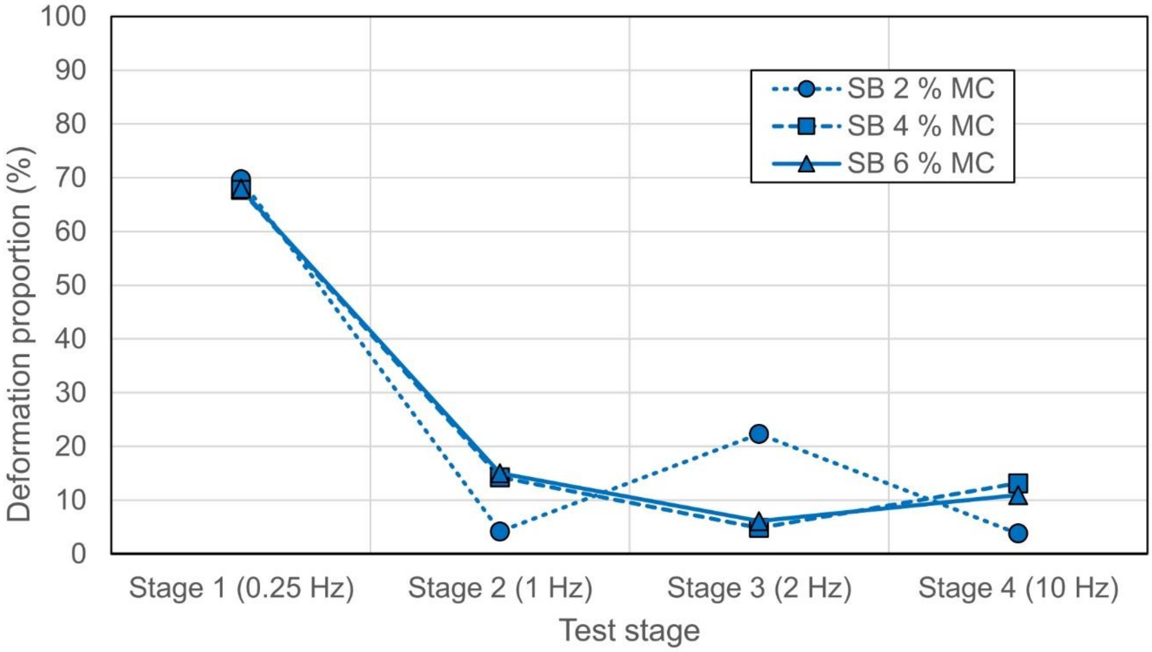

Figure 14: Distribution of deformation proportions across loading stages for subballast (SB) material

It is worth noting that while the analysis of proportions of deformations suggests that the AB material did not undergo vibratory compaction, plotting the rate of deformation (RoD) against load cycles indicates that the vibratory compaction in the AB material was not negligible. Figure 15 shows that while Stages 1, 2 and 3 required 500 - 1500 loading cycles to reach a RoD that approached 0 mm/s, Stage 4 required 1000 - 4000 loading cycles to reach similar values. This points to the fact that on a cycle to cycle basis, the Stage 4 loading frequency (10 Hz) was able to sustain non-negligible RoDs that were greater than the previous stages. This is despite the fact that significant densification had already occurred by the time Stage 4 had started.

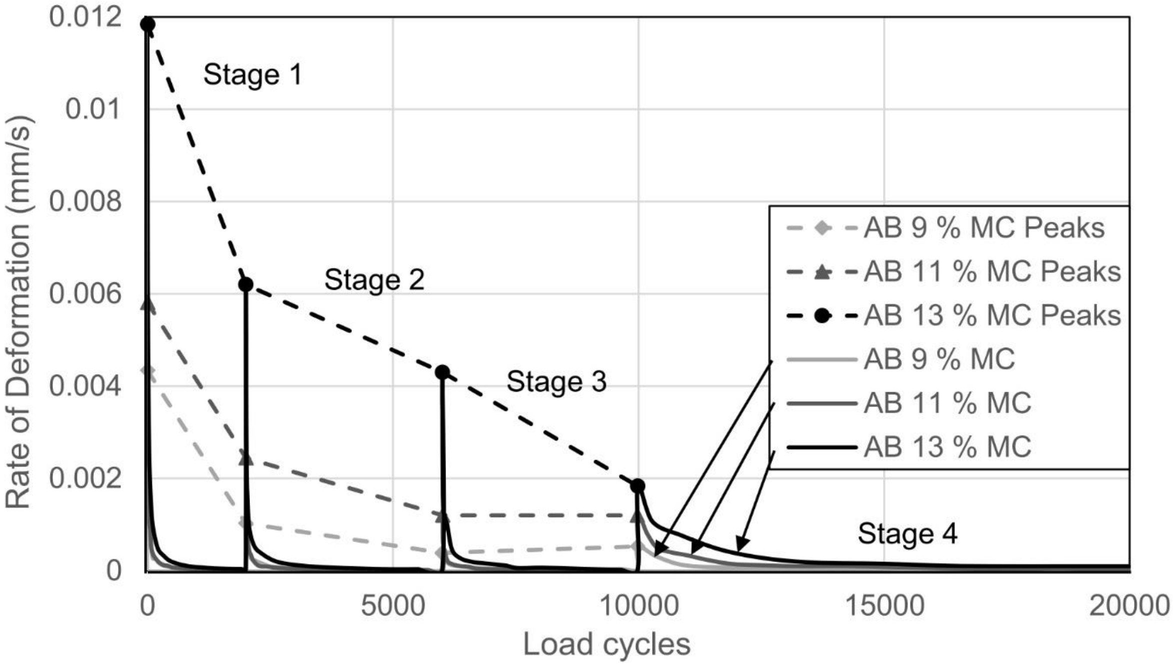

Figure 15: Rate of deformation of subgrade (AB) material across all loading stages

These findings have implications for accelerated laboratory testing of formation materials. In railway engineering it is common to test deformation characteristics of ballast layers at high frequencies (≥10 Hz) in the laboratory (Du Plooy ,2015). The results presented above suggest that when testing formation materials, accelerated testing may lead to unrealistic deformation patterns if the frequency at which the material will begin to undergo vibratory compaction is not considered. The finer AB material was less prone to this vibratory compaction behaviour as evidenced by the consistency of deformation proportions across moisture contents in Figure 13. This view is supported by industry, whereby it is recommended that vibratory compaction methods are `not suited to materials with high silt and/or clay content' (Franki, 2008). The SB material had 5 % total clay and silt content while the AB material contained 18 %. Therefore, the AB material is less susceptible to this behaviour. However, Figure 15 showed that vibratory compaction in materials with higher fines content may still occur at higher frequencies, providing further justification to be cautious when performing accelerated testing at high frequencies on formation materials.

The effect of moisture changes on the deformation of the materials under cyclic loading is presented in Figure 16 and Figure 17 for the AB and SB materials respectively. The relative increase in deformation between the AB 11% MC formation and the AB 13% MC material was significantly greater than the increase in deformation between the AB 9% MC material and AB 11% MC material. Deformation behaviour in the AB material was therefore found to be non-linear in relation to the moisture content. This is in agreement with findings from Vorster et al. (2017) who found that an increase in moisture content caused an incremental increase in the deformation until a certain moisture content was exceeded in materials with an appreciable fines content. Large deformations will occur past this critical moisture condition, given the same material and loading conditions. In comparison to the AB material, the SB material shows a gradual increase in deformation with increasing moisture content. There is however no evidence of the aforementioned critical moisture condition beyond which large deformations will occur.

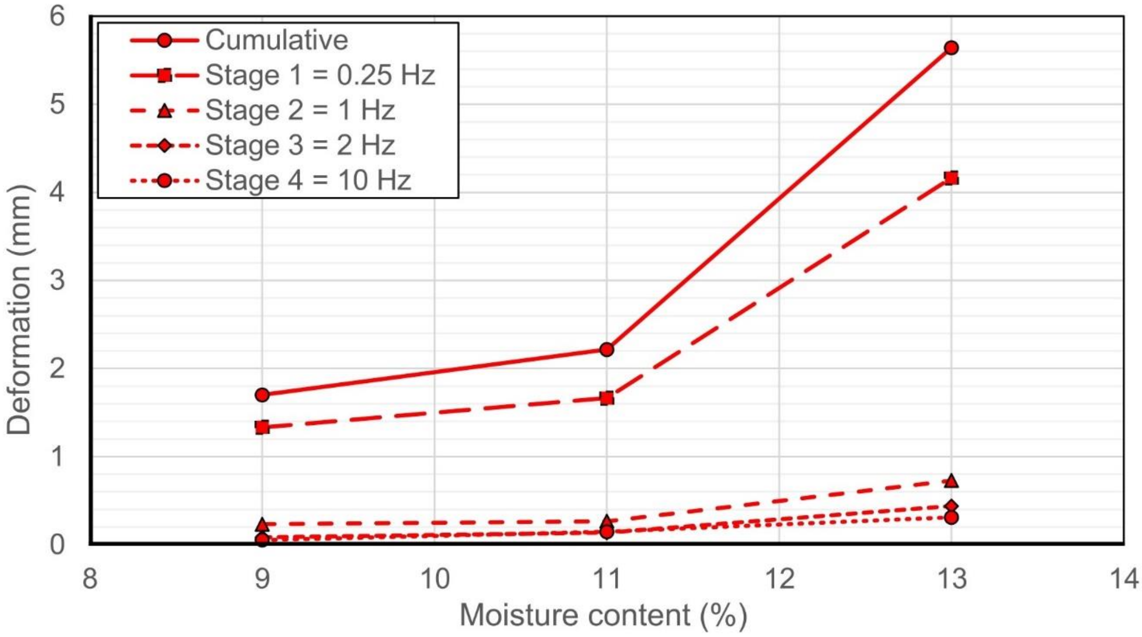

Figure 16: Permanent deformation of subgrade (AB) material as a function of moisture content at different testing stages

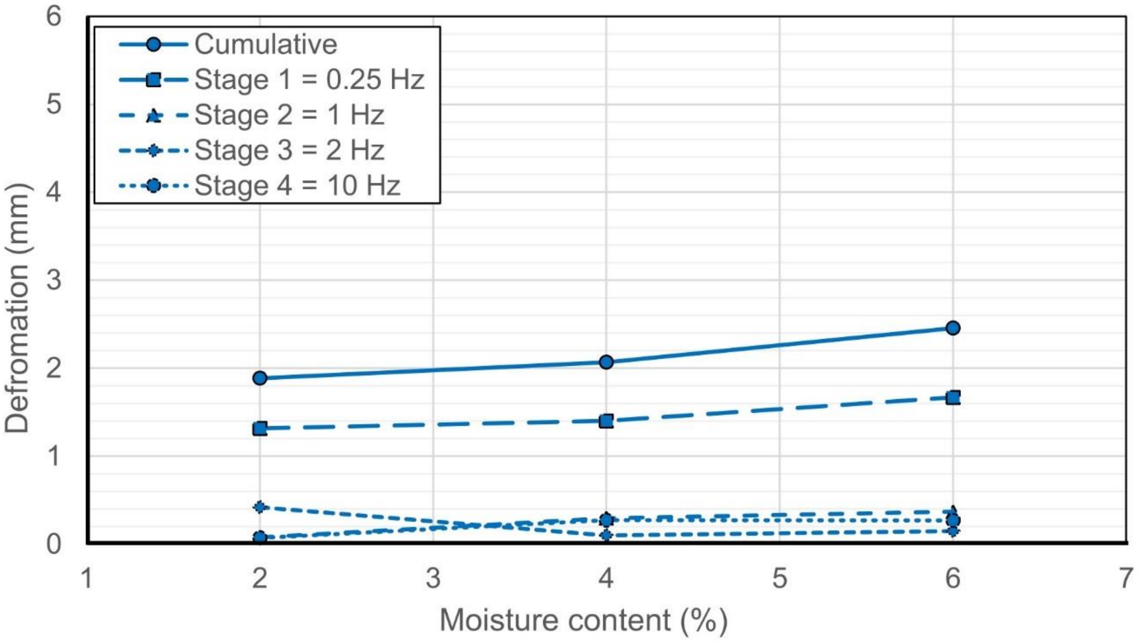

Figure 17: Permanent deformation of subballast (SB) material as a function of moisture content at different testing stages

The overview of deformations in the AB and SB materials presented in this section revealed that the effect of moisture content change on deformation was fundamentally different for both materials. The presence of significant fines in the AB material caused a non-linear increase in deformation with increase in moisture content (Figure 16). In comparison, the change in deformation with moisture content is approximately linear for the SB material (Figure 17). This behaviour may be related to the SWRC which shows little suction and hence strength change over the considered moisture content range for SB materials and more significant variation in the case of the AB material. The implication of this is twofold. Firstly, it is important that AB materials are protected against moisture changes by providing adequate drainage and a free-draining SB layer constructed above the AB layer. These steps will prevent an accumulation of moisture that could lead to wetting collapse. Secondly, the SB material is only differentiated from the AB material by its relative lack of fines. Should the SB material accumulate clayey and silty fines from material breakage and contamination from outside sources, the SB material could also experience larger deformations.

The cumulative deformation of the AB and SB materials as presented in Figure 16 andFigure 17 are summarised in Figure 18 as total deformation of the respective materials. Figure 18 can be viewed as complimentary to Figure 10. Considered together, these figures show how material deformability and change in soil suctions are directly related. It is important to consider the change in deformations in the two materials as a function of moisture content.

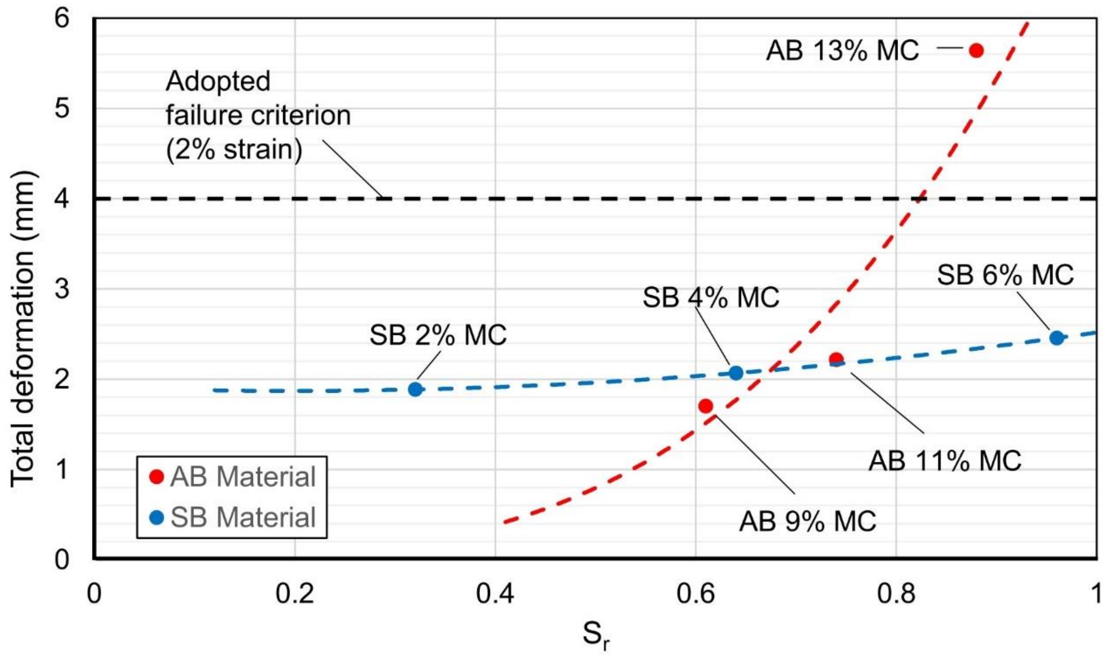

Figure 18: Comparison of total deformation of the subgrade (AB) and subballast (SB) materials against degree of saturation (Sr)

3.3. Change in material deformability due to soil suction

Increased moisture content was associated with increased deformation in both the AB and SB materials, but to different degrees. As a comparison of Figure 10 and Figure 18 showed, an increase in moisture content in the SB material caused an almost linear increase in deformation, while an increase in moisture content in the AB material showed a proportionally larger deformation at higher values of moisture content as plastic collapse occurred.

In this study the deformability of the material at a given moisture state was taken as an indirect indication of its strength in relation to other moisture states. Figure 19 shows a direct comparison of these values of deformability and a clustered bar chart of suctions found in the respective materials. The comparison illustrates the strengthening effect of suctions in the AB material, as well as the difference in suction and deformation behaviour between the AB and SB materials.

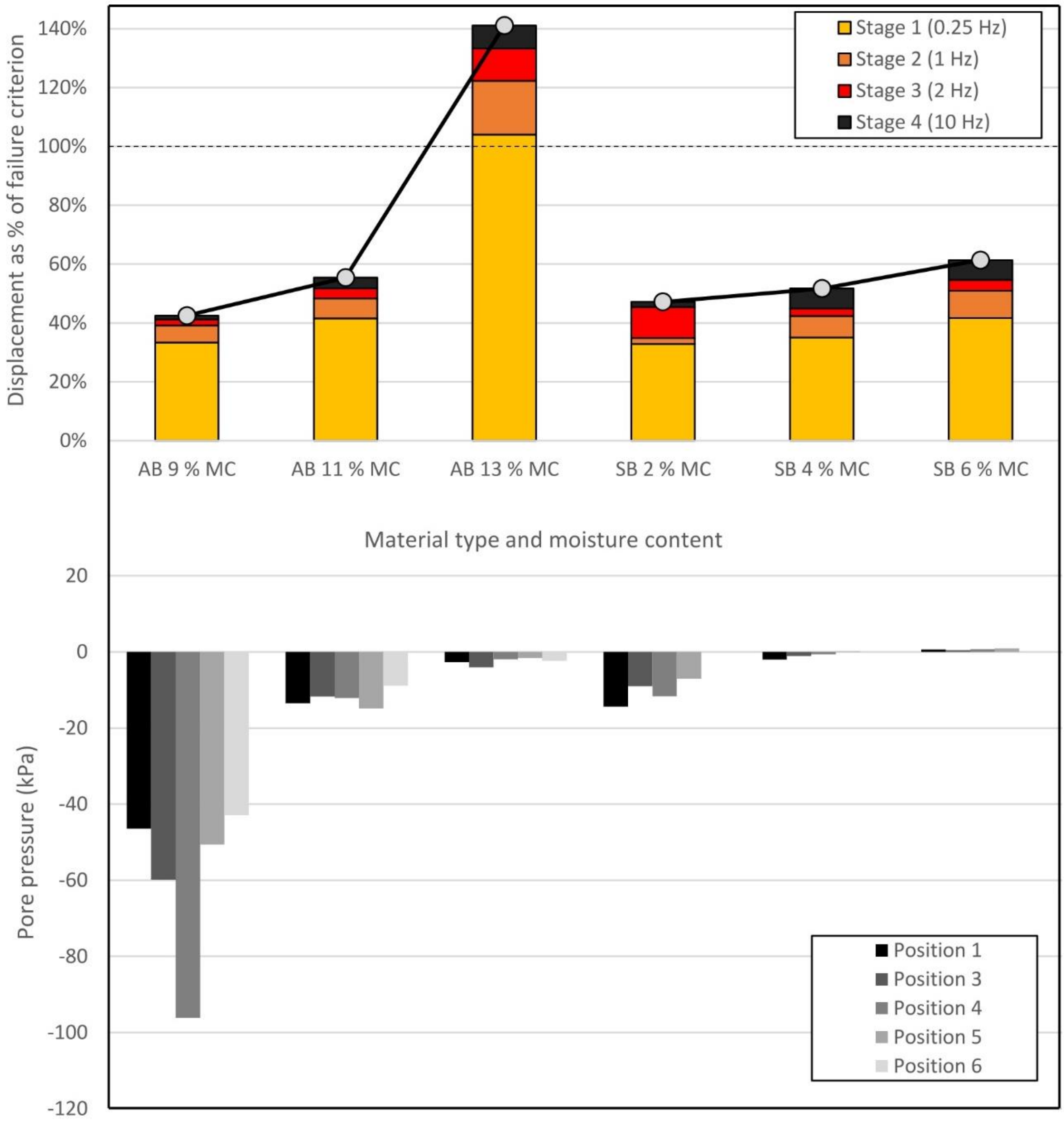

Figure 19: Comparison of soil deformability with changing moisture content (top) and soil suctions of tested materials (bottom)

Deformations of 141 % of the adopted failure criterion were found under low suction conditions (3 kPa - 5 kPa) in the AB material. A slight increase in suctions up to 10 kPa - 15 kPa however resulted in a marked decrease in deformation to 55 % of the failure criterion. Further drying showed that the AB material could generate higher suctions to the magnitude of 40 kPa - 100 kPa. These suctions caused a further strengthening/stiffening of the material to 43 % of the failure criterion. The greatest increase in performance was noted between 5 kPa and 15 kPa, wherein the deformation decreased by 90 % of the failure criterion.

The SB material reached a maximum deformation of 61 % of the failure criterion in effectively saturated conditions (all pore pressures measured were positive). When the degree of saturation decreased, suctions in the range of 7 kPa - 14 kPa were generated, leading to a decreased deformation of 47 % of the failure criterion. The SB material showed low suctions when compared to the AB material, leading to comparatively little strength gain between the wettest and driest moisture states tested. The AB material at its driest state (AB 9 % MC or $S_r = 0.61$) was sufficiently strengthened by high suctions to deform less than the driest SB material (SB 2 % MC or $S_r = 0.32$).

These findings point to the fact that suction and deformation testing on the AB material yields the most potential for improvement in current design methods. Both extremes of the suction range have implications for the deformation properties of AB (subgrade) materials. High S_r values lead to accelerated deformation, while low S_r values lead to significantly higher suctions than found in the SB (subballast) material, thereby strengthening the material through suction stress. The granular SB materials pose a greater challenge in terms of accurately measuring suctions (due to the low suction magnitude) and moisture content and provide less valuable information even if measured correctly. The relatively small magnitude of suctions present in the SB material means that suctions have a small impact on soil strength when compared to the suctions generated in the AB material. This is demonstrated by the near constant deformation of SB material with an increase in moisture content as opposed to the non-linear increase in deformation of AB material with moisture content.

4. Conclusions

This generic study was aimed at demonstrating the effect of soil suction on the relative deformation behaviour of two common South African railway materials. A well-drained, relatively coarse grained subballast (SB) material and less well-drained finer grained subgrade (AB) material were tested under different moisture conditions and loading frequencies in a box test. The relative deformability of the chosen materials in the box tests is viewed as indicative of the material strength as would be found in-situ, despite the different stress states in the box and in-situ environments.

The following conclusions are presented:

- For the SB material, deformation was found to increase approximately linearly with MC and the effect of MC was found to be small. No acceleration in deformation of the SB occurred as the moisture content increased. Suction magnitudes measured in the SB material were small (<10 kPa) or absent and did not play a significant role in material behaviour.
- The AB material showed a greater range of both positive and negative pore pressures during testing depending on the moisture content. Once a critical moisture content value was exceeded, rapid deformation ensued, resulting in non-linear deformation with further load cycles. Elevated suctions at low moisture content resulted in high strength that was substantially reduced as the moisture content increased, resulting in increasing deformation. This was also reported by Vorster et al. (2017) who showed rapid deformation past a critical moisture content value in railway embankment materials. This behaviour is closely related to the suction response of this material as demonstrated by the SWRC.

- The AB material experienced failure in terms of the adopted failure criterion as moisture content increased while the SB material did not reach failure. This can again be linked to the suction response as a result of moisture change as described by the material's SWRC.
- During cycling loading, the majority of deformation occurred in the first loading stage (0.25 Hz loading frequency) as the material densified. Relatively large deformation occurred despite the fact that the cyclic loading stages were preceded by a period of static loading at the same load magnitude. This agrees with findings by Vorster et al. (2017) showing that formations that are stable under static loading will continue to deform under cyclic loading of the same load magnitude.
- The AB material showed a consistent deformation proportion between load stages independent of the moisture state, indicating that there is a relationship between the deformation proportion and the loading frequency for that material.
- Higher rates of deformation at increased loading frequencies (10 Hz) in both materials tested suggest that accelerated testing methods (i.e. application of higher frequencies to achieve a given number of load cycles) are not suitable for formation materials without adequately accounting for this frequency-dependent effect.

In terms of the effects of climate change, the results show that the performance of the well-drained SB materials are unlikely to be detrimentally affected, while the performance of the less well-drained finer grained AB materials could be affected. The deformation data from the box tests suggest that an increase in in-situ moisture content is likely to result in a loss of shear strength and increased deformation in the AB material. It is therefore recommended that the pore pressure-strength relationship of the AB material be considered when assessing the impact of future climate change. This recommendation applies to embankment fill material as reported by Vorster et al. (2017) and is likely to also be applicable to poorly drained materials in general. A further study into in-situ suction monitoring of a railway formation with seasonal weather changes is also recommended, as it may be valuable to examine fluctuation in soil suctions between the driest and wettest parts of the year as a result of rainfall infiltration.

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