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Reliability of using laboratory-determined soil water characteristic data for mine waste cover design

D.J. Williams *School of Civil Engineering, The University of Queensland, Australia*

T.K. Rohde *School of Civil Engineering, The University of Queensland, Australia*

Abstract

Soil water characteristic curves (SWCCs) used for the design of covers over mine wastes, are typically determined in the laboratory by performing drying tests on samples in a Tempe cell. In some cases, re-wetting is also carried out. The advantage of using drying tests is that they are carried out from the saturated state at a given sample test density, so that there is some chance of obtaining repeatable results. However, re-wetting is carried out from the arbitrary end-point of a drying test, giving a different re-wetting curve from each of these points. SWCC data may also be measured directly in the laboratory and in the field. Depending on the uniformity, stress history, structure and any cementation of soils under laboratory or field conditions, their SWCC data may be very different from the SWCC data collected after sample preparation and saturation for laboratory Tempe cell drying testing. The paper presents in situ, laboratory and field SWCC data for mine waste covers that highlight the strong influence that structure, cementation, sampling disturbance, sample preparation, saturation, uniformity, construction control and stress history can have on the data. They cast some doubt on the design of mine waste covers based solely on the use of laboratory-determined SWCCs.

1 Introduction

Other researchers have noted the variance between laboratory and field measurements of soil water characteristic data, e.g. recently in relation to soil covers (Shurniak, 2003; INAP, 2003). The paper illustrates this further by describing mine waste cover case studies from Queensland Energy Resources Ltd (QERL) in Queensland, Kidston Gold Mine in Queensland and Cadia Hill Gold Mine in New South Wales, Australia. For QERL, the performance of an instrumented thick mono-layer cover constructed from in situ overconsolidation and weakly cemented materials is described. The focus of the Kidston and Cadia case studies is the performance of instrumented store/release covers. The field instrumentation comprises time domain reflectometry (TDR) moisture and matric suction sensors installed in the covers, in addition to a local weather station measuring rainfall, air temperature, relative humidity, solar radiation, and wind speed and direction.

2 QERL's thick mono-layer cover

2.1 Climatic setting

QERL is located in a hot, humid summer climate. The site experiences a long-term average annual rainfall of about 880 mm, spread throughout the year, with higher rainfall during the summer months of December to February (Australian Bureau of Meteorology). The average annual number of rainfall days is about 66. Average annual pan evaporation is about 1,600 mm, while annual average actual evapotranspiration is about 800 mm (91% of rainfall, according to the Australian Bureau of Meteorology). The average annual daily temperature ranges from 18 to 28°C. Over the last 5 years, annual rainfall has averaged only about 400 mm.

2.2 Testing of cover materials

The QERL site is underlain by overconsolidated Quaternary alluvium and Tertiary age weakly cemented weathered shale, which were selected for use in a 6 m thick mono-layer cover over spent oil shale. Testing of the alluvium and weathered rock included gravimetric moisture content (mass of water/mass of solids, expressed as a per cent), total suction, field density and electrical conductivity determinations on borehole samples, and laboratory drying SWCC and saturated hydraulic conductivity testing (Williams et al., 2006a). Total suctions were obtained using a psychrometer, osmotic suctions were obtained from the measured electrical conductivity values, and matric suctions were obtained by subtracting the osmotic suctions from the total suctions.

Figures 1 and 2 show the measured gravimetric moisture content and estimated degree of saturation profiles with depth, respectively. Figure 1 shows high gravimetric moisture contents at about 20 m depth, corresponding to the boundary between a saturated gravel layer and an underlying clay layer. Figure 2 shows full saturation at 15–20 m depth, at about 80 m depth and below about 130 m depth, indicating perched water tables at about 15–20 m and 80 m depth, above the permanent groundwater table at about 130 m depth.

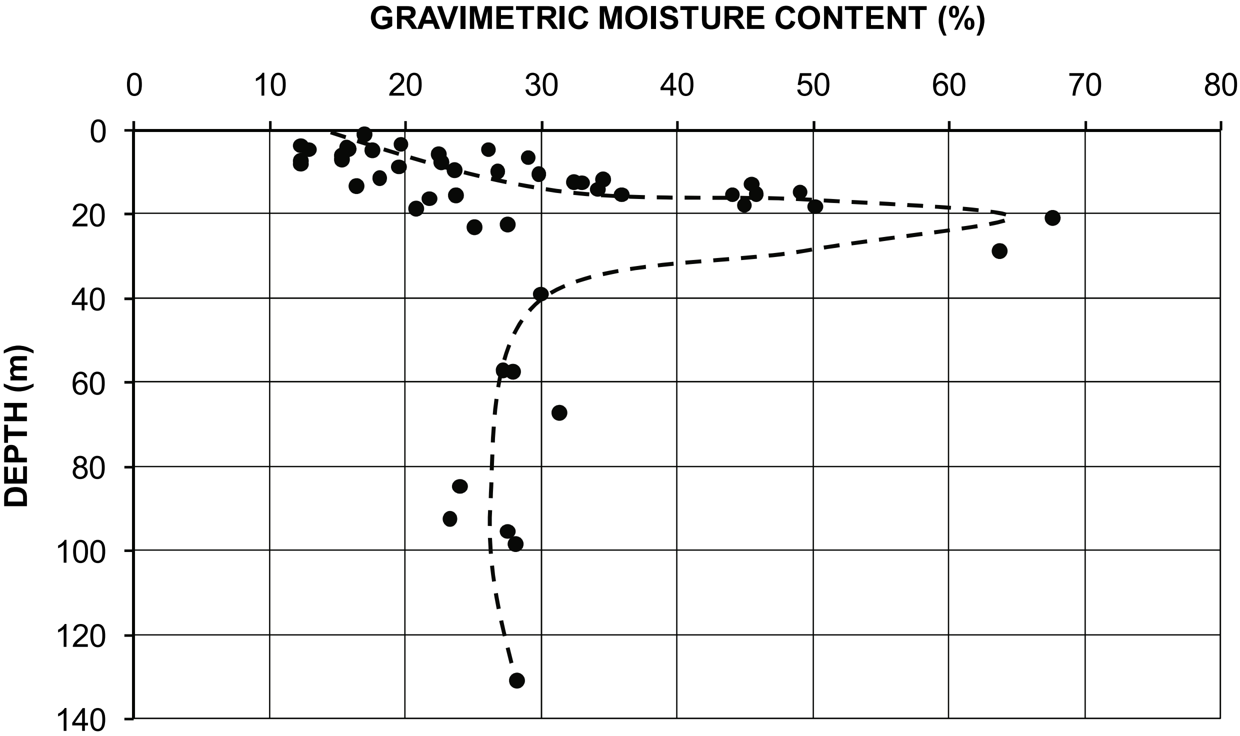

Figure 1 Gravimetric moisture content depth profile for QERL overburden and weathered rock

Figure 3 shows the gravimetric moisture content versus matric suction data, which includes measured drying data and the estimated SWCC for the in situ overburden and weathered rock, field data for the same material re-handled to form a cover, and laboratory drying SWCCs. The moisture data are plotted in terms of gravimetric moisture content, rather than the more conventional volumetric water content measured in the laboratory Tempe cell, since all of the field moisture data were measured gravimetrically.

Figure 3 demonstrates the dramatic effect of laboratory disturbance of the overconsolidated alluvium and weakly cemented weathered shale on their ‘stiff’ in situ unsaturated behaviour. Matric suctions maintain high values in situ, generally in excess of 1,000 kPa, even at high gravimetric moisture contents, while laboratory sample preparation and saturation destroy these high suctions. A very new cover of the same material recorded intermediate matric suctions at typical field moisture contents, while ageing effects restored the high in situ matric suctions for older covers.

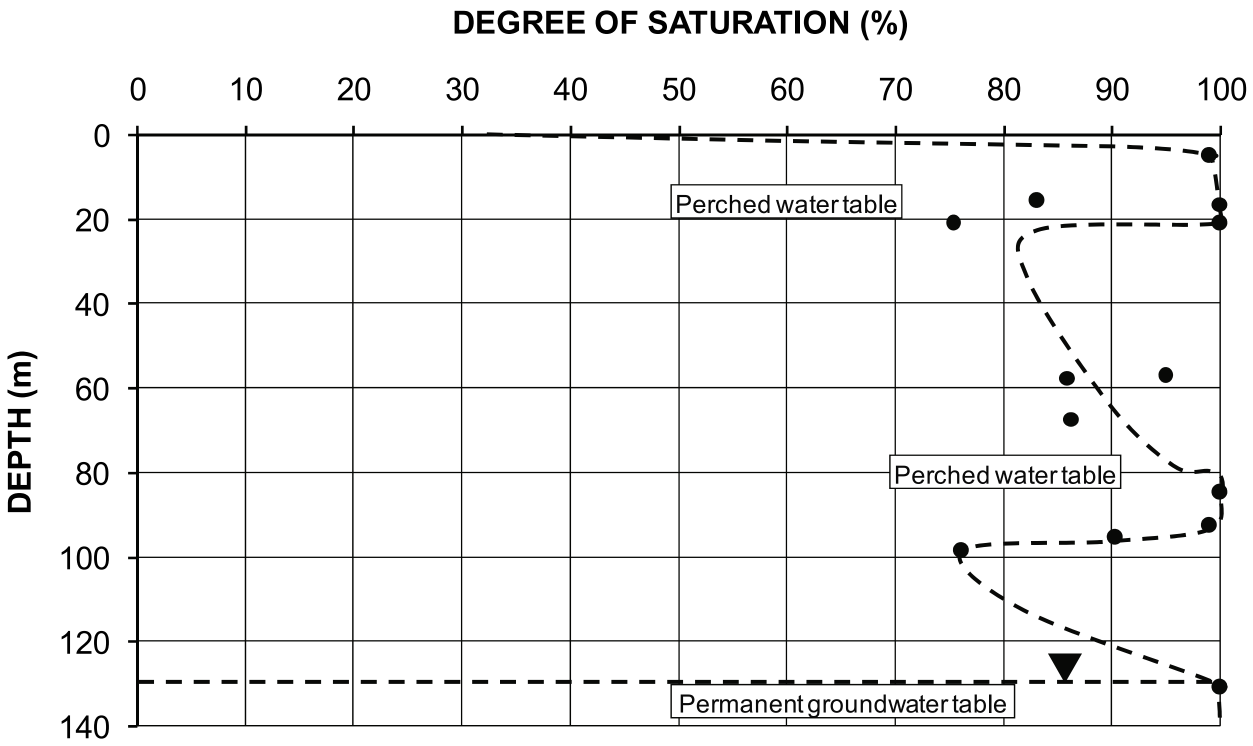

Figure 2 Degree of saturation depth profile for QERL overburden and weathered rock

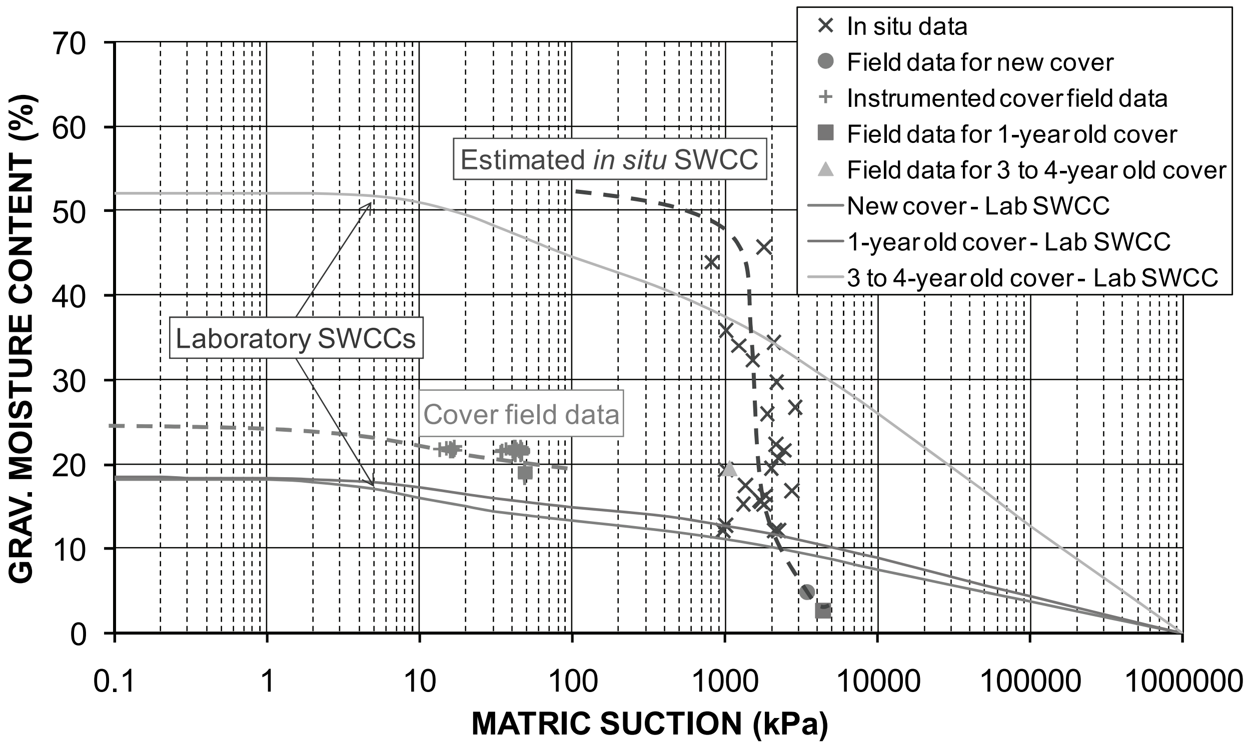

Figure 3 Comparison between field and laboratory-determined SWCC data for QERL overburden and weathered rock

3 Kidston's store/release cover

3.1 Climatic setting

Kidston Gold Mine is located in a dry sub-tropical climate. The site experiences a long-term average annual rainfall of about 700 mm, which falls mainly in intense storms over the 3 month summer from about December to February or March (Australian Bureau of Meteorology). The high intensity of the storms results in high runoff coefficients to the ephemeral streams. The average annual number of rainfall days is about 45. Average annual pan evaporation is about 2,100 mm, while annual average actual evapotranspiration is about 600 mm (86% of rainfall, according to the Australian Bureau of Meteorology). The average annual daily temperature ranges from 18–30°C. Over the last 10 years, annual rainfall has averaged only about 550 mm.

3.2 Cover details

Kidston employed store/release covers (Williams et al., 1997) on the flat tops of their potentially acid generating waste rock dumps. The store/release covers comprised a 0.5 m thick compacted clayey sealing layer (comprising clayey mine overburden) overlain by a minimum 1.5 m thick, loose, rocky soil mulch layer (comprising more coarse mine overburden), which was left mounded, and was vegetated with native shrubs, eucalypts and grasses. The purpose of the sealing layer was to hold-up rainfall infiltration into the mulch, to be removed through evapotranspiration. The store/release cover was instrumented with volumetric water content and matric suction sensors, which have been monitored for over 10 years (Williams et al., 2006b).

3.3 Selected field SWCC data

The volumetric water contents and matric suctions monitored from 2000 to 2002 at selected depths within Kidston's store/release cover are combined in Figure 4. Figure 4 shows that the seasonal drying and wetting cycles to which Kidston's store/release cover is subjected results in a cycling of the moisture state of the store/release cover. In addition, the upper part of the cover remains generally drier and hence at higher matric suction than the lower parts of the cover, which generally trend increasingly wet with depth. The high, near-saturated (low matric suction) volumetric water contents at all depths indicate that all sensors were located in loose, rocky soil mulch cover material, rather than the underlying compacted sealing layer.

Figure 5 shows the volumetric water contents and matric suctions over 6 monthly intervals from 2000 to 2002 at 0.35 m depth. Figure 5 highlights that at 0.35 m depth, during the early life of the cover the unsaturated behaviour of the material is somewhat unstable, being affected by seasonal climatic conditions and physical changes to the cover. However, after a few years of seasonal drying and wetting cycles it stabilises and tracks a constant SWCC. It is apparent from Figure 4 that this is also generally the case at other depths within the cover.

3.4 Comparison of field and laboratory SWCC data

Figure 6 compares the field and laboratory-determined SWCCs. In Figure 6, the laboratory SWCC for compacted clay corresponds to the field curve at 1.77 m depth and the laboratory SWCC for rocky soil mulch corresponds to the other field curves.

Figure 6 shows that the laboratory-determined SWCCs provide poor estimates of the unsaturated behaviour of the materials in the field. In particular, the laboratory SWCC for the compacted clay is a very poor estimate of the field response of the sealing layer in the field and the laboratory SWCC for the rocky soil mulch is only a rough average of the responses of the rocky soil mulch in the field. Therefore, the design of a store/release cover based on laboratory-determined SWCCs would provide a poor estimate of field behaviour.

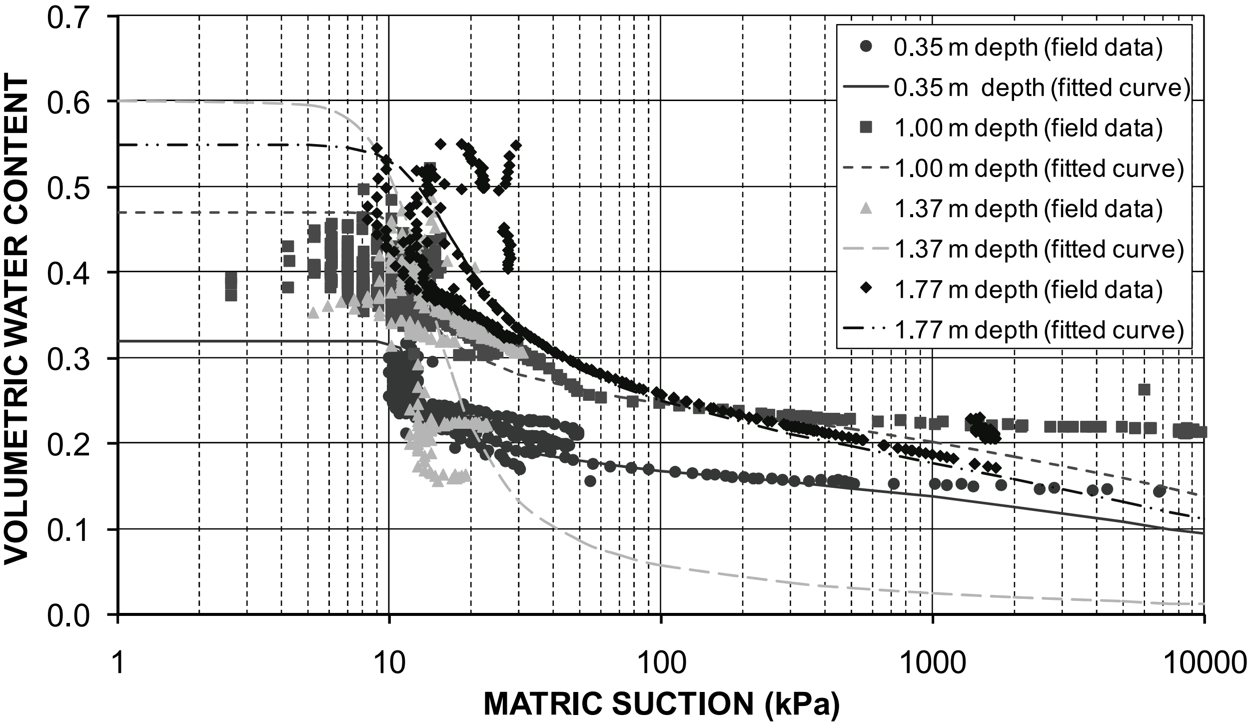

Figure 4 Combined volumetric water content and matric suction field data at selected depths within Kidston's store/release cover from 2000 to 2002

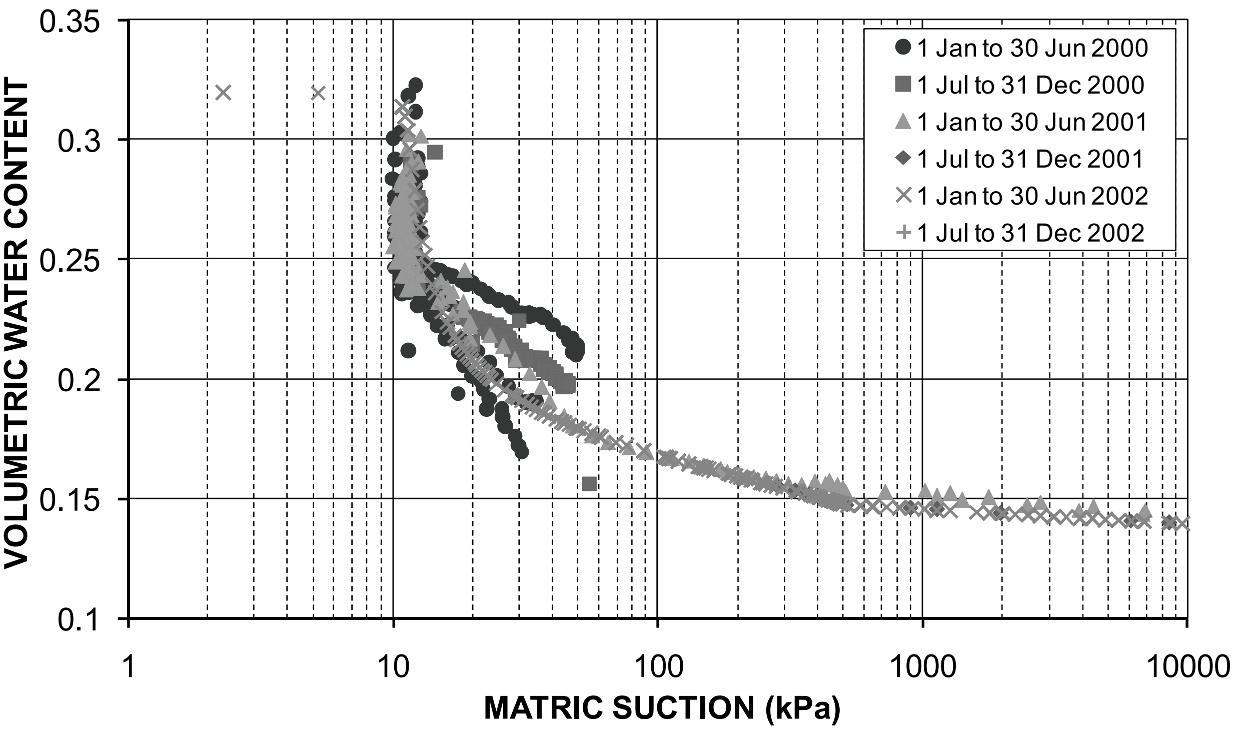

Figure 5 Six monthly volumetric water content and matric suction field data at 0.35 m depth within Kidston's store/release cover from 2000 to 2002

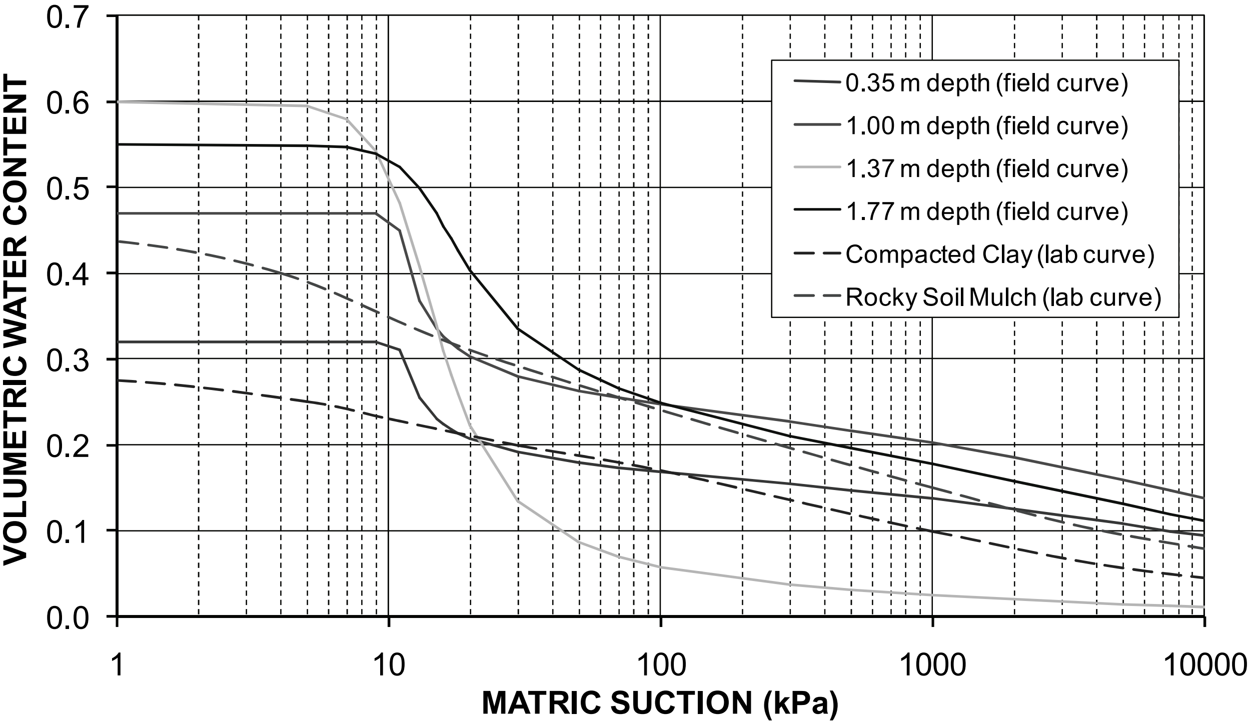

Figure 6 Comparison between field and laboratory-determined SWCCs for Kidston's store/release cover materials

4 Cadia's store/release cover

4.1 Climatic setting

Cadia Hill Gold Mine is located in a temperate climate. The site experiences a long-term average annual rainfall of about 886 mm, spread throughout the year, with somewhat higher rainfall during winter (Australian Bureau of Meteorology). The average annual number of rainfall days is about 94. Average annual pan evaporation is about 1,500 mm, while annual average actual evapotranspiration is about 580 mm (65% of rainfall, according to the Australian Bureau of Meteorology). The average annual daily temperature ranges from 6–20°C. Over the last 3 years, annual rainfall has averaged only about 770 mm.

4.2 Cover details

Cadia trialled store/release covers on the flat top of a 15 m high trial waste rock dump covering 0.7 ha. The cover trials made use of natural clays and waste materials, and were aimed at demonstrating the suitability of waste materials for this purpose in the absence of sufficient natural clays. Three alternative covers were trialled, each employing different nominal 0.5 m thick sealing layers; which were each overlain by a minimum 1.5 m of loose rocky soil mulch comprising a mixture of benign trafficked waste rock (nominally passing 100 mm) and tailings harvested from the tailings storage facility, in a nominal 5:1 dry mass ratio. The three sealing layers comprised: (i) compacted natural clays, (ii) a compacted 5:1 mixture of trafficked waste rock and harvested tailings (TWR/dry tailings) and, (iii) trafficked waste rock pushed into tailings slurry (TWR/wet tailings). The store/release trial covers were instrumented with volumetric water content and matric suction sensors, which have been monitored for over 2 years (Rohde, 2009).

4.3 Initial moisture state of trial covers

Figures 7 and 8 show, respectively, the initial volumetric water content and matric suction profiles with depth through the three trial covers.

Figure 7 shows that the rocky soil mulch moisture profiles above the compacted clay and TWR/wet tailings sealing layers are similar, while that above the compacted TWR/dry tailings sealing layer is highly variable. This is likely the result of poor mixing of the tailings into the trafficked waste rock. Figure 7 also highlights the drier as-placed state of the compacted clay seal, despite efforts to moisture condition the clay prior to compaction, and the expected very much wetter as-placed state of the TWR/wet tailings seal. Figure 8 shows similar matric suction profiles for the rocky soil mulch in all trials, while the compacted clay seal is much drier than the other two seals.

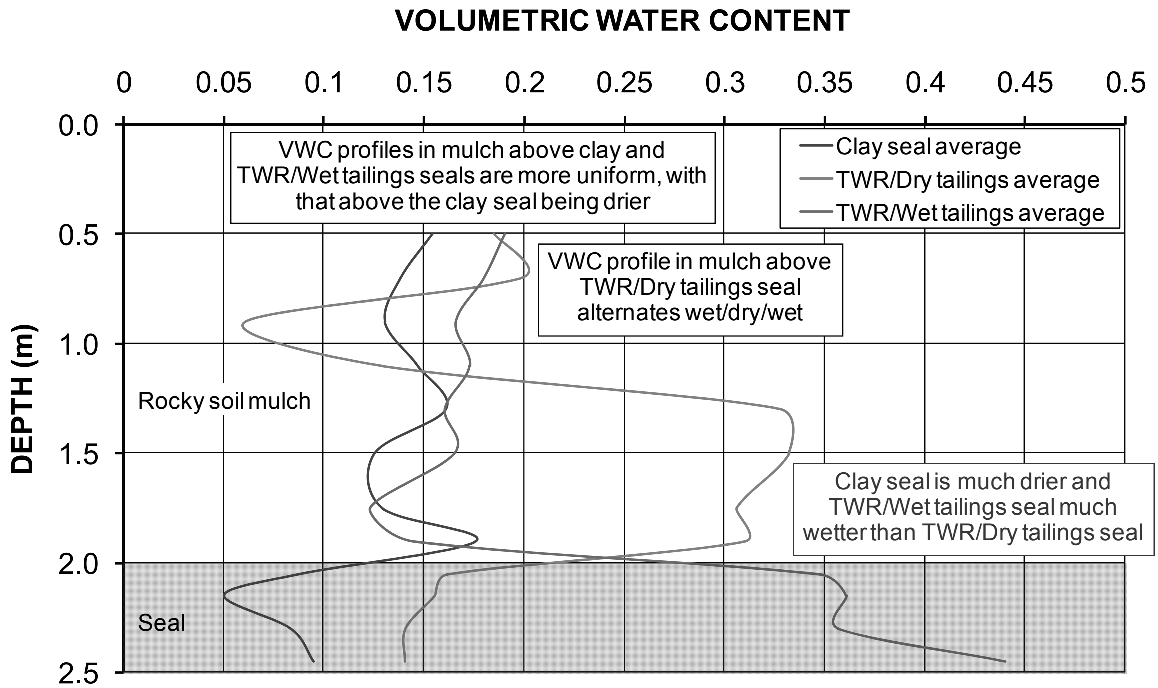

Figure 7 Initial volumetric water content profiles with depth through Cadia trial covers

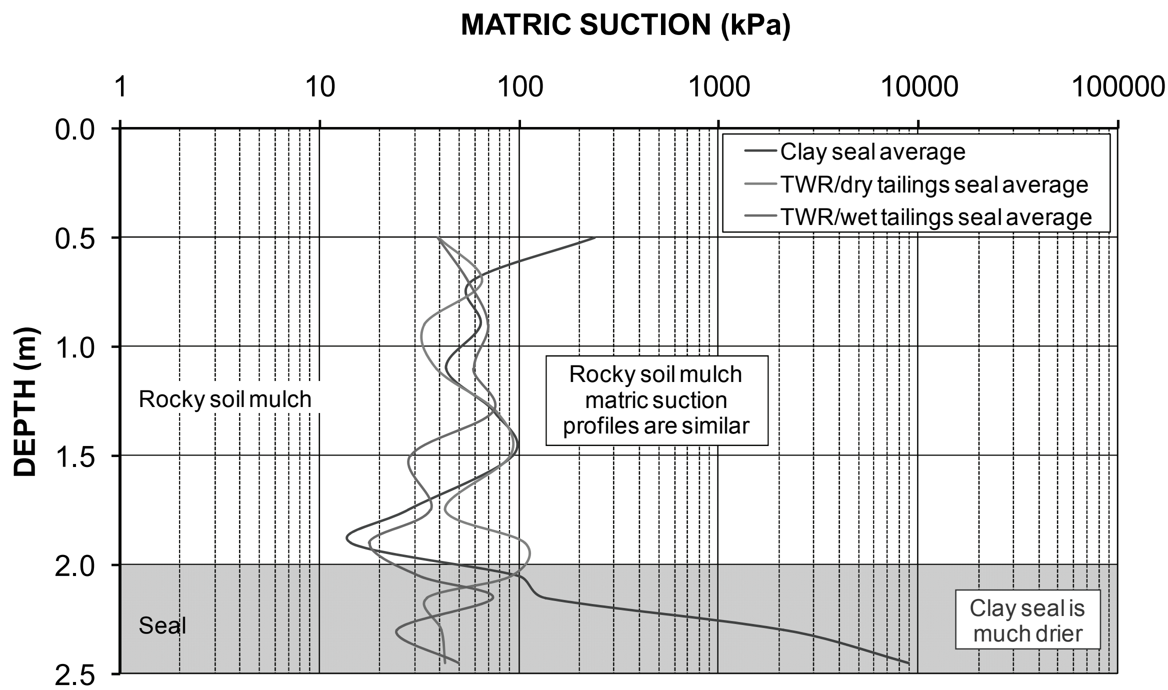

Figure 8 Initial matric suction profiles with depth through Cadia trial covers

4.4 Comparison of field and laboratory SWCC data

Figures 9, 10 and 11 show, respectively, the field SWCC data for the loose TWR/dry tailings rocky soil mulch above the compacted clay, TWR/dry tailings and TWR/wet tailings sealing layers. Also, shown is the laboratory fitted SWCC for the rocky soil mulch, scalped to pass 6.5 mm, and various fitted field SWCCs (fitted using the method of Freeland et al., 1994).

Figures 9 to 11 show a huge spread of field SWCC data within each cover and huge disparities between covers, for the same cover material. Clearly, there was a huge variation in the uniformity and relative density of the placed rocky soil mulch, both within covers and between covers, despite these being constructed using better quality control than would be typical of cover construction at mine sites. The laboratory fitted SWCC is at best a crude average of the field data.

Figures 12, 13 and 14 show, respectively, the field SWCC data for the compacted clay, compacted TWR/dry tailings and TWR/wet tailings sealing layers. The compacted TWR/dry tailings sealing layer achieved the most uniform field SWCC data (Figure 13), and the best fit between field and laboratory data. The compacted clay sealing layer field SWCC data are notable for their dryness (Figure 12, due to the dry initial state of the clay borrow), while the TWR/wet tailings SWCC data are notable for their wetness (Figure 14, due to the wet tailings).

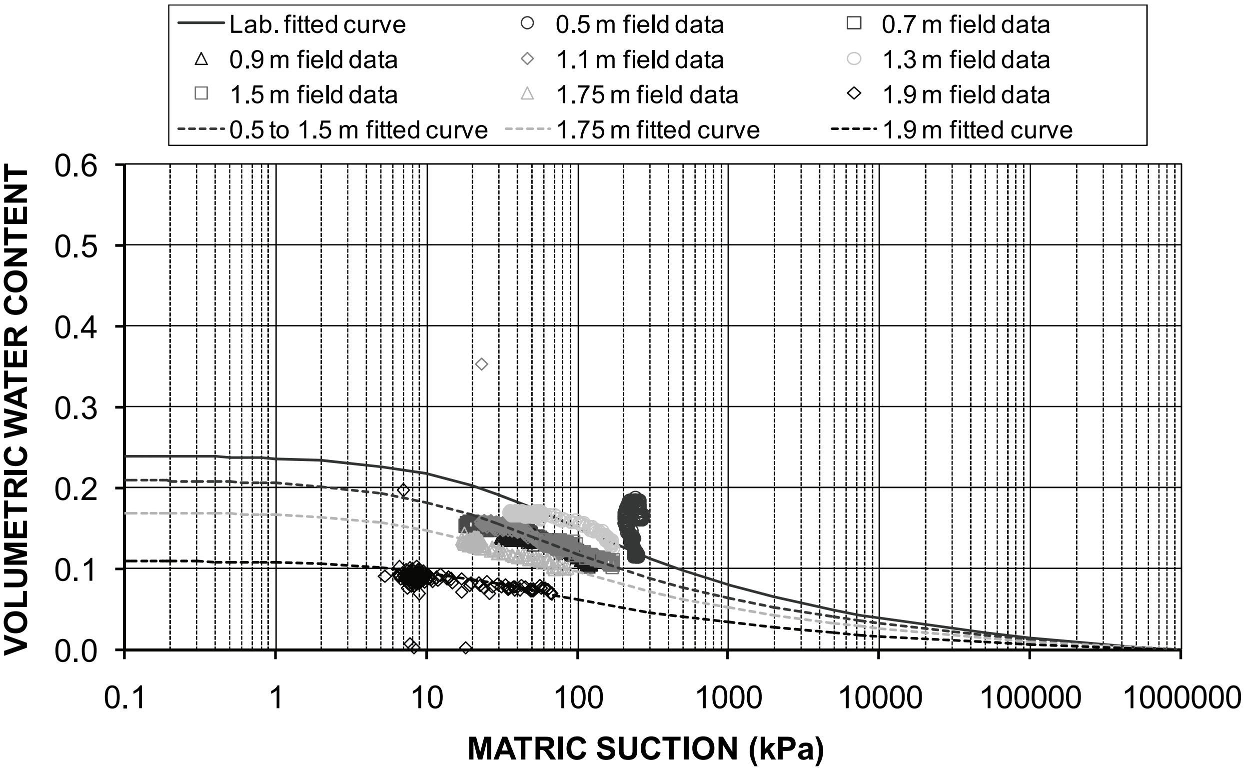

Figure 9 Comparison between field and laboratory-determined SWCC data for Cadia's rocky soil mulch over a compacted clay sealing layer

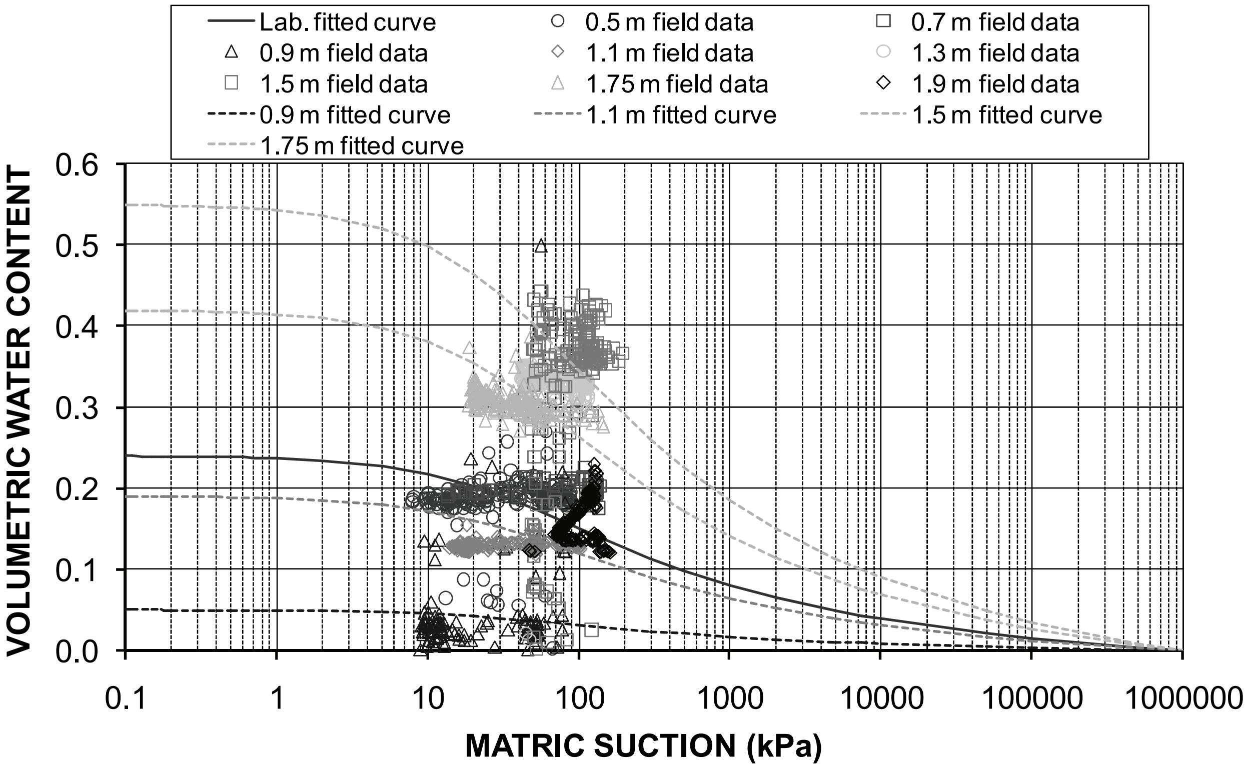

Figure 10 **Comparison between field and laboratory-determined SWCC data for Cadia's rocky soil mulch over a compacted TWR/dry tailings sealing layer**

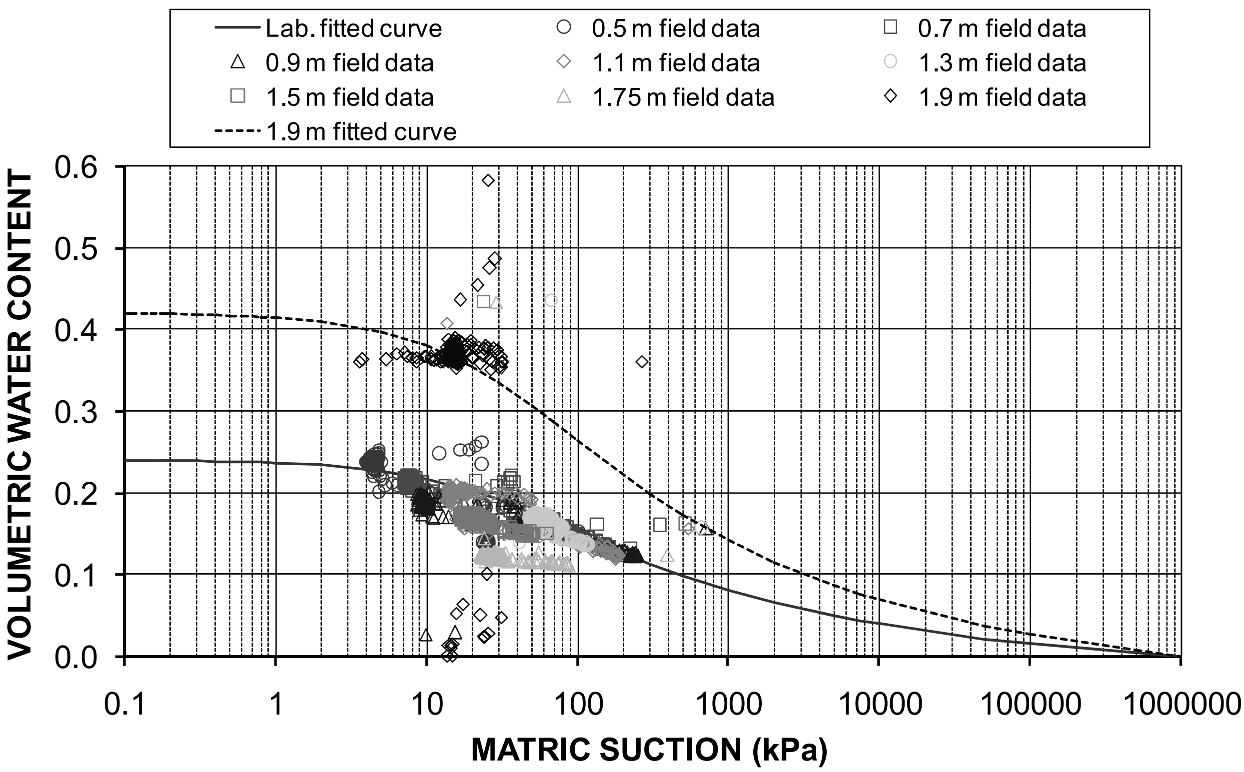

Figure 11 **Comparison between field and laboratory-determined SWCC data for Cadia's rocky soil mulch over a TWR/wet tailings sealing layer**

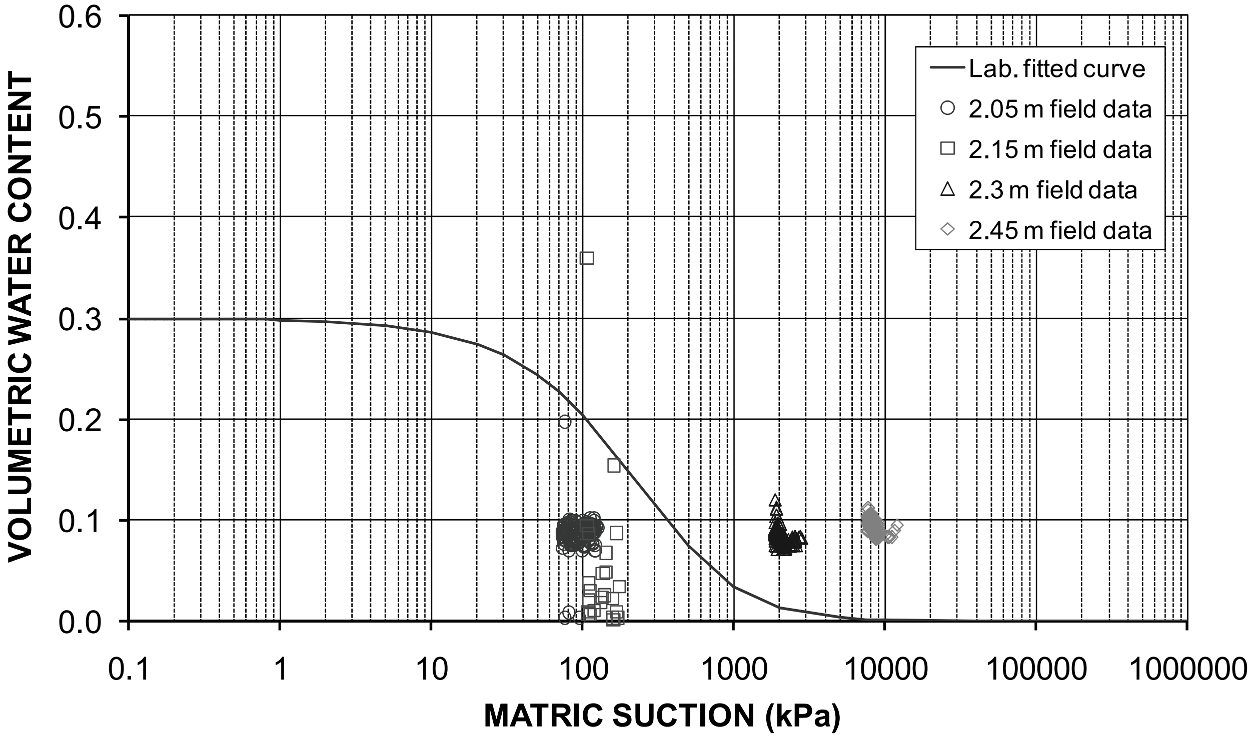

Figure 12 Comparison between field and laboratory-determined SWCC data for Cadia's compacted clay sealing layer

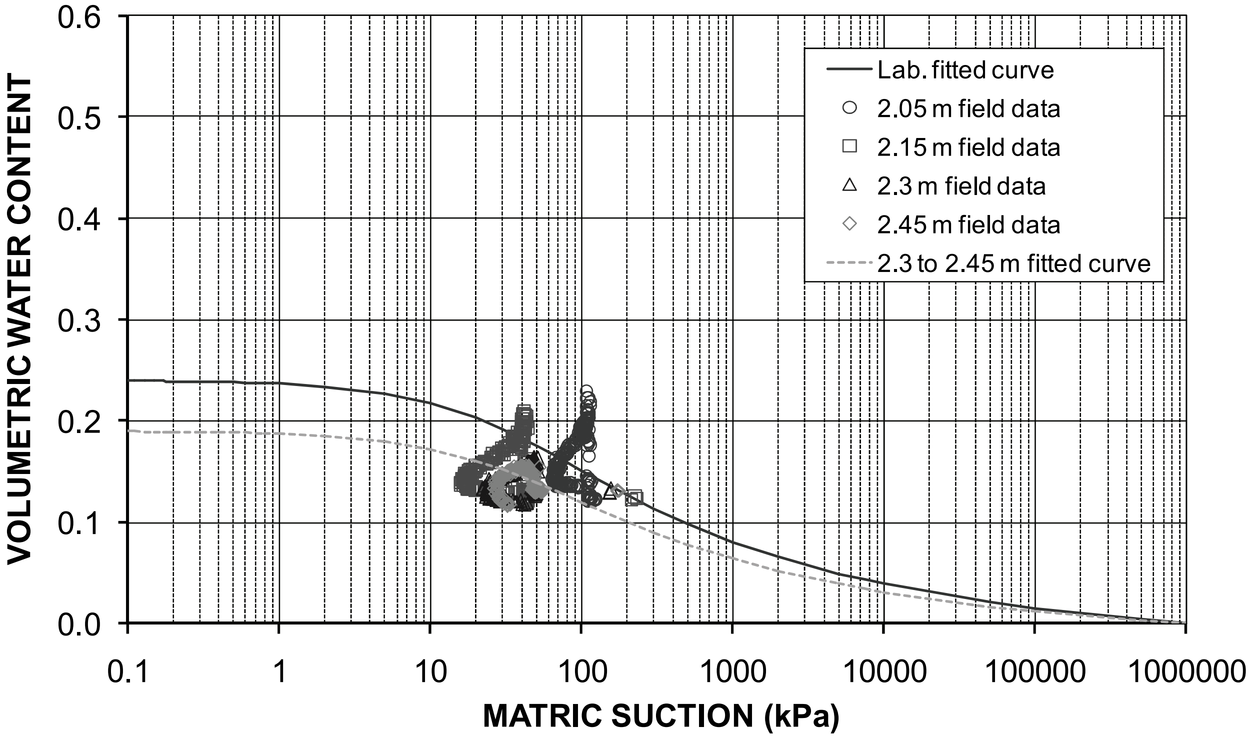

Figure 13 Comparison between field and laboratory-determined SWCC data for Cadia's compacted TWR/dry tailings sealing layer

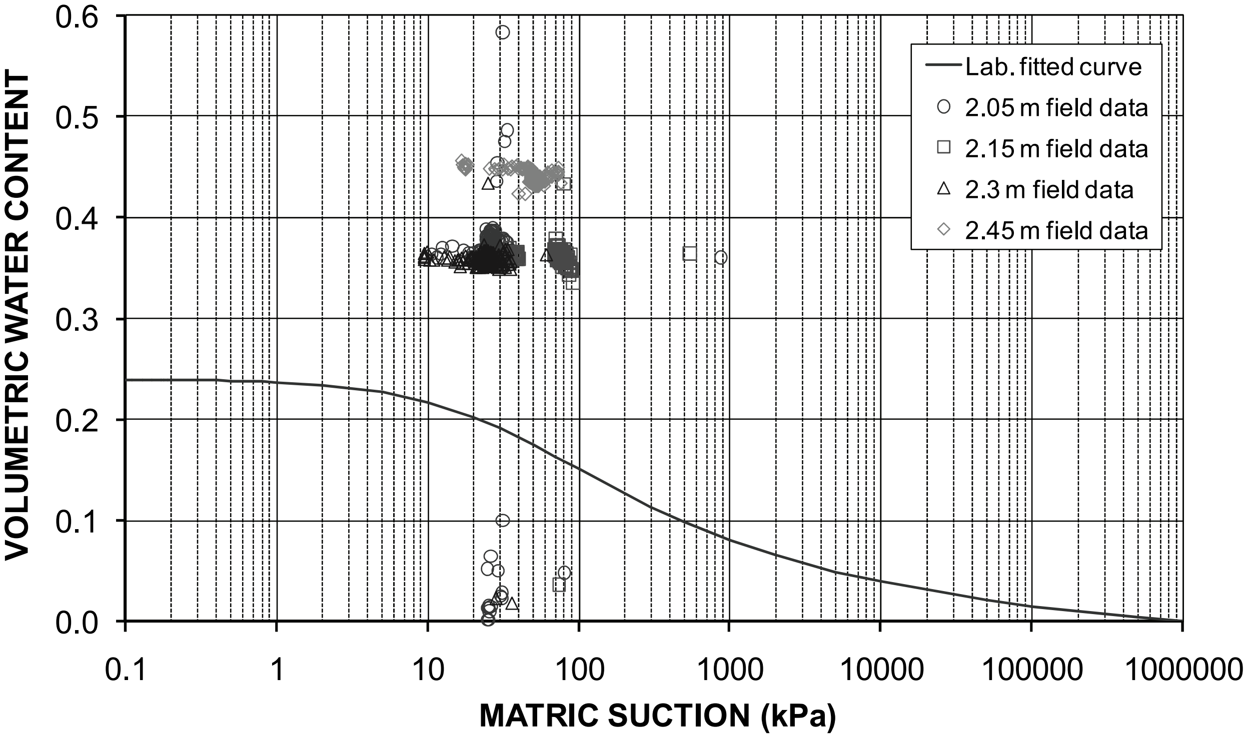

Figure 14 Comparison between field and laboratory-determined SWCC data for Cadia's TWR/wet tailings sealing layer

5 Conclusions

The paper clearly demonstrates the potential discrepancies between the unsaturated behaviours of soil cover materials under in situ, laboratory test and re-constructed field conditions. Any structure and cementation that the materials may possess in situ is largely destroyed by sampling disturbance, sample preparation and saturation prior to laboratory SWCC testing.

At QERL, the destruction of in situ overconsolidation and weak cementation on re-handling is demonstrated by the much 'stiffer' field SWCC compared with the laboratory drying SWCC. A very new cover of the same material recorded intermediate matric suctions at typical field moisture contents, while ageing effects restored the high in situ matric suctions for older covers.

The affect of ageing of the Kidston store/release cover materials is demonstrated by somewhat unstable initial unsaturated behaviour, which stabilises after a few years of seasonal drying and wetting cycles. The field SWCC response is not well estimated by laboratory drying SWCC test results. The store/release trial covers at Cadia display a lack of uniformity and variable relative density, resulting in highly variable field SWCC data that are very different from laboratory Tempe cell data obtained for the same materials.

The implications of these findings for the design of soil covers over mine wastes under unsaturated conditions are that laboratory drying SWCC data, generally obtained using reconstituted samples from a saturated state, will destroy the effects of any structure and cementation that exist in situ, and therefore may not be at all representative of in situ conditions. Material uniformity and construction control can also have a very large influence on field SWCC data.

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