WARRIP
WESTERN AUSTRALIAN ROAD RESEARCH
AND INNOVATION PROGRAM

Development of a standardised test method for measuring capillary rise of non-cohesive soils – Stage 2

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SUMMARY

Main Roads WA (Main Roads) requires that pavements are not constructed within the zone where capillary rise may adversely affect the performance of the pavement. To comply with this requirement, pavement designers often conduct laboratory tests to determine the capillary rise height on fill material (often non-cohesive materials). However, no standard test methodology is specified for this purpose, resulting in designers adopting different and inconsistent procedures.

To overcome this issue, WARRIP Project 2018–07 was initiated, with the objective of investigating the mechanics of capillary rise and the development of a standard test method for measuring capillary rise height of non-cohesive soils.

The first part of this report includes an overview of the capillary rise phenomenon, as well as how it is considered in pavement design procedures in Australia and internationally. A list of equations to estimate capillary rise of non-cohesive soils based on soil properties was also investigated along with a comparison between estimated capillary rise heights for WA soils and laboratory (or field) measurements. The report also summarises relevant test methods for determining capillary rise to guide the development of a standardised test method.

The second part of this report describes the development of the proposed test method from a previous test method used for the Southern Gateway project and the University of Western Australia research. In the method, the test specimen is prepared by firstly compacting the soil into cylindrical plastic moulds. The specimens are then placed in a water bath for the specified test duration. At the end of testing, the moisture content at various heights above the water level are measured. The capillary rise test result is the minimum height at which there has been no change in moisture content. The method was developed from testing three types of sand and crushed limestone. Recommendations are made in relation to the density and moisture content of test specimens and the duration of testing which varies with the type of non-cohesive soil.

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1.1 BACKGROUND

Main Roads WA (Main Roads) requires that pavements are not constructed within the zone where capillary rise may adversely affect the performance of the pavement. To comply with this requirement, pavement designers often conduct laboratory tests to determine the capillary rise height on fill material (often non-cohesive materials). However, no standard test methodology is available for this purpose, resulting in designers adopting different and inconsistent procedures. No other road agency in Australia requires the determination of a capillary rise height in non-cohesive materials.

Main Roads generally has not suffered premature failure on the metropolitan network as a result of capillary rise when constructing on sand. In recent years Main Roads has started using Brajkovich sand (clayey sand) for embankments and also materials excavated from basins. The effect of this on pavement performance as a result of capillary rise effects is unknown.

This issue has been identified as part of an ongoing WARRIP project (2017-009: Main Roads Engineering Road Note (ERN) 9 Update – Stage 2). This project includes: (1) a brief literature review, (2) a review of available data and (3) a recommendation on minimum capillary rise allowance requirements based on (1) and (2). The development of a test method for testing capillary rise was not part of WARRIP project 2017-009.

This project focussed primarily on gaining a greater understanding of the capillarity of soil and water in non-cohesive granular soils that are typically used for pavement construction in the Perth metropolitan area, and secondly on developing a standardised test method for determining capillary rise in non-cohesive material by reviewing published literature, test methods, and previously undertaken laboratory investigations.

1.2 OBJECTIVES

The aim of this study is to develop a standardised test method for measuring capillary rise in non-cohesive soils. To do this a laboratory investigation was undertaken using a similar method as proposed for the standardised test method. The results from the laboratory tests were subsequently analysed to quantify the following issues related to the test method:

- Should a specific moisture condition be specified in the test method, and if so, what should this be?
- Should a specific density condition be specified in the test method, and if so, what should this be?
- Does material type influence required test duration, and if so, what should these durations be?
- Does material type influence capillary rise, and if so, what should the test specimen height be?
- What is the definition of capillary rise as determined by the test method and how are results to be interpreted using the test method?
- Is the test method suitable for a range of non-cohesive materials?

1.3 OUTLINE OF THE PROJECT

The project has been divided into the following tasks:

- Stage 1
  - define the factors contributing to capillary rise (such as water vapour movement and condensation) to enable the development of a measurable definition for capillary rise
  - review national and international methods for measuring capillary rise, including the test methodology proposed by UWA
  - develop a preliminary test methodology including apparatus, sample preparation and calculations

  - purchase and set up additional equipment for testing
  - select materials to be tested.
- Stage 2
  - laboratory testing of the selected materials – including particle size distribution, particle density, dry density/moisture content relationship and capillary rise testing
  - data analysis of laboratory outcomes to define test method items including test duration, sample preparation, measurements and final calculations
  - preparation of a final report and a final standard test method

This report represents the final report of the project and includes the work undertaken in Stage 1 and Stage 2 as detailed above.

2 CAPILLARY RISE

2.1 INTRODUCTION

Capillary action or capillarity for free water with the soil occurs when the water adhesion to the soil is stronger than the cohesive forces between the water molecules. Capillary fall occurs when the capillarity forces are inadequate to hold all of the soil moisture and some of the soil water drains down due to the force of gravity. Capillary rise occurs when the capillarity forces are greater than the forces of gravity and soil moisture is drawn upwards. Capillarity occurs in every direction and surface water ponding on road shoulders has a potential to be drawn laterally into the pavement layers. This project only considers capillarity in one dimension, vertical.

2.2 MECHANICS OF CAPILLARY RISE

Capillary rise is the phenomenon where a liquid rises within a soil or fine bore above the line of atmospheric pressure (phreatic surface). This happens because adjacent molecules at the surface are attracted and resist tensile forces. The attraction force is measured by the surface tension, which is defined as the amount of work or energy required to produce a unit increase in the area of a liquid surface. Above the phreatic surface, a negative pore water pressure exists, with magnitude equal to the height of the point above the phreatic line multiplied by the unit weight of water (Hird & Bolton 2017, Lambe & Whitman 1969, Remson & Randolph 1962).

The height of capillary rise of water in a capillary tube is determined by Equation 1 (Fredlund and Rahardjo 1993).

$$h_c = \frac{2T_S}{\rho_w g r} \qquad 1$$

where

h_c = capillary height of pure water in a clean glass tube

T_S = surface tension of water

ρ_w = density of water

g = gravitational acceleration

r = radius of the capillary tube

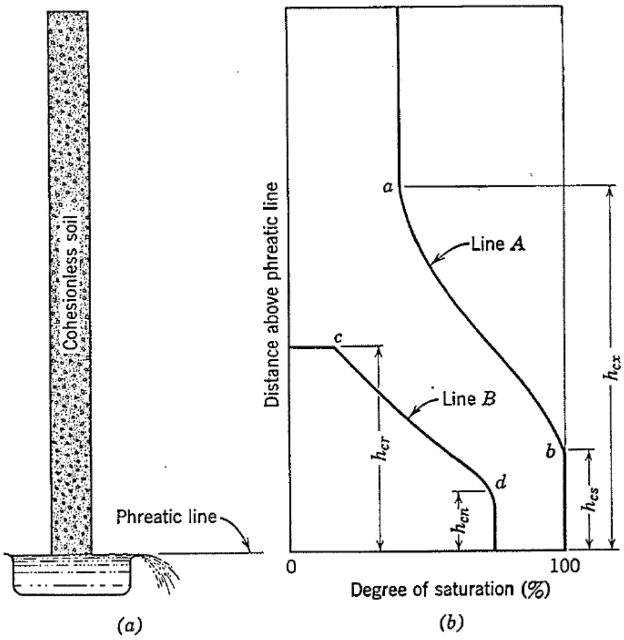
Figure 2.1 illustrates capillary rise on a cohesionless soil. Line A represents the degree of saturation (Equation 2) versus height when the soil in the tube is initially saturated and allowed to drain until a static condition is reached. Line B represents the degree of saturation versus height when water is placed at the bottom of the tube and equilibrium is reached. The following heights can be identified:

- h_{cx}: maximum capillary head
  - maximum elevation where continuous water exists above the phreatic surface
- h_{cs}: saturation capillary head
  - highest elevation for which saturation (or near saturation) exists, above which the soil is in an unsaturated condition
  - point ‘b’ marks the ‘capillary fringe'
- h_{cn}: minimum capillary head

  - distance from the phreatic surface to the highest elevation where saturation (or near saturation) exists
- h_{cr}: capillary rise
  - distance from the phreatic surface to the maximum height water rises

When water drops (line A), small voids above larger voids can support the water. If water is coming from below (line B), the water would not have passed the larger voids to reach the smaller voids. Therefore, the soil has a higher water content when drying (capillary fall) compared to when wetting (capillary rise) (Lambe & Whitman 1969, Sweere 1990).

Figure 2.1 Capillary heads in soil



Notes:

(a) tube of cohesionless soil

(b) plot of degree of saturation against distance above the phreatic line

Source: Lambe and Whitman (1969)

$$S = \frac{V_w}{V_v} \tag{2}$$

where

S = degree of saturation

V_w = volume of water

V_v = volume of voids (Fredlund and Rahardjo 1993).

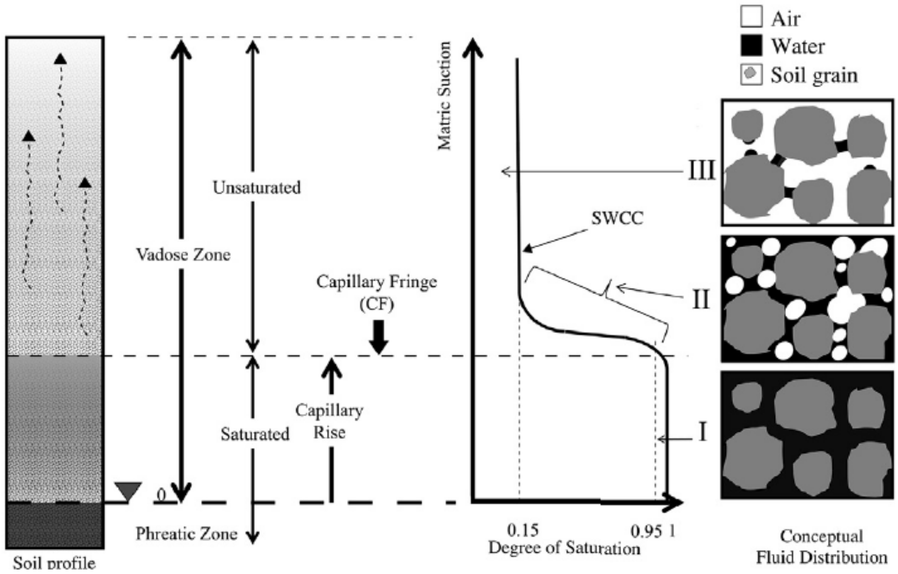
Hird & Bolton (2017) identify the following zones within Line A, which are illustrated in Figure 2.2:

- Zone I (from the phreatic line to point ‘b’ in Figure 2.2): zone of lowest suction, saturation or near saturation with discontinuous air bubbles
- Zone II (from point ‘b’ to point ‘a’ in Figure 2.2): zone where both air and water phases can be continuous as the suction exceeds the capillary pressure and air can enter from above or bubbles can resist water rising from below

- Zone III (above point 'a' in Figure 2.2): isolated water droplets only exist as pendular bridges between grains.

According to Silliman et al (2002 cited in p. 78 of Hird & Bolton 2017), the transition from Zone II and Zone III depend on the grain sizes.

Figure 2.2 Conventional understanding of the vadose zone suction and degree of saturation, derived by draining water from a saturated soil

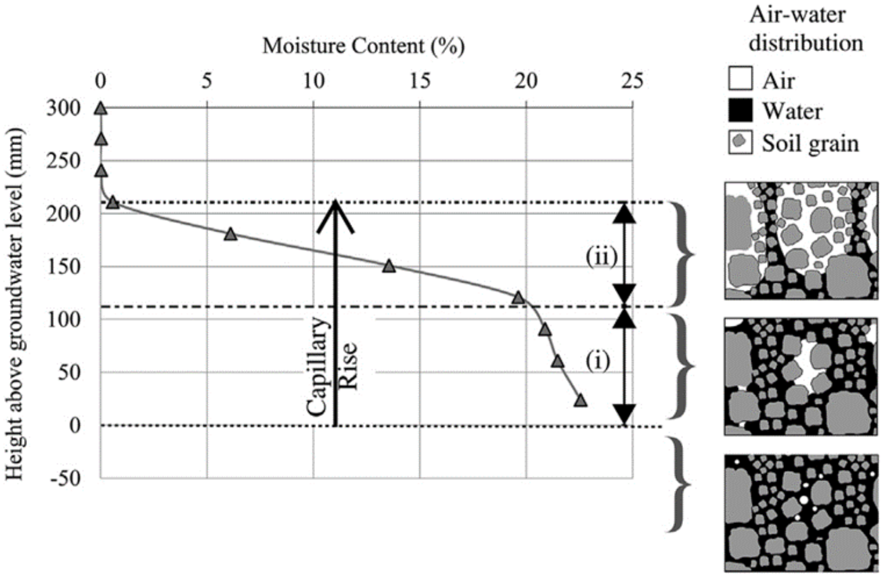


Source: Hird & Bolton (2017)

Figure 2.3 illustrates the conceptual fluid distribution within a soil matrix when the tube is initially dry and water is allowed to rise until equilibrium (capillary rise). Two zones were identified by Hird and Bolton (2017):

- Zone (i): quasi-saturated zone (degree of saturation above 0.8), where larger voids accommodate occasional air bubbles
- Zone (ii): 'zone of funicular fingering forms by water percolating upwards in increasingly narrow channels defined by grains smaller than D10, by the contact zones of other grains, and by the encroaching atmospheric air that surrounds them'.

Figure 2.3 Suggested elements of the vadose zone for water rising into dry sand



Source: Hird and Bolton (2017).

2.3 THE EFFECT OF CAPILLARY RISE ON DESIGN MODULUS

There are two main concerns regarding capillary effects on the life of a pavement, which are: 1) water ingression in asphalt layers causing stripping; 2) moisture in granular (pavement and subgrade) materials reducing design modulus and therefore their capacity to support loads. This section is focused on the latter, presenting an explanation of how capillary rise affects design modulus of non-cohesive granular materials based on findings of a study conducted by Wu et al. (1984).

The authors performed resonant column tests on five fine-grained cohesionless soils to investigate the influence that capillary stresses have on low-amplitude shear modulus (G_0). They found that there was a peak value of shear modulus that occurred at low degree of saturation values (from 5 to 17.5% for the soils tested).

According to Wu et al. (1984), for clean dry sands, shear modulus at small strains is dependent on two variables, namely the effective stress and the void ratio (e). Aitchison and Bishop (1960 cited in p. 1190 of Wu et al 1984) proposed the following equation 3 to calculate effective stress of a soil containing two pore fluids (air and water).

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \tag{3}$$

where

σ' = effective stress

σ = external pressure

u_a = air bubble pressure

u_w porewater pressure

χ = empirical parameter representing the proportion of the soil suction $(u_a - u_w)$ that contributes to the effective stress. ($\chi = 1$ for fully saturated soils and $\chi = 0$ for dry soils).

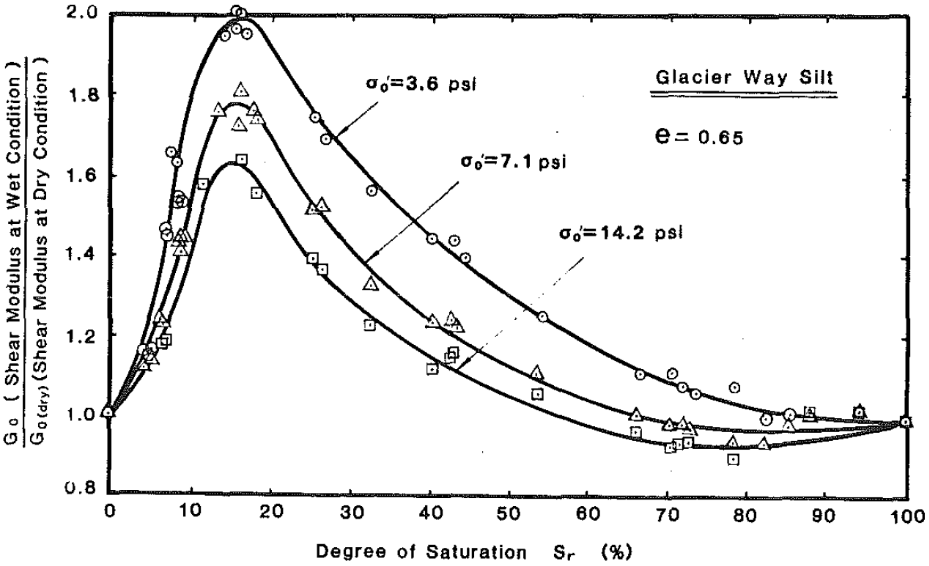
Source: Wu et al. (1984).

The strength of an unsaturated soil is a function of the angle of internal friction, cohesion, soil suction and stress state (Fredlund & Rahardjo 1993). Equation 3 shows that the effective stress of a soil depends not only on the soil suction, but also on the degree of saturation (S_r) of the soil. Therefore, high soil suction values do not necessarily lead to high effective stress, as the value of χ approaches 0 for dry soils.

According to Whitlow (2000), soils wetter than the optimum water content tend to have χ very near to 1.

Figure 2.4 shows example results obtained for glacier way silt. There is a peak modulus value (denoted by the ratio of the shear modulus at wet condition divided by the shear modulus at dry condition) that occurs approximately at the same degree of saturation independent of the confining pressure (σ_0'). The figure also shows that capillary effects are most important at lower confining pressures and decrease as the confining pressure increases. Near saturation, the shear modulus decreases to a value below the value at dry condition.

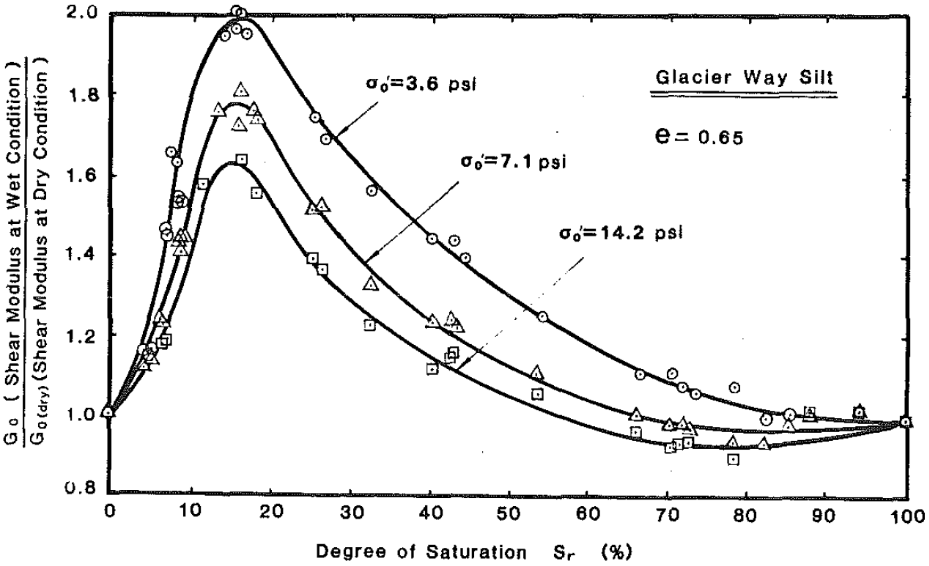
Figure 2.4 $G_0/G_{0(dry)}$ versus degree of saturation for glacier way silt



Source: Wu et al. (1984).

The correlation between optimum degree of saturation (where maximum G_0/G_0(dry) occurs) and effective grain size obtained by Wu et al. (1984) is illustrated in Figure 2.5.

Figure 2.5 Relationship of optimum degree of saturation versus D_{10} for five test materials



Source: Wu et al. (1984).

The results presented by Wu et al. (1984) show that as soil approaches saturation within the capillary zone, the effective stress and therefore, modulus of the granular material can be lower than dry values. As the degree of saturation decreases, the modulus increases and can achieve values higher than at dry condition.

2.4 FACTORS RELATED TO CAPILLARY RISE

This section provides an overview of different factors related to capillary rise height. These parameters are inter-related. The list provided is not necessarily comprehensive, it encompasses the main factors believed to be relevant to the current study.

2.4.1 PORE SIZE (PARTICLE SIZE AND POROSITY)

Capillary rise in soils is sometimes modelled as a system of unconnected parallel capillary rise tubes with a radius equivalent to the soil's average pore size (Aghajani et al. 2011).

Pore size is determined by particle size and porosity. The diameter of pores in the soil matrix is the most significant contributor for the capillary rise height. Larger and more uniform grain sizes result in larger pore size and lower capillary rise. According to Li et al. (2018), the maximum capillary rise height is mainly determined by the distribution of large pore size.

The pore size also determines the amount of time the soil takes to reach an equilibrium. The water takes longer to travel through small pores. Therefore, fine-grained soils, with smaller pore sizes, take longer to reach an equilibrium; whereas coarse grained soils reach an equilibrium in much shorter time.

2.4.2 CONTACT ANGLE

The contact angle is the angle between a liquid and a solid surface. Its magnitude depends on the adhesion between molecules. A perfect wetting material has a contact angle of zero. Higher contact angles lead to less wettability. Coarser grained soils generally have a higher contact angle (less wettable) than finer texture soils (Aung 2012, Salim 2016, Schwartz 1980 cited in pp. 3 of Salim 2016,).

The contact angle depends on many factors, such as water potential (potential energy of water per unit volume relative to pure water in reference conditions), roughness and temperature (Liu et al. 2014)

Sulman (1919 cited in p. D6 of Remson & Randolph 1962) reported a hysteresis of contact angle phenomenon where the contact angle of a wetting front is larger than that of a liquid receding to a position of rest following saturation.

2.4.3 SOIL SUCTION

Soil suction is a combination of matric suction (also called capillary pressure) and osmotic suction. The matric suction originates from physical interaction effects, whereas the osmotic suction originates from chemical interaction effects. The matric suction arises from interactions between the pore water and the soil solids. It can be assumed to be inversely proportional to the effective pore radius. The osmotic suction comes from the presence of dissolved solutes (salt) particles in the pore water and is generally less significant (Aung 2012, Barbour 1998, Fredlund et al. 2012, Jindal 2016, Sweere 1990).

For many geotechnical problems, if no salts are added to the soil, matric suction changes are assumed to be similar to total suction changes (Fredlund et al. 2012).

Equation 4 represents the total suction components (Fredlund et al. 2012)..

$$\psi = (u_a - u_w) + \pi \tag{4}$$

where

ψ = total suction

$(u_a - u_w)$ = matric suction (kPa)

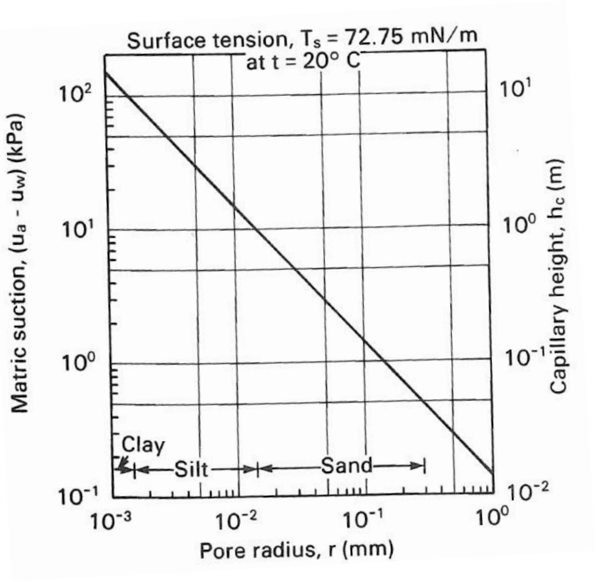
u_a = pore air pressure (kPa)

u_w = pore water pressure (kPa)

π = osmotic suction (kPa)

As the moisture content within a soil decreases, matric suction increases. The soil moisture at a given suction value can be correlated with the height of capillary water above the phreatic line, as the suction is equal to the vertical distance from the phreatic line multiplied by the unit weight of the water. Figure 2.6 shows the relationship among pore radius, matric suction and capillary height.

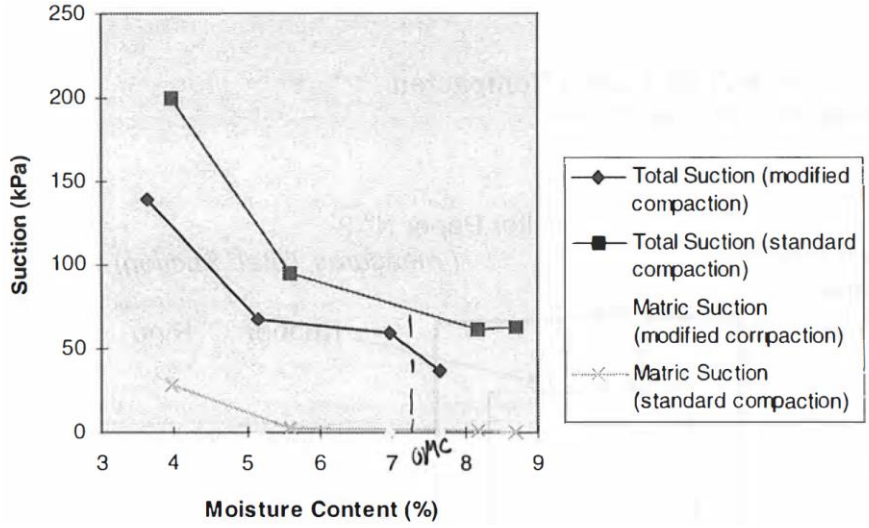
Figure 2.6 Relationship among pore radius, matric suction and capillary height



Source: Fredlund and Rahardjo (1993).

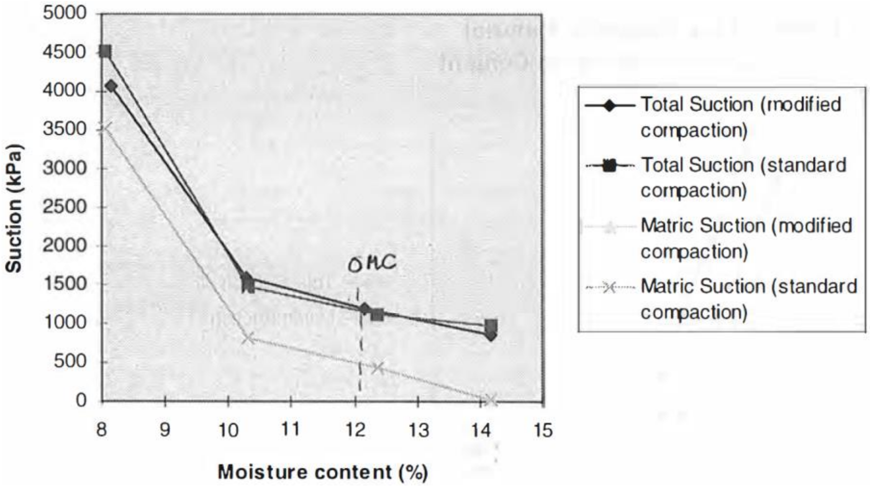
Walker (1997) reported suction measurements from two trial pavement sections composed of a thin asphalt over granular basecourse, subbase and free draining layers. The trial sections were located in Dandenong, Victoria. Suction measurements were taken from a clay subgrade material, weathered sandstone marginal base material and basalt basecourse material. The results indicated that there is an inflection in the curve suction versus moisture content near the optimum moisture content (OMC). Wet of OMC, the rate of reduction in suction with increasing moisture content is less prominent than dry of OMC, as illustrated in Figure 2.7, Figure 2.8 and Figure 2.9, respectively for crushed basalt base material, sandstone marginal quality base material and clay subgrade material.

Figure 2.7 Crushed basalt base material ─ suction vs moisture content



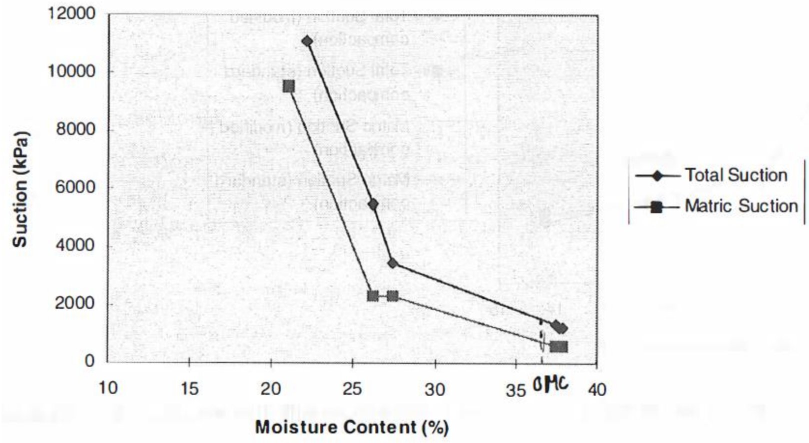
Source: Walker (1997).

Figure 2.8 Sandstone marginal quality base material — suction vs moisture content



Source: Walker (1997).

Figure 2.9 Clay subgrade material — suction vs moisture content



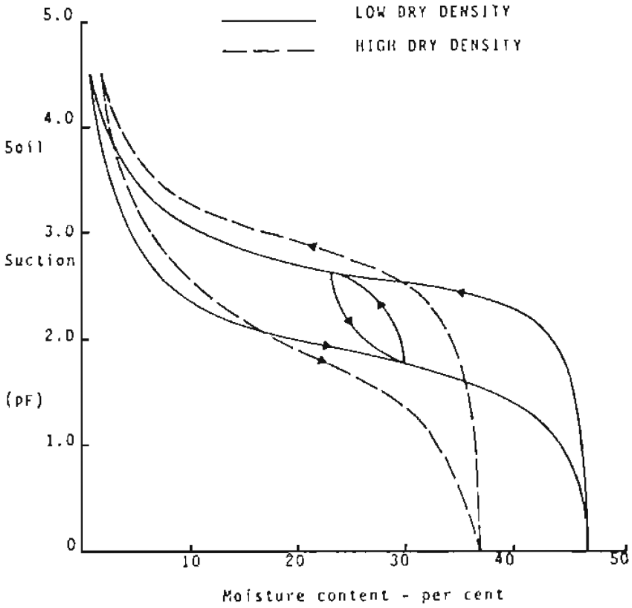
Source: Walker (1997).

Additionally, Walker (1997) found that for the materials tested at a given moisture content, an increase in compactive effort only resulted in minor or sometimes insignificant change in suction.

Marsh and Coleman (cited in p. 196 of Morgan 1974) identified three behaviours:

- Incompressible soils (such as sands): increase in density decreases the amount of water held at low suctions, increases the suction at which air first enters the soil pores and increases the amount of water held at high suctions (refer Figure 2.10).
- Compressible soils (such as clays): increase in density decreases the amount of water held at both high and low suctions and decreases volume change in the soil.
- Partially compressible soils: suction/moisture content relationship generally corresponds to incompressible soil at low dry densities and compressible soil at high dry densities.

Figure 2.10 Typical soil suction – moisture content curves showing the effect of density variation



Source: Morgan (1974).

2.4.4 DENSITY OF THE LIQUID

The density of the liquid is inversely proportional to the height of capillary rise (Fetter 1994 cited in p. 9 of Salim 2016).

2.4.5 VISCOSITY OF THE LIQUID

Hydraulic conductivity decreases with viscosity of the fluid (Moore 1939 cited in p. 11 of Salazar 1967). According to Barbour (1998), water viscosity increases near particles.

2.4.6 SURFACE TENSION

Surface tension plays a major role in capillarity with a decrease in surface tension resulting in a proportional decrease in capillary pressure (Jindal 2016).

2.4.7 TEMPERATURE

Capillary pressure decreases linearly with temperature. However, the full mechanism of how this happens is not well understood (Grant & Bachmann 2002). As the temperature increases, surface tension decreases, and the soil can lose water which was previously held by capillarity when the temperature was lower (Free 1911, Meeuwig 1964). According to Grant and Bachmann (2002), the reduction in water surface tension with temperature, however, only explains about one fourth of the magnitude of change in capillary pressure with temperature. The authors suggest the most likely other mechanisms to explain this phenomenon are the solute effects on the soil solution surface tension and/or temperature-induced changes in contact angles. Temperature can have a significant effect on solubility, with some surfactants decreasing the surface tension of pure water. A study by King (1981 cited in Grant & Bachmann 2002) shows that contact angle decreases with increasing temperature.

2.4.8 EVAPORATION AND CONDENSATION

According to Free (1911), diffusion of water vapour through soils is very slow. Appreciable evaporation takes place only at the soil surface or within a few centimetres depth. As capillary water evaporates, capillary pressure increases, and water is drawn from below to restore equilibrium. Continued evaporation is accompanied by continued capillary supply as long as the evaporation is not faster than the water supply.

However, according to a theoretical study conducted by Ramon and Oron (2008), there are two mechanisms associated with phase change (evaporation/condensation), namely mass loss/gain and vapor recoil. If only mass loss/gain is considered, the mass of water lost through evaporation is replenished by capillarity, and the mass gained by condensation is opposed by gravity. For small temperature changes, the system shows a stable equilibrium state. However, for higher mass transfer rates or larger capillary radii, the authors show that the effect of vapor recoil is dominant. Vapor recoil results in a force directed into the liquid body for both evaporation and condensation. Therefore, it results in a lower equilibrium height, in addition to higher oscillation frequencies.

2.4.9 ATMOSPHERIC CONDITIONS

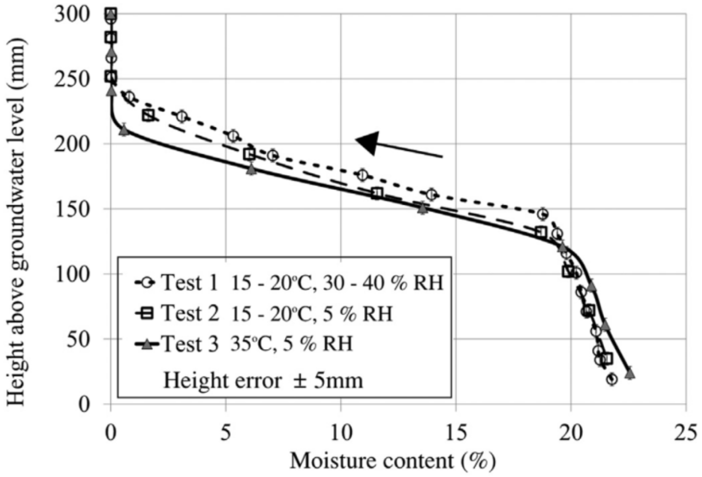
Hird and Bolton (2017) conducted capillary rise testing on dry sand at different temperature and relative humidity conditions. Table 2.1 summarises the test conditions and height of water above the phreatic surface observed by the authors. A maximum height difference of 35 mm was observed. Figure 2.11 illustrates the soil water characteristic curve obtained by the authors (the arrows indicate the direction of the flow).

Table 2.1: Summary of test conditions and results for the testing conducted by Hird and Bolton (2017)

Test ID	Test conditions	Temperature (°C)	Relative humidity (%)	Height of water above the phreatic surface (mm)
1	Variable temperature and relative humidity	15 – 20	30 – 40	252
2	Variable temperature and low humidity	15 – 20	5	236
3	Constant elevated temperature and low humidity	35	5	217

Source: adapted from Hird and Bolton (2017).

Figure 2.11 Moisture content curves for rising head tests on a column of Fraction D sand using pure water for Test 1, Test 2 and Test 3.



Source: Hird and Bolton (2017).

Netterberg and Haupt (2003) reported significant increase in soil suction with increasing temperature measured in four pavement sections in South Africa. In some instances, the authors observed a suction-induced stiffening of the granular base resulting in an increase of radius of curvature.

3 CAPILLARY RISE CONSIDERATION IN PAVEMENT DESIGN

3.1 AUSTRALIAN PRACTICE

3.1.1 WESTERN AUSTRALIA

ERN9 (Main Roads 2013) specifies that a drainage layer not less than 300 mm in depth is required under granular pavements in cuttings where the subgrade may be adversely affected by capillary rise. Additionally, ERN9 (Main Roads 2013) states that full depth asphalt pavements must not be constructed below the water table or in a location where capillary rise may adversely affect the performance of the asphalt, even when sub-soil drainage has been installed.

Main Roads Engineering Road Note No. 5 (2003) cites typical values of matric suction of 50 mm for sandy gravels to 600 mm for clayey gravels and presents the following equation 5 for calculation of matric suction.

$$PB_W = \frac{15}{D_{10}} to \frac{25}{D_{10}} \tag{5}$$

where

PB_W = matric suction in mm

D_{10} = sieve opening in mm that 10% of the material passes (the value is obtained from the grading curve).

3.1.2 NEW SOUTH WALES

The Roads and Maritime Services (RMS 2015) typically uses an Upper Zone Formation (UZF) layer between the subbase and the subgrade. The UZF is composed of two layers, namely a Selected Material Zone (SMZ) with minimum thickness 300 mm and Lower UZF.

Additionally, RMS (2013) specifies a 900 mm minimum distance between the underside of the SMZ and the top of bridging layers/drainage layers/earth fill foundation treatment layer, which are defined as follows:

- Bridging layer: ‘A layer located at the foundation of the formation in an embankment constructed from granular earth fill material or rock fill material with strong mechanical interlock. The purpose of the bridging layer is to provide a stable platform upon which a conforming earthworks layer can be constructed.’ (RMS 2014).
- Drainage layer: ‘A layer located at the foundation of the formation in an embankment or within a cutting, constructed of free draining material with grading as specified in Clauses 3.2.5 and 3.4.5. The purpose of the drainage layer is to provide a pathway for the free drainage of excess water from the foundations of embankments or cuttings. The drainage layer is usually wrapped in geotextile to prevent its contamination or blockage over time from adjacent fine-grained material.’ (RMS 2014).
- Earth fill: ‘Material consisting of fine material and coarse particles distributed throughout the layer filling any voids so that when compacted produces a dense stable embankment.’ (RMS 2014).
- The 900 mm minimum distance comprises earth fill/rock fill material.

RMS (2015) also recommends soaked CBR is used for fine-grained materials that can wet up through capillary action in high rainfall areas (4-day or 10-day soak depending on the annual rainfall and drainage conditions). The guide also provides a table showing typical ratios of equilibrium moisture content (EMC) and optimum moisture content (OMC) at modified compaction for different conditions (refer to Table 3.1).

Table 3.1: Typical ratios of EMC to OMC at modified compaction

Layer	Conditions	Equilibrium moisture content/Optimum moisture content (EMC/OMC)			
		Normal moisture state		Unusually moist state	Wet saturated state
Base	Unbound granular	0.60		0.80	> 1.0
	Post-cracking cemented	1% cement	0.70	0.85	> 1.0
		2% cement	0.80	0.90	> 1.0
Subbase	Arid climate	0.70		0.85	> 1.0
	Moderate climate	0.75		0.90	> 1.1
	Wet climate	0.85		0.95	> 1.1
Subgrade	Arid climate	0.75		0.9	> 1.1
	Moderate climate	0.92		1.05	> 1.1
	Wet climate	1.00		1.1	> 1.15

Sources: Emery (1985), Harris and Lockwood (2009) & RMS (2018).

Finally, the RMS *Technical Guide Standard Pavement Subsurface Drainage Details* (2014b) states that subsurface drains are usually installed where the groundwater table is high. Trench drains are installed within and adjacent to pavements to drain water from within pavements and intercept the ground water table.

In summary, although RMS does not have a clear requirement regarding distance between the water table and the pavement and capillary rise testing, it includes other requirements that minimise the risks of moisture ingression to the pavement though capillary rise, such as the use of improved subgrade layers and subsurface drains.

3.1.3 QUEENSLAND

The Queensland Department of Transport and Main Roads (TMR 2013) states that moisture from seepage and infiltration from water table fluctuations can be controlled by the installation of properly designed pavement and subgrade drains, but only when subgrade moisture is subject to positive pore pressures. Where the water table is likely to affect the subgrade, CBR testing in accordance with Test Method Q113A (TMR 2020) is carried out, a 10-day soaked testing condition as opposed to the typically adopted 4-day soaked testing, to act as a guide to typical moisture conditions.

TMR's *Road Drainage Manual Chapter 11 Road Surface and Subsurface Drainage Design* (TMR 2019) refers to the *Austroads Guide to Road Design Part 5A* (Austroads 2013) in relation to capillary rise in soils. According to Austroads (2013), the rise in capillary water can be calculated using equations 6 and 7 (Austroads 2013):

$$h_c = \frac{10C}{eD_{10}} \tag{6}$$

where

h_c = capillary rise (mm)

C = an empirical constant that depends on the shape of the grains and varies from 0.1 to 0.5 cm^2 (for perfect spheres, C= 0.1 cm^2)

D_{10} = Allen Hazen's effective grain size, based on the sieve opening in cm that 10% of the material passes. The value is obtained from the grading curve.

$$e(void\ ratio) = \frac{V_v}{V - V_v} \qquad 7$$

where

V = total volume (units)

V_v = total volume of voids (units)

Austroads (2013) mentions that the height of capillary rise of the groundwater should be calculated to ensure that excess water does not enter the pavement, but does not provide details on how this should be considered in the design. It is not clear from the document what the recommended distance between the water table level and the top of the subgrade is in relation to the calculated capillary height.

In flood plains and low-lying areas where a permanent high-level water table exists, TMR (2019) suggests raising the subgrade level by 1.2 m above the water table where possible. If not possible due to geometric constraints, TMR (2019) states that consideration should be given to the use of soaked conditions and in some situations a cement or bituminous stabilised subbase and/or base.

TMR Pavement Design Supplement (TMR 2018) does not mention specific requirements related to the height of capillary rise.

3.1.4 SOUTH AUSTRALIA

The South Australian Department of Planning, Transport and Infrastructure (DPTI) Supplement to the Austroads *Guide to Pavement Technology Part 2* (DPTI 2018) does not mention specific requirements related to the height of capillary rise.

Due to the climatic conditions in South Australia, subsurface drainage is not typically used unless water seepage has been identified by a ground water site investigation (DPTI 2018).

3.1.5 VICTORIA

VicRoads Code of Practice, *Selection and Design of Pavements and Surfacings RC 500.22* (VicRoads 2018) does not mention specific requirements related to the height of capillary rise.

VicRoads (2015) states that should the contractor encounter groundwater or seepage, proposed corrective measures should be taken to the superintendent for review.

3.1.6 COMPARISON OF AUSTRALIAN ROAD AGENCIES

A summary of the requirements relating to water ingress in the pavement and height of capillary rise by each of the Australian road agencies is presented in Table 3.2.

Table 3.2: Comparison of requirements related to height of capillary rise by road agency

State	Requirements
Main Roads (1) (Western Australia)	• Granular pavements: drainage layer not less than 300 mm in depth is required in cuttings where the subgrade may be adversely affected by capillary rise. • Full Depth Asphalt pavements: must not be constructed where capillary rise may adversely affect the performance of the asphalt, even when sub-soil drainage has been installed.
RMS(2) (New South Wales)	• Use of soaked CBR in areas of high rainfall where fine-grained materials get wet through capillary rise. • Presumptive design CBR values are lower where the water table is high. • Requires a selected material zone. • Provides guidance in relation to equilibrium and optimum moisture content at different moisture conditions for consideration by the designer.
TMR(3) (Queensland)	• Refers to Austroads (2013) for calculating the height of capillary rise in soils.

State	Requirements
	• If geometric considerations allow: suggests raising the subgrade level by 1.2 m above the water table in flood plains and low lying areas where a permanent high-level water table exists. • Otherwise: suggests consideration of soaked conditions and in some situations the use of a cement or bituminous stabilised subbase and/or base.
DPTI(4) (South Australia)	• No specific requirements.
VicRoads(5) (Victoria)	• No specific requirements.

Sources:

1. *Main Roads (2013).*
2. *RMS (2018).*
3. *TMR (2018).*
4. *DPTI (2018).*
5. *VicRoads (2018).*

3.2 INTERNATIONAL PRACTICE

Most of the international literature reviewed considers capillary rise by relating it to frost action or specifies the use of drainage systems when the water table is in close proximity to the pavement rather than defining a required distance between the water table and the pavement.

The Federal Highway Administration *Geotechnical Aspects of Pavements Reference Manual* (FHWA 2017), for example, cites the use of a capillary break system, but does not specify any requirements in terms of minimum distance between the groundwater table and the pavement.

The Hong Kong Highways Department (2014) specifies, as a general requirement, that sub-soil drainage is installed to prevent the water table from rising to within 600 mm of the formation level. This would allow the designer to use a higher soil strength in assessing the pavement thickness rather than considering a soaked condition. The document also provides a method for assessing the distance between the water table and the top of the subgrade that is required for a certain value of subgrade CBR as a function of the subgrade soil plasticity index, the vertical pressure due to the pavement on the in situ soil and soil suction.

In Sweden, the highest groundwater table level permitted is 300 mm below the surface of the subgrade (Dawson 2008).

No other specific requirements in terms of determining a minimum required distance between the water table and the pavement to account for capillary rise effects were encountered in the literature.

4 ESTIMATION OF CAPILLARY RISE OF NON-COHESIVE SOILS

4.1 LITERATURE

Hillman and Cocks (2007) reported capillary rise of Perth sands tested for infrastructure projects of 450 mm based on laboratory testing. The authors suggest that a total distance between the pavement and the water table of 600 mm is adopted to allow for capillary rise plus capillary gap.

Table 4.1 shows typical values of capillary rise for different drainage materials provided by NAASRA (1983).

Table 4.1: Typical values of capillary rise

Material	Particle size range (mm)	Capillary rise (mm)	Minimum thickness of drainage layer (mm)
Fine sand	0.05–0.25	300–1000	2000
Medium sand	0.25–0.5	150–300	600
Coarse sand	0.5–2	100–150	300
Well grained sand	0.25–2	150–1000	2000
Fine gravel	2–6	20–100	200
Coarse gravel	6–20	5–20	Nominal minimum 100 mm layer
One sized aggregate	> 5	< 5	

Source: NAASRA (1983).

Equations 8 to 13 present equations proposed by various authors to estimate the height of capillary rise on sands from other soil parameters, such as mean or effective diameter of the soil particles, porosity and void ratio.

$$h = \left(\frac{2.9}{d}\right)^{0.92} \qquad 8$$

where

h = capillary rise (in)

d = mean diameter of grain (mm)

Source: Valle-Rodas (1944).

$$h_k = 0.45\frac{1-\sigma}{\sigma}\frac{1}{d_{10}} \qquad 9$$

where

h_k = capillary rise (cm)

σ = porosity

d_{10} = effective diameter of the soil particles in cm

Source: Polubarinova-Kochina (1962).

$$h_c = \frac{2\sigma \cos \lambda}{\rho_w g R} \qquad 10$$

where

h_c = capillary rise (cm or mm)

σ = surface tension of the fluid (g/s^2 or kg/s^2)

λ = contact angle of the fluid meniscus with the capillary tube wall (degrees)

ρ_w = density of the fluid (g/cm^3 or kg/m^3)

g = acceleration of gravity (cm/s^2 or m/s^2)

R = radius of the capillary tube (cm or mm)

Source: Fetter (1994).

$$h_c = -990 ln D_{10} - 1540 \qquad 11$$

where

h_c = capillary rise (mm)

D_{10} = effective grain size (mm) – ranging from 0.0006 to 0.2 mm

Source: Lane et al. (1947).

$$h_c = \frac{C}{e D_{10}} \qquad 12$$

where

h_c = capillary rise (mm)

C = constant varying between 10 and 50 mm^2 depending on surface impurities and grain shape

e = void ratio

D_{10} = effective grain size (mm)

Source: Peck et al. (1974), Yoder and Witczak (1975).

$$h_c = \frac{\sigma n}{\sqrt{2\eta \rho_w g k_s}} \cos \alpha + (1+n)\, h_a \qquad 13$$

where

h_c = height of capillary rise (mm)

h_a = height of capillary fringe or air entry height (mm)

η = viscosity of water (Pa.s)

ρ_w = density of water (g/cm^3 or kg/m^3)

g = gravity acceleration (cm/s^2 or m/s^2)

k_s = saturated hydraulic conductivity (m/s)

n = porosity of the soil

α = contact angle (degrees)

Source: Liu et al. (2014).

For typical Perth sands, Clayton (2008) calculated capillary rise values ranging from 0.25 m to 1.25 m using Equation 12.

Table 4.2, Table 4.3 and Table 4.4 present typical capillary rise values for different soils proposed by various authors originating from the United States of America.

Table 4.2: Capillary rise test data for cohesionless soils (A)

Sediment	Average grain diameter (cm)	Representative d_{10} (cm)	Pore radius = $d_{10}/5$ (cm)	Capillary rise (cm)
Fine silt	0.0008	0.0002	0.00004	3750
Coarse silt	0.0025	0.00063	0.00013	1154
Very fine sand	0.0075	0.0019	0.00037	405
Fine sand	0.0150	0.00375	0.00075	200
Medium sand	0.03	0.0075	0.0015	100
Coarse sand	0.05	0.0125	0.0025	60
Very coarse sand	0.20	0.050	0.010	15
Fine gravel	0.50	0.125	0.025	6

Source: Adamski et al. (2005).

Table 4.3: Capillary rise test data for cohesionless soils (B)

Sediment	Average grain diameter (cm)	Pore radius (cm)	Capillary rise (cm)
Fine silt	0.0008	0.0002	750
Coarse silt	0.0025	0.0005	300
Very fine sand	0.0075	0.0015	100
Fine sand	0.0150	0.003	50
Medium sand	0.03	0.006	25
Coarse sand	0.05	0.01	15
Very coarse sand	0.2	0.04	4
Fine gravel	0.5	0.1	1.5

Source: Fetter (1994).

Table 4.4: Capillary rise test data for cohesionless soils (C)

Soil	Particle size d_{10} (mm)	Void ratio	Capillary rise (mm)
Silt	0.006	0.95–0.93	3590
Fine sand	0.03	0.36	1660
Medium sand	0.02	0.48–0.66	2400
Coarse sand	0.11	0.27	820
Silty gravel	0.06	0.45	1060
Sandy gravel	0.2	0.45	280
Fine gravel	0.3	0.29	200
Coarse gravel	0.82	0.27	50

Source: Lambe and Whitman (1969) based on Lane et al. (1947).

4.2 WESTERN AUSTRALIAN CAPILLARY RISE TEST RESULTS

Available capillary rise test results were summarised and compared to the estimated capillary rise using different equations (Engineering Road Note 5, Lane et al. 1947, Peck et al. 1974, Polubarinova-Kochina 1962, Valle-Rodas 1944)).

For the equations that required a void ratio, 0.50 was assumed, based on data provided by Cocks and Teague (1987) and McInnes (2003) for typical Perth sands.

Where capillary rise height was determined, the results are presented in Figure 4.1, where the second plot is a zoom of the first plot for height of capillary rise from 0 to 1000 mm. Table 4.5 describes each sample. It is noted that many of the equations used to estimate capillary rise are meant for sands only, and some of the samples tested do not fall in this category (samples 23 to 30) even though they are included in Figure 4.1.

Figure 4.1 Measured and estimated capillary rise

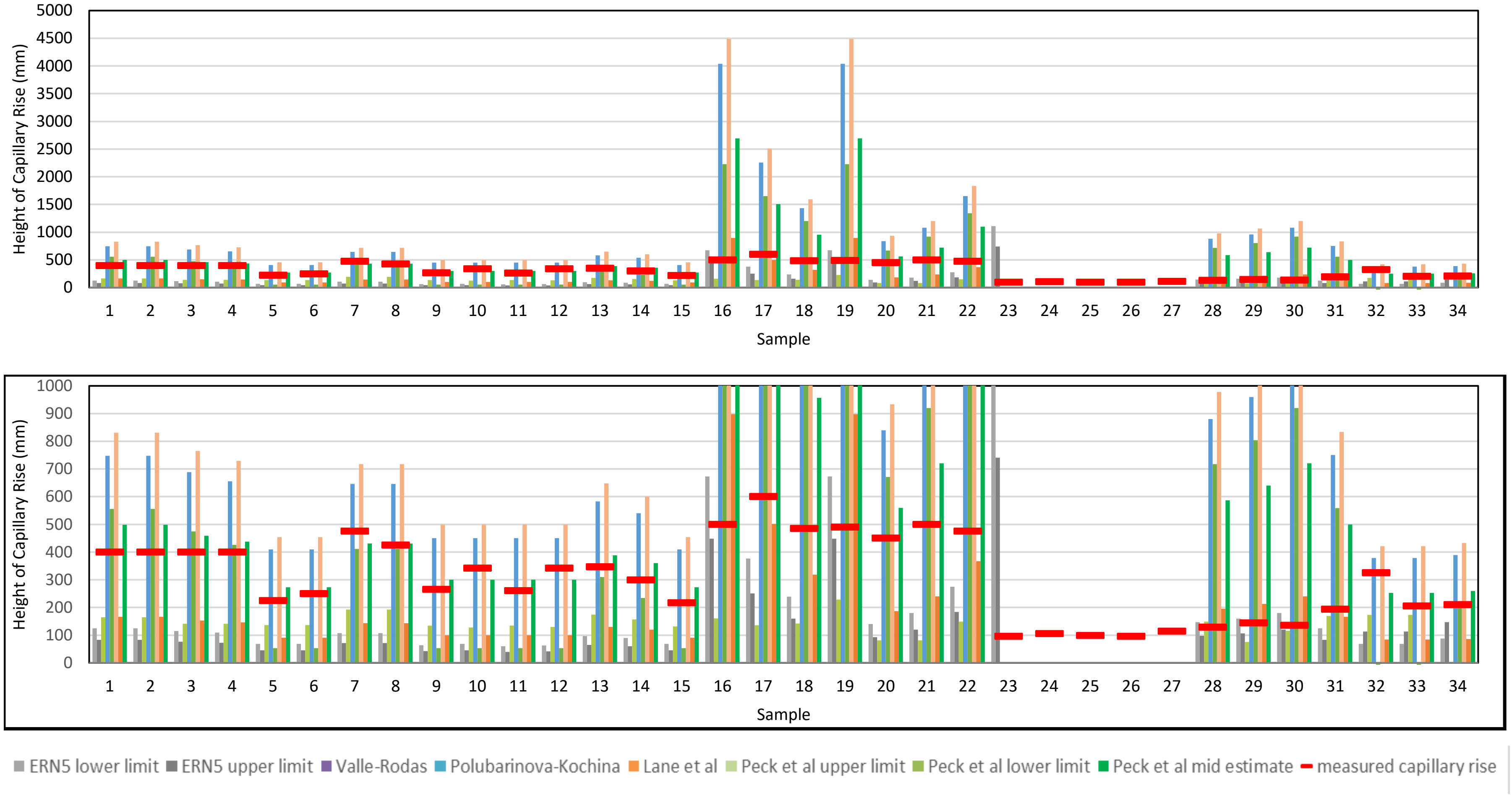


Table 4.5: Capillary rise test samples

Project	Source of information	Sample location	Sample(s)	Material information	Comment
New Perth Bunbury Highway	Southern Gateway Alliance Document No. 02.40-GT-RP-001-0 January 2008 Clayton (2008)	Not defined	1	Tamala sand compacted dry to 94% of Maximum Modified Dry Density (MMDD)	Capillary height defined as '0.65*OMC – standard deviation'.
		Not defined	2	Tamala sand compacted at OMC to 94% of MMDD	
		Not defined	3	Bassendean sand	The measured capillary rise shown in Figure 4.1 is based on field observations rather than laboratory testing. Capillary height defined as '0.65*OMC-standard deviation'. Field testing was carried out along the Old Bunbury Road and Pinjarra Road (6 sites total).
		Not defined	4	Bassendean sand	
Not specified	Main Roads database, Excel Spreadsheet '06BY606-609 Capillary Rise PSD MC white, yellow sand'	Macaulay sand pit, Lot 1307 Mills Road, Coolup	5 and 6	White sand	Available test results only show moisture content by depth and do not include OMC. The measured capillary rise shown in Figure 4.1 was defined as a moisture content of approximately 10%.
		Baldivis Explosives Reserve Stakehill Road, Baldivis	7 and 8	Yellow sand	
Not specified	Main Roads database, Excel Spreadsheets 'Peel Deviation Capillary Rise and CBR tests' and 'Capillary Rise Data Bunbury'	Bunbury, MacAuley's Lot 1307 Site G14	9	White/grey sand	–
			10	Yellow/white sand	–
		Bunbury, McShane Lot 101	11	Grey/white sand	–
			12	Yellow/white sand	–
		Bunbury, Baldivis Stage 2	13	Yellow sand	–
		Bunbury, Wandalup Farm Lot 109	14	Grey/white sand	–
		Bunbury, Cukela Lot 158	15	Not detailed	–
Not specified	Main Roads database, Doc Number M&PT95010-2 26 February 1997	Avon, Ski Lake Road, Kellerberrin	16 to 22	Brown coarse sand	Capillary rise estimates are not accurate as D_{10} could not be accurately defined (it falls in between sieve sizes 0.075 mm and 0.0135 mm).
Bath Structure_Lloyd	Local Geotechnics Report on Material or Soil Properties	Lloyd Street, Midland	23 and 24	Sandy clay	Tested in accordance with AS 5101.5-2008 (for stabilised materials), which prescribes a test duration of 72 hr (even though the report cites a period of 10 days), on compacted samples to e height of 300 mm. This method is considered
			25 and 26	Clay	
			27	Pindan sand	

Project	Source of information	Sample location	Sample(s)	Material information	Comment
Street Rail Track, Midland	(Capillary Rise Test) 27 March 2015	–	28 to 30	Limestone	inadequate to determine the capillary rise of the materials tested, as the capillary rise can occur for much longer periods (especially in clays) and achieve much higher heights. The short duration of the tests is believed to be the reason why the measured capillary rise is very low. PSD not available for samples 24 to 27.
		(Imported fill)	31	Fill sand	
UWA final student project	Li (2018)	Unknown	32	Safety Bay sand compacted dry	–
			33	Safety Bay sand compacted at 70% of OMC	Capillary rise height defined as the height where the moisture content equals the initial moisture content.
			34	Brickies sand compacted at 70% of OMC	Capillary rise height defined as the height where the moisture content equals the initial moisture content.

The analysis shows that none of the equations used to estimate the height of capillary rise were accurate in predicting the height of capillary rise measured in the laboratory or in the field. It is noted, however, that the laboratory tests were conducted following different test methodologies, as currently no standard test method exists.

Some of the test results might be misleading, as the test period is believed to have been too short to allow for the samples to reach equilibrium. Some of the finer sands were only tested for 7 days whereas coarser sands were tested for up to 33 days, clay samples from Lloyd Street were only tested for 72 hours, resulting in total capillary rise of around 100 mm, which is less than the values obtained for sands.

5 TEST METHODS

5.1 SUCTION TESTS

Although it is understood that Main Roads is seeking for a test method to directly measure capillary rise in a column of soil, Section 5.1 presents a brief overview on matric suction tests. The matric suction can be directly correlated to a capillary height, as presented in Figure 2.6.

It is believed that matric suction testing may provide a quicker way to estimate capillary moisture, as the moisture content of interest can be targeted rather than having to wait for the capillary rise to reach an equilibrium in a column test.

It is noted however, that local experience utilising soil suction tests for estimation of capillary rise was not proven successful. Clayton (2008) conducted soil suction testing on Tamala sand and Bassendean sand for the Main Roads Southern Gateway project. The results of the suction tests indicated capillary height values significantly higher than what was observed in the field or measured through laboratory capillary rise tests. It was decided not to use the soil suction test results in the Southern Gateway project. Clayton (2008) indicated that the test procedure may have not been correctly followed.

5.1.1 ASTM D 6836 - 02

ASTM D 6836 - 02 *Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge* describes five methods for determining soil water characteristic curves (SWCC). Methods A and E seem to be the most appropriate for sands.

Method A consists of applying a matric suction on an initially saturated specimen by reducing the pore water pressure, while maintaining the pore gas pressure at the atmospheric condition. As suction is applied, the volume of water that flows from the specimen is measured and the remaining water content calculated. For each increment of suction, it is necessary to wait for equilibrium for at least 48 hours. For suction less than 500 kPa, equilibrium is considered established when the air-water interface has not moved for at least 24 hours (48 hours for suction between 500 to 1000 kPa). The increments depend on the pore size distribution and desired level of detail.

Method E consists of applying different matric suctions to the specimen by applying varying angular velocity at a centrifuge. The SWCC is obtained by measuring the volume of water displaced from the soil at each velocity.

ASTM D 6836 - 02 provides a method to define SWCC for a capillary fall scenario. Although the intent of Main Roads is to determine capillary rise (from dry or at least non-saturated soils), it is recommended that Main Roads considers exploring ASTM D 6836 or a similar method.

5.1.2 OTHER TESTS

Fatahi (2007) summarised a number of matric soil suction measurement devices in a table, which is partially reproduced in Table 5.1 (only tests potentially applicable to non-cohesive soils have been included).

Table 5.1: Soil suction measurement devices and their details

Device name	Suction range (kPa)	Available standard	Test location	Comments	Available types	Reference
Standard tensiometer	0-100	N/A	Lab/Field	Accurate, good contact is required between the sensor tip and the soil, easily installed, but has difficulties with cavitation and air diffusion through the ceramic cup. Should be saturated before the test.	Mechanical Bourdon type pressure sensor Electronic diaphragm type transducer	Cassel and Klute (1986), Stannard (1992)
High capacity tensiometer	0-1500	N/A	Lab/Field	Small, quick, reliable, high air entry pressure ceramics.	Cyclic prepressurisation	Ridley and Burland (1993), Guan and Fredlund (1997)
Tempe pressure cell	0-100	ASTM D2325	Lab	One sample per test, high equilibrium time, not suitable for wetting procedure.	1400/1405 Tempe pressure cell with 3 cm and 6 cm cylinders	Soil Moisture Equipment Corp. (1995)
Hanging column	0-80	ASTM D6836 (1)	Lab	Applicable for large samples, can be connected to data logger, can be combined with tensiometer-coiled TDR probe.	SWC-HCA, 1502C Tektronic cable tester	Or and Wraith (1999)
Pressure plate	0-1500	ASTM D 2325, ASTM 6836, and ASTM D 3152	Lab	Accurate, simultaneous measurement of several samples is possible, but equilibrium on dry samples is slow.	5 bar, 10 bar and 15 bar	Hilf (1956)
Imperial College instrument	0-1500	N/A	Lab/Field	Accurate and very quick, good contact between porous stone and pressure transducer is required and it can have a wide application in the field.	Miniature pressure transducer with Entran Ltd EPX series	Ridley and Burland (1993)
Centrifuge method	0-120	ASTM D6836 (2)	Lab	Indirect measurements, different matric suctions are applied by varying the angular velocities.	Temperature control centrifuge	Singh et al. (2001)
Thermal conductivity sensor	0-1500	N/A	Lab/Field	Indirect measurement using a variable pore size ceramic sensor, fairly precise, easily installed, but relatively expensive and complex electronics required.	AGWA-II and FTC-100	Phene et al. (1971), Wong et al. (1989)
Fredlund SWCC Device	0-1500	N/A	Lab	Applying overburden pressure and applying various stress paths, used for both drying and wetting paths, ability to measure diffused air, used for remoulded or undisturbed samples.	SWC-150 and SWCC-100	Padilla et al. (2005)

1. *Method A (refer Section 5.1.1).*
2. *Method E (refer Section 5.1.1).*

Source: adapted from Fatahi (2007).

5.2 PUBLISHED AUSTRALIAN TESTS

5.2.1 AS 5101.5-2008 (R2017), RMS TEST METHOD T172 AND TMR TEST METHOD Q125D

The Australian Standard 5101.5-2008 (R2017): *Absorption, swell and capillary rise of compacted materials* sets out a procedure for testing capillary rise of unbound, bound and self-cementing materials. This method describes capillary rise testing on specimens compacted in a cylindrical mould with 115.5 mm height. The specimen is placed in water, in a dish to a depth of 10 mm, at room temperature for 72 hours. The height of capillary rise is measured from the base of the rise of water into the specimen based on visual assessment of the specimen.

RMS Test method T172 (2012) – Capillary rise and absorption of modified or bound road construction materials and TMR Test Method Q125D (2014) – Capillary rise of stabilised material present similar procedures to AS 5101.5-2008 (R2017). These test methods are only applicable for road construction materials that gain tensile strength with time. They are not intended to be used with non-stabilised cohesionless granular materials. The specimen is compacted, cured and placed in water for 72 hours. The height of capillary rise is measured based on a visual assessment.

5.2.2 COMMENTS

AS 5101.5-2008 (R2017), RMS Test Method T172 (2012) and TMR Test Method Q125D (2014) are not considered applicable for testing capillary rise in cohesionless granular materials for the following reasons:

- These methods require the specimen to hold together without any covering or mould.
- The capillary rise is determined as the rise of the capillary front after 72 hours, which is a short time for the capillary rise to reach equilibrium in the materials intended to be tested, based on available capillary rise test results conducted on Perth sands.
- The capillary rise is determined visually, which is not always possible in cohesionless soils and does not provide an indication of moisture condition over depth.

5.3 SOUTHERN GATEWAY ALLIANCE

5.3.1 TEST METHOD

Clayton (2008) describes capillary rise tests carried out on two WA sands for the Southern Gateway project, namely Tamala sand and Basendean sand. Testing was conducted as follows:

- The sample was compacted inside a 100 mm diameter acrylic tube to a total height of 600 mm using a target density and moisture content (samples were compacted to 94% of Modified Maximum Dry Density).
- Pieces of geofabric and mesh were placed at the base of the tube to retain the sample.
- A perforated film was placed at the top of the tube to prevent evaporation.
- The tube was immersed in 100 to 200 mm of water and left for a specified period (the report mentions that the tests were run over four months).
- At the end of the test, the tube was cut to remove samples every 50 mm to determine the moisture content versus depth curve.

To investigate the influence of an exceptional flood event, Clayton (2008) performed some duplicate tests where the water level was raised by 300 mm for 96 hours to simulate a flood and then reduced to the original height.

Additionally, suction tests were performed using a similar methodology to ASTM D 6836 – 02.

To define a capillary rise height of interest, Clayton (2008) used Emery's (1988) equations for prediction of equilibrium moisture content (EMC). The author indicated that EMC for the materials tested was likely to be 0.65 times the OMC. To allow a variation of one standard deviation, the author adopted the 75th percentile of OMC and adopted the capillary rise height of interest as being the height for which the soil moisturewas 0.65 of the 75th percentile OMC (i.e.: 0.65*(OMC–StdDev)).

5.3.2 COMMENTS

The study carried out by Clayton (2008) represents important progress in understanding capillary rise behaviour of WA sands and the challenges associated with defining and measuring capillary rise height.

Some of the interesting findings were:

- The results indicated that the initial moisture content of the samples did not affect the final results.
- No significant difference in the final results for the samples that were temporarily inundated (water raised by 300 mm for 96 hours) could be observed.
- Field sampling of Bassendean sand indicated higher capillary rise heights compared to the laboratory measured values (the author mentions boundary effects of the tube as a possible reason).

Rather than reporting a height of capillary rise based on visual assessment (as per 5.2.1 AS 5101.5-2008 (R2017), RMS Test Method T172 and TMR Test Method Q125D), Clayton (2008) reported the moisture content versus height curve and determined the capillary rise height of interest as a function of EMC (and OMC). This is a preferred methodology, as visual detection of moisture in sands can be difficult and also because capillary moisture below the equilibrium moisture content expected in the field should not pose a risk to the pavement.

The following issues have been identified regarding the capillary rise test methodology adopted:

- Test duration: the report notes that the test duration was 4 months. No indication was given when or if the capillary rise had reached an equilibrium. The duration of the test is not practicable for a standard test method intended to be routinely used/required on projects.
- Atmospheric conditions: the test method does not define atmospheric conditions. As presented in the literature review, temperature and moisture conditions have an influence on the capillary rise equilibrium.
- Cover requirements: the report only mentions the use of a 'perforated film' at the top of the tube to prevent evaporation, without providing any details.
- Compaction level: the use of a 1 m long acrylic tube limits the compaction method and achievable density of the sample.
- Apparatus: the methodology adopted consisted of cutting the acrylic tubes at the end of each test, which is not desirable for a standard test method intended to be routinely used/required on projects.

Clayton's (2008) suction tests seem to have been unsuccessful, as the results appear to be significantly higher than what was obtained with the capillary tubes or measured in the field. The author mentions that hysteresis between capillary rise and fall may have played a role (as suction tests are meant to test capillary movement from initially saturated conditions). However, the author also mentions that wetting and drying cycles of sands are typically quite similar, and the suction tests conducted may have not followed a correct procedure.

5.4 UWA

5.4.1 TEST METHOD

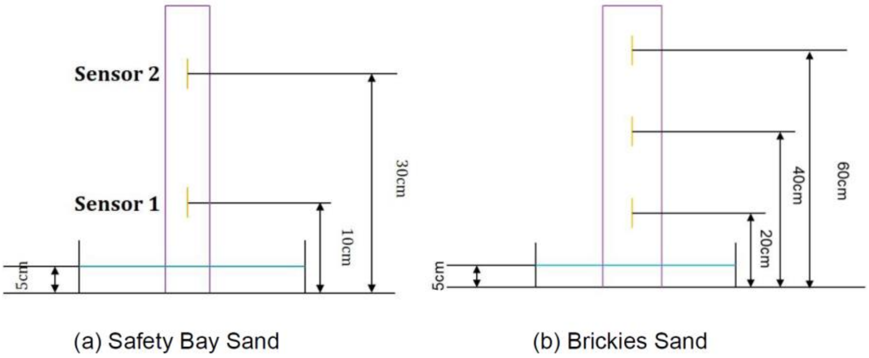
The University of Western Australia (UWA) proposed a new test method for measuring capillary rise in cohesionless soils. The methodology is summarised below:

- Preparation:

  - Compact the sample inside a plexiglass tube with diameter 150 mm and height 1 m (the sample is to be compacted to a desirable height based on the expected/estimated height of capillary rise – i.e. it is not necessary to compact it to 1 m height if the expected capillary rise is much lower than that). Two methods of compaction were used:
    - compaction every 100 mm using a vibration table for dry samples
    - manual compaction every 100 mm using a compaction rammer for samples compacted at 70% of OMC (details on the rammer mass or number of blows were not reported).
  - Place moisture sensors at different heights during compaction (refer to Figure 5.1).
  - Place the tube with the soil sample in a water container set to keep the water level constant.
  - Conduct the experiment in a temperature-controlled room.

The samples compacted at 70% of OMC aimed at simulating conditions closer to what is encountered in the field.

Figure 5.1 Sensor locations for testing samples



(a) Safety Bay Sand (b) Brickies Sand

Source: Li (2018).

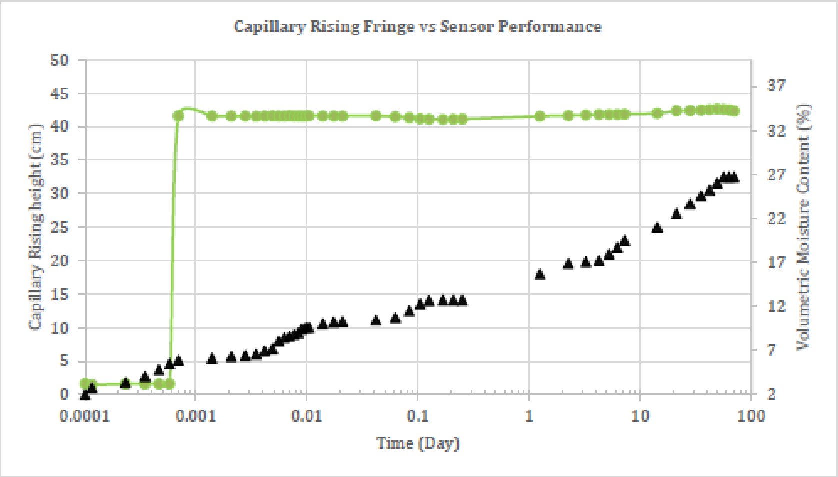
- Data collection
  - Visually observe the capillary fringe taking measurements every minute until the rate of capillary rise reduces dramatically, then observe and record the height to which the water has risen approximately every 3 to 6 hours.
  - Coloured water (using potassium permanganate) to be used with samples compacted at 70% OMC to facilitate visual assessment.
  - Take measurements until equilibrium is reached (where equilibrium is defined as when both sensor measurements and visual readings are steady for one week).
  - Collect samples for moisture content every 50 mm.
  - Plot capillary rise versus time.

5.4.2 UWA TEST RESULTS

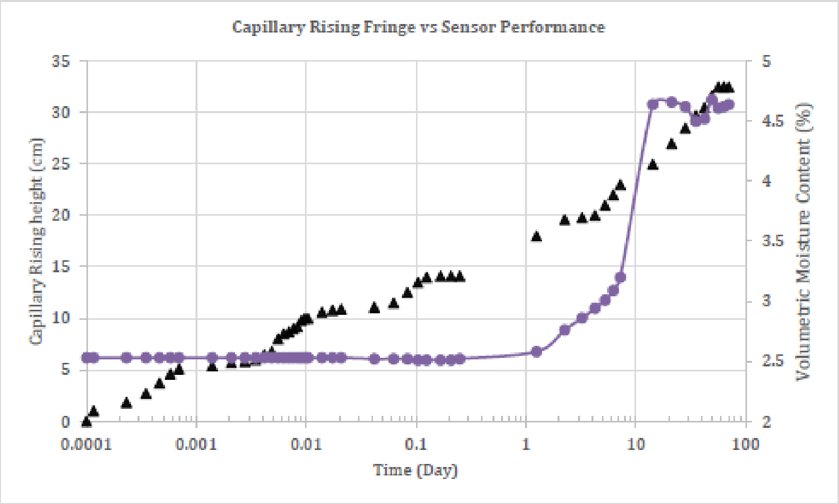
Li (2018) used the procedure to test two WA sands, namely Safety Bay sand and Brickies sand. A capillary rise height versus time and a final moisture content versus height curve could be derived from the results of the test. Two initial moisture conditions were used (dry and 70% of OMC).

The results for Safety Bay sand are summarised in Figure 5.2 (capillary rise and sensor recording versus time), Figure 5.3 (moisture content versus height for initially dry sample) and Figure 5.4 (moisture content versus height for sample compacted at 70% of OMC). The results for the Brickies Sand are summarised in Figure 5.5 (moisture content versus height for sample compacted at 70% of OMC).

Figure 5.2 Capillary rise and sensor recording variation against time – Safety Bay sand compacted dry



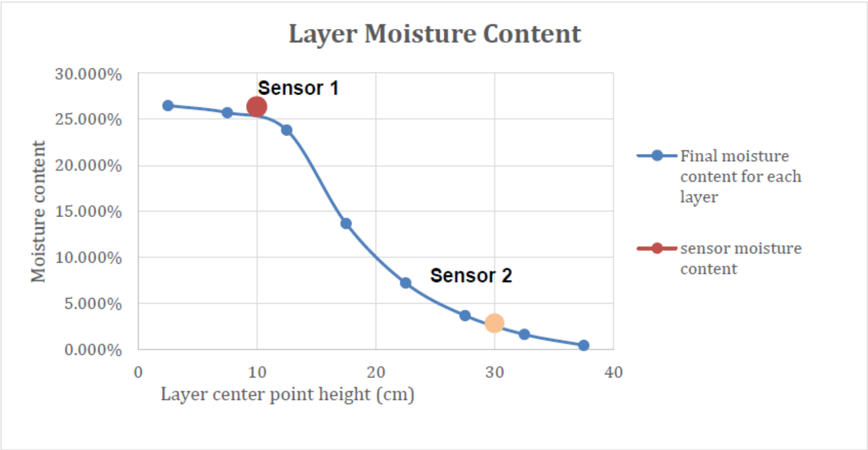
(a) Sensor 1 at 5cm above ground water level



(b) Sensor 2 at 25cm above ground water level

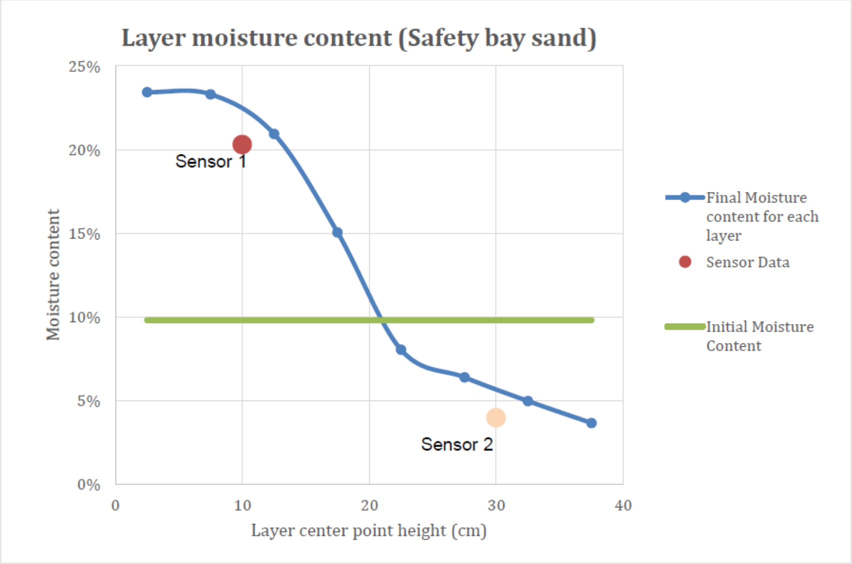
Source: Source: Li (2018).

Figure 5.3 Comparison of sensor measurement and finalised sample moisture content – Safety Bay sand compacted dry



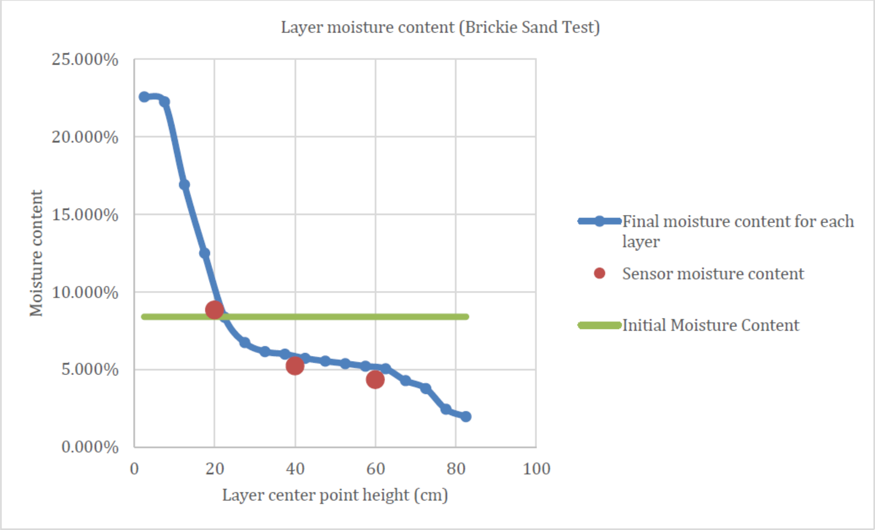
Source: Source: Li (2018).

Figure 5.4 Comparison of sensor measurement and finalised sample moisture content – Safety Bay sand compacted at 70% of OMC



Source: Source: Li (2018).

Figure 5.5 Comparison of sensor measurement and finalised sample moisture content – Brickies sand compacted at 70% of OMC



Source: Source: Li (2018).

The capillary rise heights recorded by Li (2018) are presented in Table 5.2.

Table 5.2: Summary of UWA results

	Height of capillary rise (mm)	
	Compacted dry	**Compacted at 70% of OMC**
Safety Bay Sand	325	205
Brickies Sand	Not tested	210

Source: Li (2018).

Li’s (2018) report does not present the moisture sensor readings for the Safety Bay sand and Brickies sand compacted at 70% of OMC.

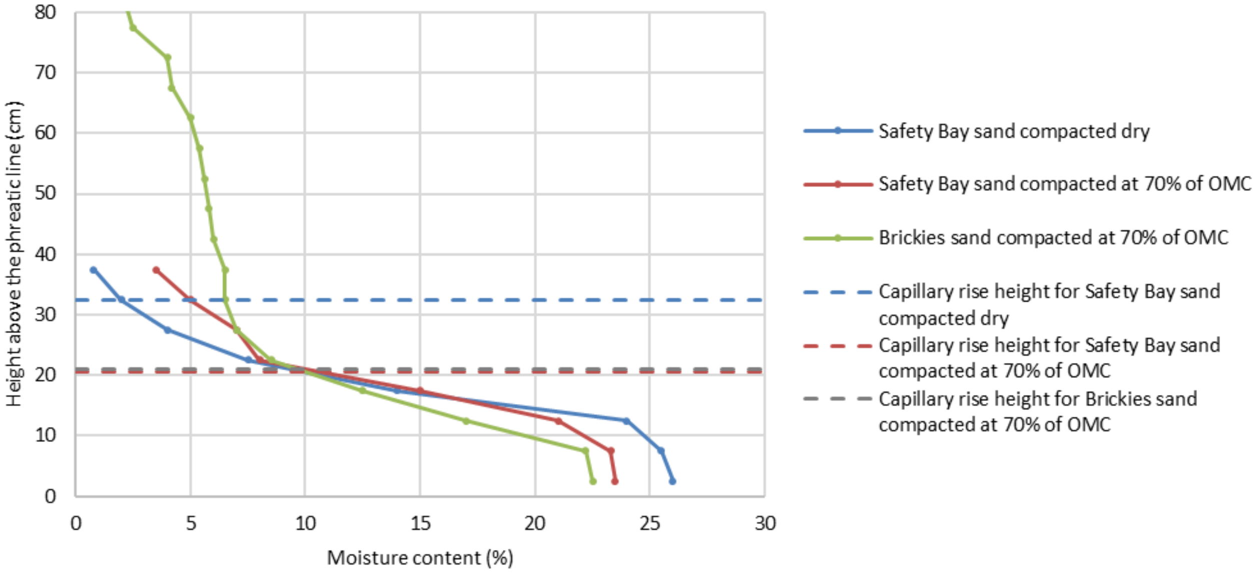
5.4.3 COMMENTS

The results presented by Li (2018) show a difference of 120 mm between the height of capillary rise in the sample compacted dry and the sample compacted at 70% of OMC. It is noted, however, that the height of capillary rise for the sample compacted dry was visually assessed, whereas the height of capillary rise for the sample compacted at 70% of OMC was taken as the height at which the final moisture content is equal to the initial moisture content.

The methodology adopted by Li (2018) resulted in a moisture content of approximately 1% at the maximum capillary rise for the first case and a moisture content of approximately 10% (70% of OMC, where OMC = 14%) for the second case. A comparison between the curves in Figure 5.3 and Figure 5.4 is presented in Figure 5.6, which also shows the capillary rise height as reported by Li (2018).

It can also be observed from Figure 5.6 that if the height of capillary rise was considered to be the height where the soil is at 70% of OMC for both Safety Bay tests, the height of capillary rise would be similar, independent of the initial moisture condition of the sample. This would be consistent with Clayton’s (2008) observation, that there was no difference between the capillary rise test results of Tamala and Bassendean sands compacted dry and wet.

Figure 5.6 Comparison between UWA test results for Safety Bay sand and Brickies sand



Source: plotted using approximate data from Li (2018).

The higher moisture contents at higher heights for the sample compacted at 70% of OMC compared to the sample compacted dry may be partially due to the capillary fall/capillary rise effect, which is illustrated in Figure 2.1. However, the level of compaction achieved for each of the samples (compacted dry and compacted at 70% of OMC) is not reported. The possible difference in compaction levels achieved may explain why higher moisture contents were found within lower heights in the sample compacted dry.

Although interesting results were obtained following the test procedure used by UWA, some issues were identified:

- The use of a long (1 m) plexiglass tube does not allow compaction of the sand sample to a specified compaction level using a modified or standard calibrated compaction hammer. (Li 2018 compacted the samples either with a vibratory table or with a manual hammer at 10 cm increments, no record of the achieved compaction level is available).

- Even with the use of coloured water, Li (2018) reported that the capillary fringe was hard to visually identify.
- The test method did not define if the tube needed to be covered and how.
- Sampling at the end of the test (for moisture content verification) can be quite cumbersome given the length of the tube.
- The criteria to define capillary rise height was different for the tests where the sample was compacted dry and for the tests where it was compacted at 70% of OMC (i.e.: visual assessment versus height for which the soil is at the initial moisture content) and represented very distinct moisture content values.
- Specifying the use of moisture sensors is not desirable in a standard test method.

5.5 PROPOSED TEST METHOD

To overcome the limitations encountered in the test procedure proposed by UWA, the following changes were made in developing the proposed test method:

- Use of a thicker and more deformation resistant stackable mould (similar to a plastic concrete mould) to allow:
  - compaction to a specified compaction level (96% of Modified Maximum Dry Density based on Main Roads Specification 302 for Perth Sands subgrade preparation) using a modified calibrated compaction hammer
  - easier sampling at the end of the test (for moisture content verification).
- Moisture sensors still to be used during development of the test method to determine how long each material takes to reach equilibrium. The use of sensors assisted in defining the minimum required duration of testing for different materials based on the particle size distribution or a representative particle size. It was envisaged that the proposed test method would include a minimum duration of testing as a function of PSD or a representative particle size and would not require the use of moisture sensors. This would eliminate the need for visual assessment of the capillary front.
- Capillary rise is to be reported as moisture content versus height rather than a single value.
- A standard cover over the specimen is to be defined. Ideally, the standard cover should simulate the conditions in the field, minimising evaporation but not creating pressure inside the mould.

The testing only concentrated on capillary rise (wetting) rather than capillary fall (drying).

5.5.1 APPARATUS

The following apparatus were used for the laboratory investigation.

1. cylindrical plastic mould fitted with slots for insertion of moisture sensors
2. additional stackable cylindrical plastic moulds of known volume with an internal diameter 150 mm, height 300 mm and wall thickness of at least 10 mm. Additional moulds must have slots for insertion of the moisture sensors
3. porous/perforated base plate attachable to the mould
4. mould collar and rods to secure the specimen during compaction
5. plastic water tray capable of maintaining a constant water level at 25-50 mm above the base of the mould
6. distilled water
7. filter papers or geofabric with diameter greater than the cylindrical moulds (to stop the sand escaping from the base)
8. plastic mould cap fitted with rubber ring seal to minimise evaporation (the cap should not be tight to the point it generates differential pressure inside the mould)
9. silicone or Vaseline and tape for sealing of joints and slots

10. rachet straps and eye bolts to secure specimen during testing
11. a steel rammer, having essential dimensions complying with Table 5.3, and whose energy delivered per blow has been calibrated
12. drying cabinet set at an air temperature of 45 – 50 °C
13. balance of suitable capacity, readable to 1 g
14. moisture sensors Truebner SMT100 RS485 (Sensor dimension is approximately 180 mm × 30 mm × 12 mm)
15. steel plates with the dimension of the sensors (to be hammered through the slots in the mould after compaction and prior to the insertion of the moisture sensors)
16. data logger Truebner TrueLog100 and cables.

Table 5.3: Dimensions and tolerances for compaction apparatus

Apparatus	Value	Working tolerance
Mould		
Individual internal diameter, mm	150.0	±1.0
Average internal diameter, mm	150.0	±0.5 (1)
Height, mm	300.0	±0.5 (1)
Calculated volume, cm^3	5250	±35 (1)
Rammer		
Diameter, mm	50.0	±0.4
Drop, mm	300.0 (Standard compaction) 450.0 (Modified compaction)	±2.0 (2) ±2.0 (2)
Mass, kg	2.70 (Standard compaction) 4.90 (Modified compaction)	±0.01 (2) ±0.01 (2)
Energy delivered per blow, J	7.94 (Standard compaction) 21.62 (Modified compaction)	±0.08 ±0.08
Number of layers	5	-
Number of blows per layer	25 (varies according to compaction effort)	-
Thickness of each layer	60 (Standard compaction) 60 (Modified compaction)	±0.5 ±0.5
Energy input, kJ/m^3	187 (Standard compaction) 510 (Modified compaction)	±14 ±60

1. *Either but not both of the tolerances may be exceeded provided that the appropriate tolerance of volume is not exceeded.*
2. *Either but not both of the tolerances may be exceeded provided that the appropriate tolerance of energy blow is not exceeded.*

5.5.2 PROCEDURE

The following procedures were used to prepare and test the laboratory samples.

Preparation of the test sample

1. Determine the dry density/moisture relationship on a representative sample passing the 19 mm sieve in accordance with Test Method WA 133.1.
2. Measure the moisture content of the material.
3. Obtain a representative test sample and add the appropriate amount of moisture to ensure the material matches the % OMC required for the test
4. Cure the test increment for 12 hours or more depending upon the soil type. Record the duration of curing.

Preparation of the test specimen

1. Place filter paper on the perforated base of the baseplate and line the inside of the mould with a thin layer of Vaseline to ease specimen extraction.
2. Place the mould with the collar attached and clamp to the rods to secure the mould. Tape the inside of the mould where the slots are located to minimise moisture egress and material loss during compaction.
3. Immediately prior to compaction thoroughly mix the cured soil and determine the moisture content (w_1) of a representative fraction of the test portion in accordance with Test Method WA 110.1.
4. Compact each layer uniformly into the mould, using a modified or standard compaction rammer, to the specified laboratory density. If the height of the layer approaches the top of the mould, determine the mass of the additional mould and attach it. The joint between the moulds and later around the sensor insertion points should be made impermeable by application of Vaseline and/or silicone. Discard specimens that do not meet the above requirements.
5. Ensure the last compacted layer of the specimen is levelled off using a straight edge or a similar tool. Once the desired height of the specimen has been achieved, remove the collar and rods. Exchange with rachet straps and eye bolts to secure the specimen prior to commencement of the capillary test.
6. Obtain the weight of the specimen and moisture samples after compaction in order to compare actual against desired specimen density and moisture. The laboratory moisture ratio shall be within 5.0% of the specified moisture ratio and laboratory density ratio shall be within 1.0% of the specified density ratio.
7. Hammer metallic plates through the slots in the mould to prepare for the insertion of the moisture sensors, then insert the moisture sensors.

Capillary test

1. Place the specimen inside the water tray.
2. Commence logging of the moisture sensor prior to addition of water to establish initial sensor readings.
3. Fill the tray with distilled water to establish a phreatic line approximately 20 mm above the base of the specimen. Throughout the performance of the test the water level is maintained at this level.
4. Note and record the time at which the correct water level is initially achieved.
5. Observe and record the height to which the water has risen approximately every minute for the first couple of days and thereafter every hour. Terminate the test when the moisture sensors record the same moisture content (±1%) for one week.
6. Remove the moulds from the water and immediately, from top to bottom, dismantle stackable moulds and collect samples for moisture condition testing every 50 mm to 100 mm. Regions where moisture sensors are wetting should be extruded and collected for moisture testing in 50 mm increments, otherwise 100 mm increments shall be collected. Use the hydraulic jack and a jacking frame to extrude the specimen as necessary.
7. Determine the hygroscopic moisture content for each sample collected in accordance with Test Method WA 110.1.

6 LABORATORY TESTING

6.1 CAPILLARY RISE LABORATORY EQUIPMENT

The development of the laboratory equipment was focused on trying to use the existing equipment that is available in well-equipped soils testing laboratories.

6.1.1 SAMPLE MOULDS

The selection of the soil moulds needed to provide a sample diameter that could test graded soils with up to 20mm particle sizes and be robust enough to withstand repeated use and the dynamic forces of preparing samples with the modified compaction hammer to high target densities. Two standard moulds were identified as suitable, the 150mm diameter CBR mould and the 150mm diameter concrete cylinder mould.

The concrete cylinder mould was selected as the most appropriate because it was 300mm in length and could be relatively simple to prepare a perforated base plate and adaptor rings to permit the stacking of the mould creating a taller sample. The preparation of compacted soil samples within these concrete cylinder moulds could be readily achieved using the existing procedures for the preparation of CBR samples and the provide a mechanism to release the sample to allow the simple collection of soil moisture samples as 100mm increments.

An additional complication was encountered as part of the research where the soil moisture probes proposed for the research phase of the project were affected by the presence of metal. The soil moisture probes would be used to monitor to change in soils moisture in real time, as the water moved around due to gravity, capillary forces and evaporation. To overcome the problem of the concrete cylinder moulds being made from metal, a set of 150mm diameter PVC moulds were manufactured from PVC bore casing pipe.

6.1.2 SOIL MOISTURE PROBES

Soil moisture probes were implemented in the research phase during the development of this test method to determine the length of time needed to achieve an outcome for the capillary rise test.

The soil moisture probes comprise of Truebner SMT100 RS485 sensors with a dimension of approximately 180 mm length, 30 mm wide, and 12 mm thickness (Figure 6.1).

Figure 6.1 Truebner soil moisture probe

6.1.3 VACUUM DRYING CHAMBER

A large vacuum drying chamber was constructed as part of the research phase for this project to encase prepared samples up to 1200mm in length and vacuum dry the samples to close to 0% moisture content by applying a vacuum and heat to the soil sample. Initial attempts of applying only a vacuum to the sample did not achieve an acceptable drying rate and heating of the sample was required.

The vacuum drying chamber comprise of a 1.5m length of 200mm bore hole casing and end cap. The bore casing was placed over the completed sample and sealed against the base plate by a gasket and the base plate perforations were sealed by placing the base plate on a rubber mat. A standard air supply fitting was connected on to the top cap of the vacuum chamber to apply the negative pressure (Figure 6.2).

The sample was heated during the vacuum drying process by wrapping the sample with a product called heat tape that is used to stop water pipes from freezing in cold environments (Figure 6.3). The heat tape was connected to a variable power supply that was adjusted to apply a maximum current of 20 amps at 12 volts.

Figure 6.2 Enclosed vacuum drying apparatus

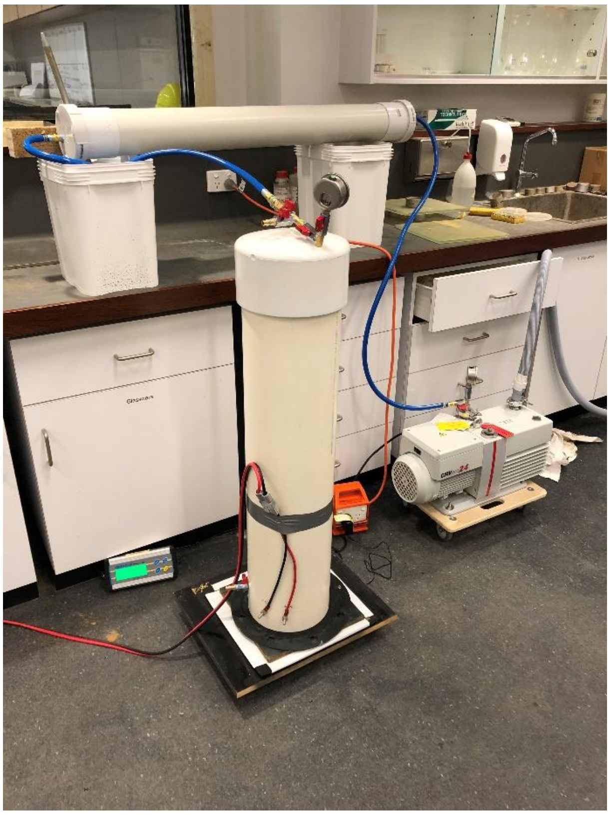


Figure 6.3 Moulded sample wrapped with heat tape

6.1.4 CONSTANT HEAD WATER BATH

The constant head water bath was constructed using a large plastic tray approximately 60mm deep and sealed 2 litre water containers with a small water outlet hole and air inlet hole cut 20mm above the bottom of the container (Figure 6.4). The volume of water drawn into the test specimens was relatively low and the 2 litre water container was sufficient to maintain the constant water level for a couple of days before it need refilling with water. Due to the loss of water due to evaporation, distilled water was used for the testing to eliminate the risk of salt build up during the 90 day tests.

Figure 6.4 Sample set-up with constant head water bath

6.2 TEST CONDITIONS

6.2.1 SAMPLE DENSITY

The theory suggests that soils with narrow void structures and large surface areas will provide higher capillarity forces allowing moisture to climb higher within the test sample. This suggest that the same soil compacted to a high density will have smaller voids and a more closely packed granular structure providing a higher level of capillary rise. The testing was structured to test each sample at two densities to investigate the effect of density on capillary rise.

6.2.2 SAMPLE HEIGHT

The effect of the sample height needs to be investigated to determine the minimum height of the test sample and understand the effects of drying from the top surface of the sample. Having the sample longer than needed adds significantly to the cost of the test and if the sample is not long enough there maybe erroneous results produced. The testing moulds allowed for almost any length of sample to be assembled in 300mm increments only limited by OSH issues of compacting the next increment whilst standing on a work platform.

For the Tamala sand sample three sample lengths, 600mm, 900mm and 1500mm samples were constructed and tested. In addition to adjustments to the sample length a PVC cap could be fitted to the end of the sample effectively eliminating any evaporation from the upper surface. Some of the samples were tested with a capped end to investigate the effect of the capillarity when evaporation from the upper surface was prevented.

6.2.3 THE EFFECT OF TIME ON THE CAPILLARITY TESTING

Like most geotechnical concepts, it was thought that the rate of capillary rise and capillary fall would follow a logarithmic trend. To investigate the effect of time and examine the rate of moisture change within the test samples, the specimens were instrumented with a soil moisture probes at 100mm increments commencing from 50mm from the base of the sample. These moisture probes measure the volumetric water content about 50mm surrounding the probe and the results logged by a digital logger. The results of the moisture probes were used to provide moisture content plots with time to investigate the progress of the capillary fall and capillary rise over the duration of the test.

6.2.4 INITIAL MOISTURE CONTENT

The initial moisture content for the investigation proved to be the most challenging parameter to investigate due to the limitations of the PVC moulds used for the testing and a developing understanding of the capillarity process. PVC moulds were used to facilitate the use of electrical soil moisture probes that would not work in a steel mould, the sample could not be placed in a hot 110°C oven for drying. There was a requirement to investigate the effect of capillary rise in the absence of any capillary moisture fall by starting with a completely dry sample.

6.3 MATERIALS AND SAMPLE PREPERATION

Four materials were tested as part of the laboratory investigation into capillary rise of non-cohesive soils. These materials were:

- Tamala sand (two sources), pale yellow, fine to medium grained, sub rounded, predominately quartz grains.
- Clayey sand, brown, fine to medium grained, containing 13% low to medium plastic fines.
- Crushed limestone, Gravelly Sand, pale grey / white, fine to medium grained sands with fine to course calcarenite gravel.

Table 6.1 shows the particle size distribution and plasticity characteristics for each of the materials tested. This information is also presented in Figure 6.5.

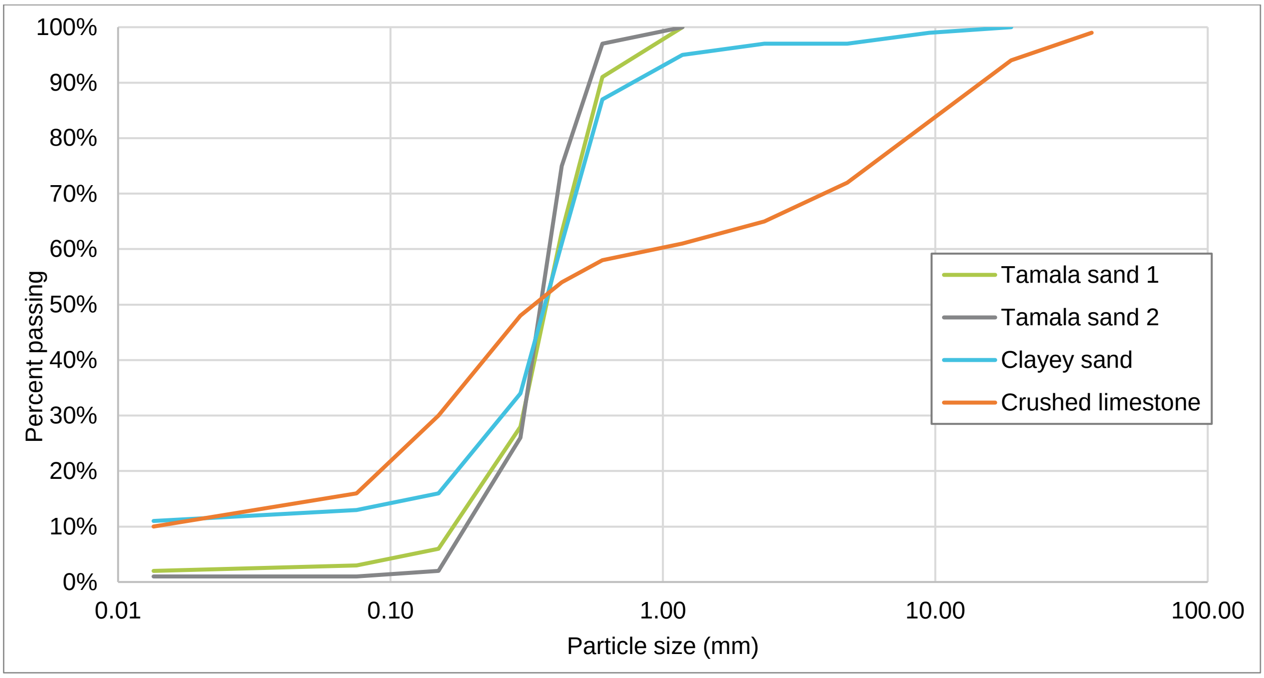
Table 6.1: Particle size distribution and plasticity characteristics of test materials

% Passing sieve size (mm)	Tamala sand 1	Tamala sand 2	Clayey sand	Crushed limestone
37.50	-	-	-	99
19.00	100	100	100	94
9.50	100	100	99	83
4.75	100	100	97	72
2.36	100	100	97	65
1.18	100	100	95	61
0.600	91	97	87	58
0.425	63	75	61	54
0.300	28	26	34	48
0.150	6	2	16	30
0.075	3	1	13	16
0.0135	2	1	11	10
Liquid limit (%)	-	-	29.3	-
Plastic limit (%)	-	-	13.2	Non plastic
Plasticity index (%)	-	-	16.1	Non plastic
Linear shrinkage (%)	0	-	4.5	0

Notes

1. *Tamala Sand was sourced from sand quarry on xxx Road xxxx.*
2. *Clayey Sand was sourced from fill material used on the NorthLink 2 project. The fill material was supplied by Brajkovich Demolition and Salvage quarry located at 91 Walyunga Road, Bullsbrook*
3. *Crushed Limestone was sourced from ???*

Figure 6.5 Particle size distribution of test materials



The majority of the investigation focused on Tamala sand as the test material. The Tamala sand samples were prepared as test specimens to the following parameters.

- Varying the sample length between 600mm, 900mm and 1500mm.
- Varying the sample density between, 90% and 100%
- Varying the moisture condition at the start of the test.
- Varying the top of the sample condition by either having the top of the sample exposed or sealing the top of the sample from evaporation with a PVC cap.

Two samples of clayey sand sourced by Brajkovich Demolition and Salvage quarry located at 91 Walyunga Road, Bullsbrook were tested at varying densities and starting moisture contents.

Two samples of crushed limestone were tested at two different densities to investigate the effect of density.

6.4 RESULTS

Table 6.2 provides a summary of the laboratory testing undertaken and the apparent capillary rise measured at the completion of each test. The degree of compaction is shown in terms of density rather than a percentage of maximum dry density to enable a comparison over the different material types.

Table 6.2: Laboratory test results

Sample ID	Material type	Compaction			MEASURED CAPILLARY RISE (mm)
		% MDD	Dry density (t/m^3)	Moisture content (%OMC)	
1*	Tamala sand 1	96	1.67	60	230
2		96	1.67	60	230
3		96	1.67	60	230
4		96	1.67	0[1]	580
5*		96	1.67	100	230
6*		96	1.67	60	230
10*		96	1.67	80	230
8	Tamala sand 2	100	1.65	0[2]	320
9		90	1.49	0[2]	280
7	Clayey sand	94	1.91	80	430
11		94	1.91	0[3]	680
12	Crushed limestone	92	1.89	0[3]	880
13		88	1.81	0[3]	880

1. *Compacted at 100% modified OMC and dried back to 0%.*
2. *Compacted at 0% modified OMC using a vibrating table.*
3. *Compacted at 80% modified OMC and dried back to 0%.*

Note:

* *Tested with a cap on.*

The measured capillary rise was calculated by determining the height of the wetting front within the samples using the final oven moistures at 50 mm increments in addition to the sensor readings at 100 mm increments, and subtracting the constant phreatic level of the water (20 mm).

6.4.1 TAMALA SAND

From the results presented in Table 6.2 and Figure 6.6 for the Tamala sand, it can be noted that for the samples compacted to the same dry or wet density, the moisture content at the start of the test did not influence the measured capillary rise. It can also be noted that testing a sample with a sealed top or cap on has not influenced the measured capillary rise of samples tested at > 60%.

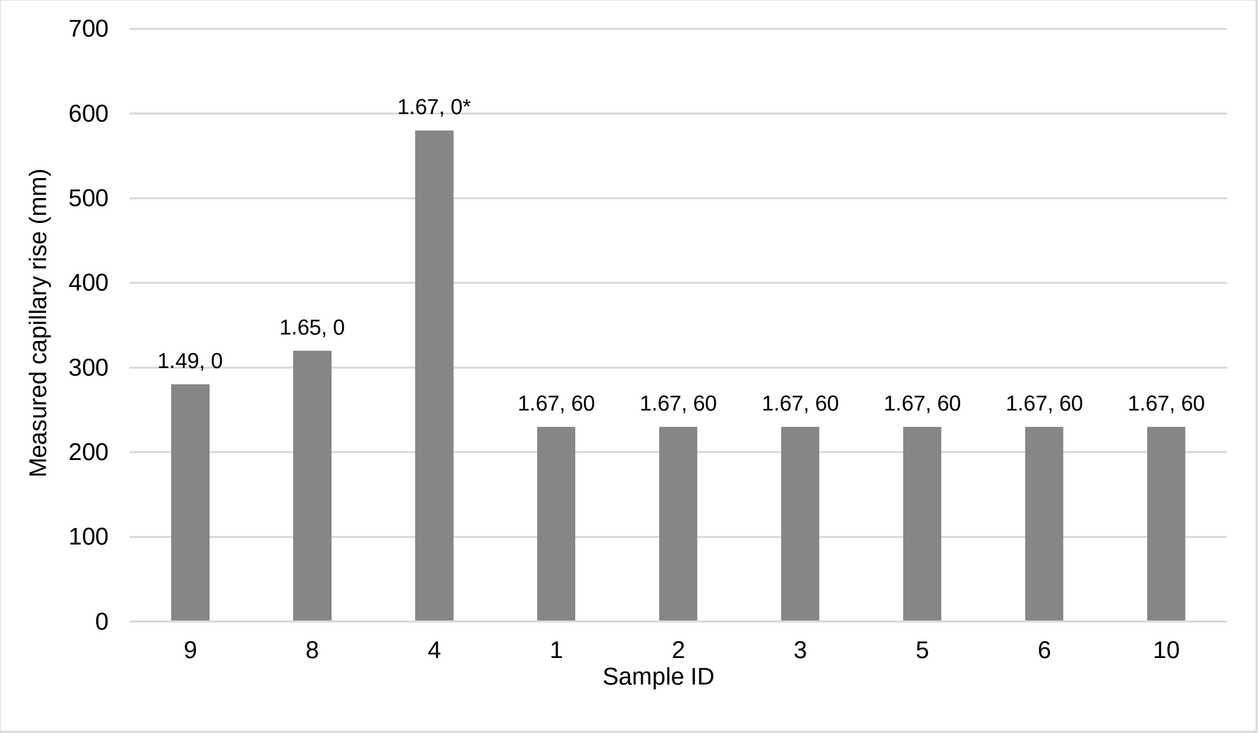
The results of the samples which were compacted at 0% OMC using a vibrating table suggest that the capillary rise in samples compacted dry were higher than those compacted with moisture present.

The results of sample 8 and sample 9 also suggest that capillary rise increases as compaction density increases. Using regression analysis, it can be estimated that capillary rise increased by 0.24 mm for every 1 kg/m^3 increase in compaction density (Figure 6.7).

Using the same analysis, the capillary rise difference between samples compacted at 0% OMC and those compacted with moisture was approximately 95 mm for Tamala sand (Figure 6.7).

The final observation suggests that samples compacted at OMC and dried back to 0% OMC before testing had the highest capillary rise, approximately 350 mm higher than samples compacted at < 60% OMC and 255 mm higher than samples compacted at 0% OMC using a vibrating table.

Figure 6.6 Tamala sand - measured capillary rise

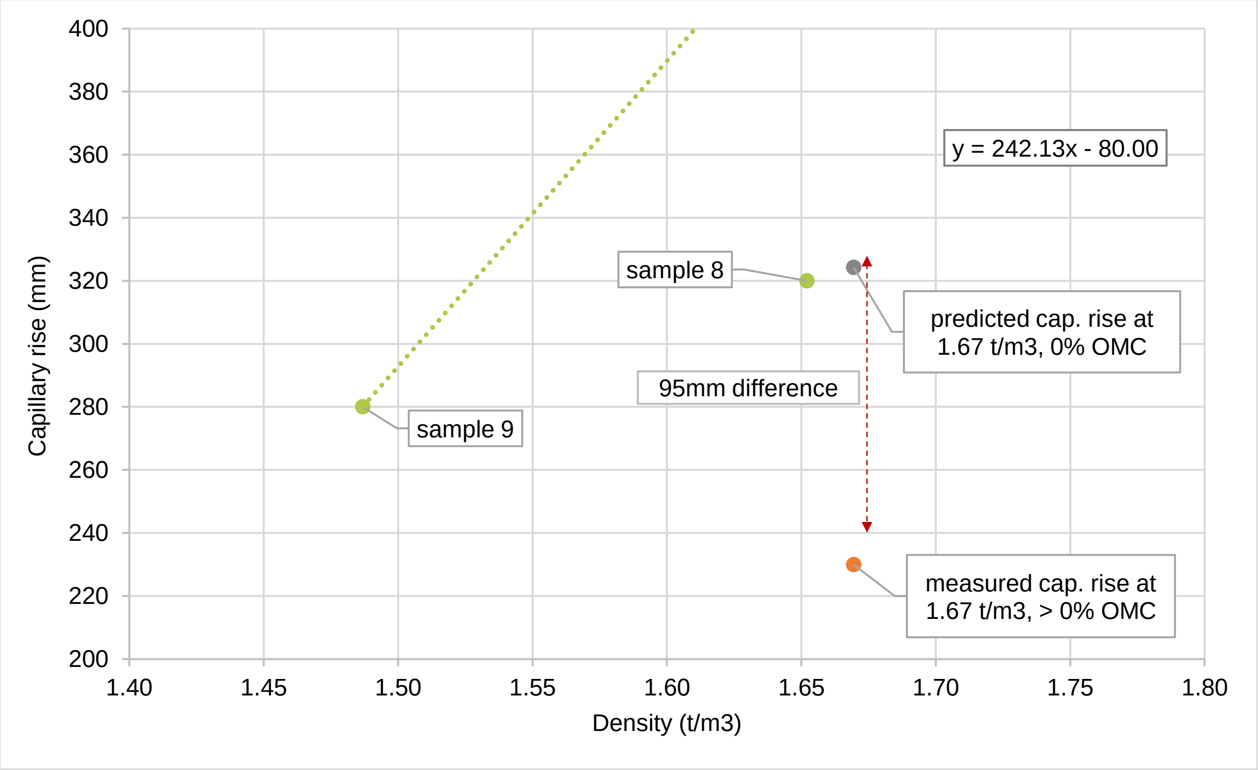


Notes:

1. Labels describe density in kg/m^3 and % modified OMC at testing.

** Sample compacted with moisture then dried back before testing.*

Figure 6.7 Tamala sand – change in capillary rise with density at 0% OMC



Note:

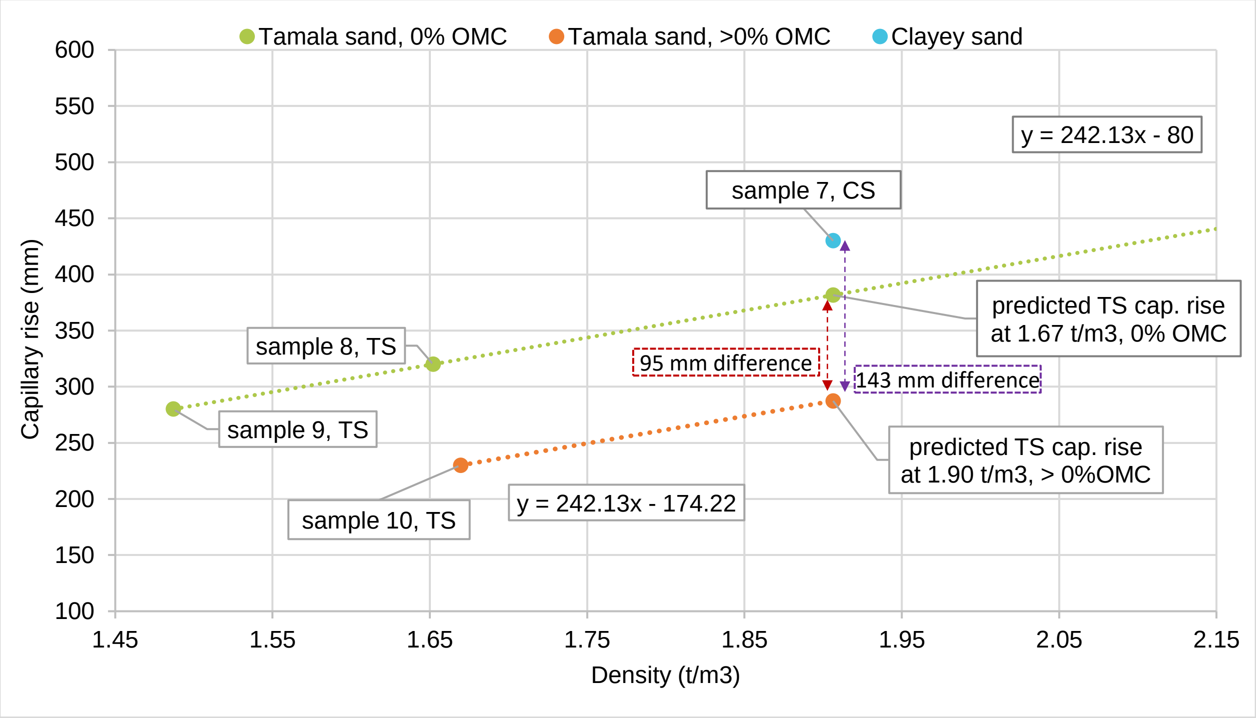
1. Samples 8 and 9 compacted at 0% OMC using a vibrating table.

6.4.2 CLAYEY SAND

From the results presented in Table 6.2 for the clayey sand, it can be noted that similar to the Tamala sands, samples which were dried back prior to testing demonstrated a higher capillary rise. For clayey sand this difference was approximately 250 mm.

Comparing the clayey sand sample 7 to the Tamala sand samples, and accounting for the observation that moisture does not affect capillary rise, the capillary rise for clayey sand was higher than Tamala sand. This may be attributed to the higher fines content of this material. This difference was calculated through regression analysis as 143 mm (Figure 6.8).

Figure 6.8 Capillary rise of clayey sand versus Tamala sand



Note:

1. Samples 8 and 9 compacted at 0% OMC using a vibrating table.

6.4.3 LIMESTONE

From the results presented in Table 6.2 for the crushed limestone samples, the previous observation that samples which were dried back before testing demonstrated a much higher capillary rise could be supported.

It may also be noted that when samples were dried back prior to testing, density did not affect the capillary rise height.

The capillary rise height of the crushed limestone at a moisture content > 60 % OMC may be in the range of 630 mm and 785 mm. This has been calculated using the differences of 95 mm and 250 mm between dry samples and wet samples for the sand materials.

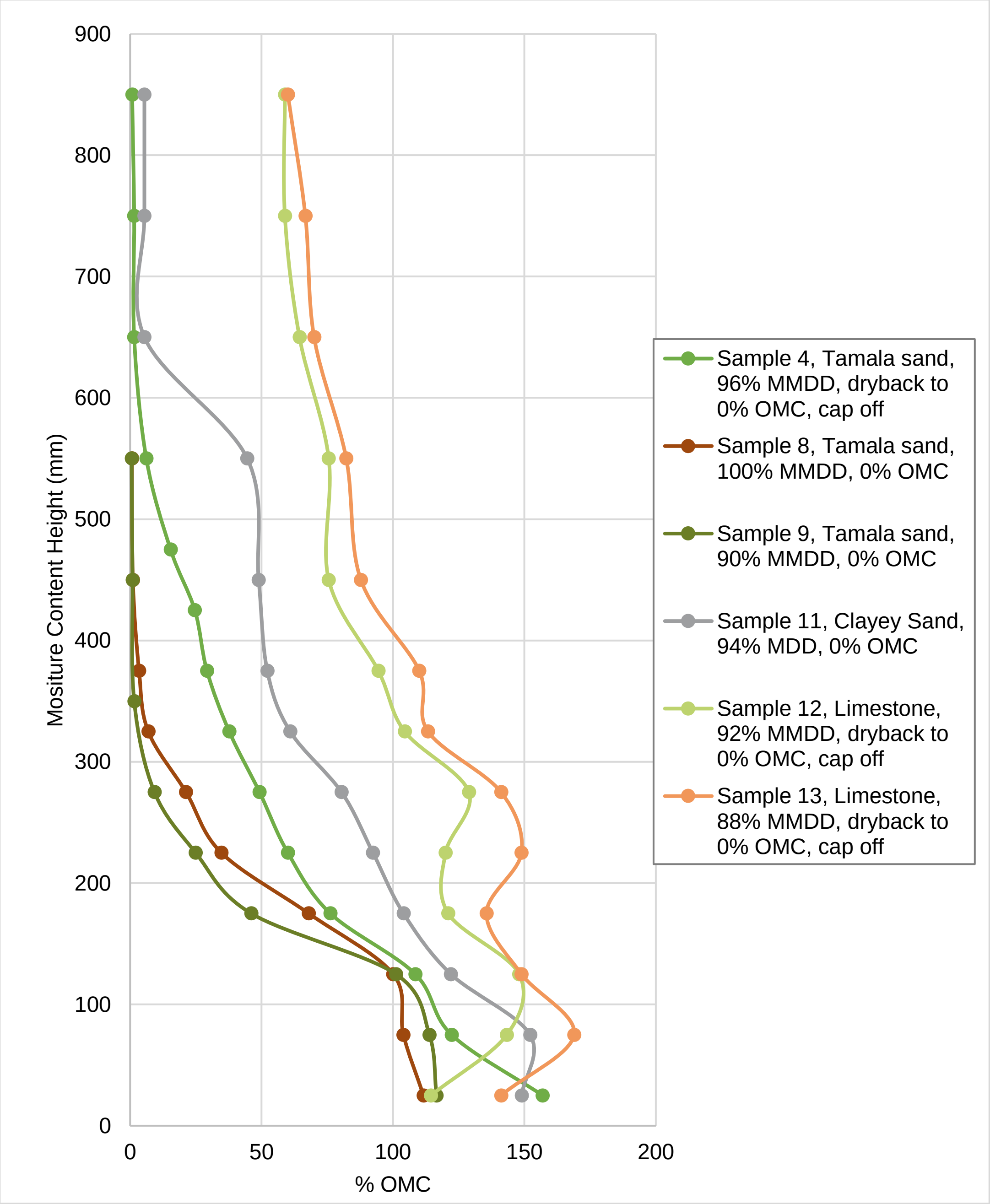
7 DISCUSSION OF FINDINGS

7.1 EFFECT OF MATERIAL ON CAPILLARITY

To study the process of capillary rise only, selected samples were dried back to approximately 0% OMC by placing the entire prepared sample into a vacuum drying chamber to draw all the moisture out. The vacuum drying of such a large sample was difficult and time consuming and required a few days to complete and specialist equipment and is outside the scope of the proposed test method however was implemented in this project to study the effect of capillary rise in isolation.

Samples 4, 8, 9, 11, 12 and 13 were dried back in the vacuum chamber and the final laboratory moisture contents in terms of % OMC at the end of the capillary rise test are shown in Figure 7.1.

Figure 7.1 Final moisture versus sample height – samples tested at 0% OMC



To understand the difference in the capillarity of each of these samples, the level which the sample reach various % OMC has been interpolated from Figure 7.1 and are presented in Table 7.1.

Table 7.1: Capillarity comparison – samples tested at 0% OMC

Sample ID	**Material type**	**Compaction**			**Level 20% OMC (mm)**	**Level 60% OMC (mm)**	**Level 100% OMC (mm)**
		% MDD	**Dry density (t/m^3)**	**Moisture content (%OMC)**			
4	Tamala sand 1	96	1.67	0[1]	450	225	138
8	Tamala sand 2	100	1.65	0	279	186	125
9		90	1.49	0[2]	240	162	125
11	Clayey sand	94	1.91	0[3]	612[4]	330	186
12	Crushed limestone	92	1.89	0[3]	>900	730	347
13		88	1.81	0[3]	>900	850	408

Notes:

1. *Compacted at 100% modified OMC and dried back to 0%.*
2. *Compacted at 0% modified OMC using a vibrating table.*
3. *Compacted at 80% modified OMC and dried back to 0%.*
4. *Sample 11 test duration was 45 days and higher levels of moisture content in the upper third of the sample are likely.*

These results of capillary rise moisture levels within completely dried samples demonstrate that the type of material has a significant impact on the amount of moisture that is drawn up into the sample.

The capillarity of the Tamala sand sample was similar to the other sand samples that started at high moisture contents. The capillarity for the clayey sand soils were lower than expected and the crushed limestone was higher than expected.

Overall these results demonstrate the soil composition has a significant effect on the capillarity and the capillarity of clayey soils may be influenced by the clay fraction absorbing moisture, swelling and then blocking potential moisture pathways.

7.2 EFFECT OF DENSITY ON CAPILLARITY

To study the effect of higher densities on the capillarity of the soils two samples at varying density were prepared and tested. It was though that as the density of a sample increased, the voids would be reduced by the more tightly arranged particles. The closer packing may then provide narrower pathways for the surface tension of the water to climb the soils structure more efficiently.

Samples 8 and 9 are Tamala sands compacted at different densities and 12 and 13 are limestone samples compacted at different densities. The final laboratory moisture contents in terms of % OMC at the end of the capillary rise test are shown in Figure 7.2.

Overall these results and those presented in section 6.4 demonstrate soil density has little effect on the capillarity of the soil in the range of densities tested.

Figure 7.2 Final moisture versus sample height – samples tested at varying density

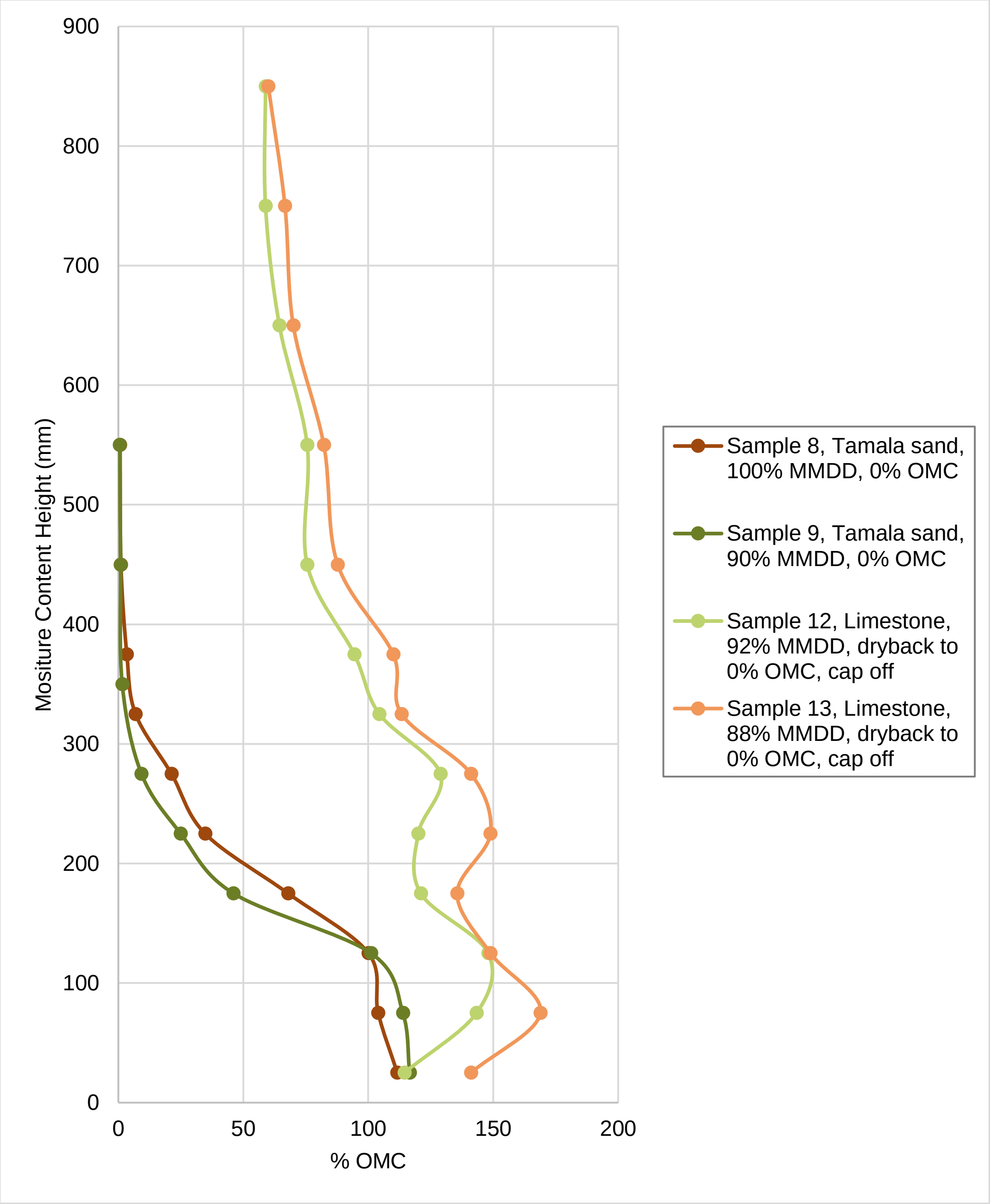


Table 7.2: Capillarity comparison – samples tested at various densities

Sample ID	Material type	Compaction			Level 60% OMC (mm)	Level 80% OMC (mm)	Level 100% OMC (mm)
		% MDD	Dry density (t/m^3)	Moisture content (%OMC)			
8	Tamala sand 2	100	1.65	0	186	156	125
9		90	1.49	0[1]	162	144	125
12	Crushed limestone	92	1.89	0[2]	730	432	347
13		88	1.81	0[2]	850	568	408

Notes:

1. *Compacted at 0% modified OMC using a vibrating table.*
2. *Compacted at 80% modified OMC and dried back to 0%.*

7.3 EFFECT OF SAMPLE HEIGHT AND TOP OF SAMPLE TREATMENT ON CAPILLARITY

The effect of varying the sample height is shown in Tamala sand specimens 1,2, 3 and 6. These samples were constructed by compacting the Tamala Sand into moulds of 600mm, 900mm and 1500mm height. Sample 1 was fitted with an airtight PVC cap and the other samples were left open to the air.

The results of the final moisture contents samples are shown in Figure 7.3 and the interpolated height of 60% OMC and 100% OMC are calculated in Figure 7.3.

Figure 7.3 Sample 1,2,3 & 6, Tamala Sand, 96% MMDD, 60% OMC

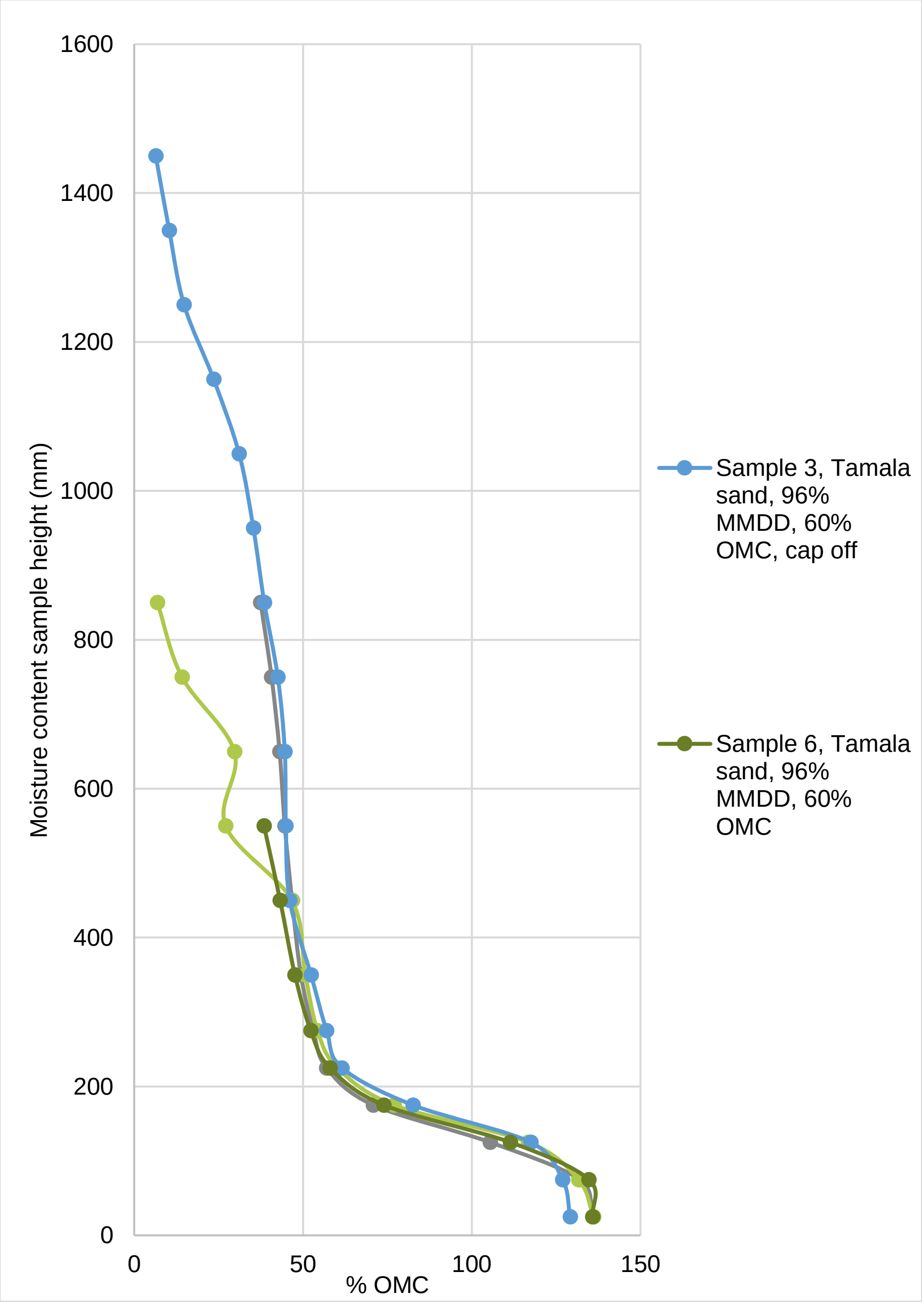


Table 7.3: Capillarity comparison – samples tested at various sample heights and end conditions

Sample ID	Material type	Sample height (mm)	Level 60% OMC (mm)	Level 100% OMC (mm)
1*	Tamala sand 1	900	214	132
2		900	225	146
3		1500	228	150
6*		600	218	140

The results indicated that the final moisture profile for capillary rise and capillary fall are very similar over the lowest 300mm of the sample. Sample 1 (900mm) has the upper surface covered with a PVC cap preventing evaporation and this sample provides very similar results to the longer sample 3 (1500mm). The samples without a PVC cap that are exposed to the atmosphere gradually dry back from the sample preparation condition of 60% of OMC to less than 10% of OMC. The shortest sample, (No 6, 600mm) appeared to follow the moisture content profile of the longer samples.

Overall, these results demonstrate sample lengths greater than 600mm have no effect on capillary rise moisture contents of 60% OMC and 100% OMC. Furthermore, sealing to upper surface of the sample has no effect on capillary rise moisture contents of 60% OMC and 100% OMC.

7.4 MOISTURE SENSOR TIME ANALYSIS

The moisture sensor time plots were very useful in developing an understanding of the soil moisture dynamics in the sample. Typically, there were three mechanisms impacting on the soil moisture:

1. Capillary rise where moisture was drawn up into the sample (capillarity).
2. Capillary fall where moisture could not be maintained at the compaction condition and the moisture naturally drained down.
3. Evaporation, where moisture was lost to the atmosphere at the top of the sample.

The three processes are shown in the capillary rise test plots to varying extents and most clearly shown in Sample 3, the longest sample.

These three processes were also shown in the moisture time plots where the upper portion of the sample reduced in moisture for the duration of the test and the lower portion of the sample increased in moisture. The compaction moisture content at a particular level was typically stable with the moisture content increasing below this level and reducing above this level. This phenomenon is shown in the moisture sensor time plots and provides some certainty in limiting the duration for the capillary rise test to a nominal time.

The sensor time plots highlight the process that capillary rise and capillary fall commence simultaneously. The rate of moisture increase at the bottom of the sample appears to occur very rapidly and within hours significant increase in moisture content is observed. The process of capillary fall occurs at a much slower rate and is fastest at the top of the sample.

The moisture sensor plots for four of the Tamala sand samples with initial moisture contents of 0%, 60%, 80% and 100% of OMC and 96% MDD. are shown in Figure 7.4 to Figure 7.7. Each sample has a similar final capillary result however the way the moisture moved around within the sample was related to the starting moisture content.

Moisture sensor time plots for all samples for selected days over the test period are provided in Appendix A.

Figure 7.4 Moisture sensor time plot – Tamala sand sample 4, 0% OMC

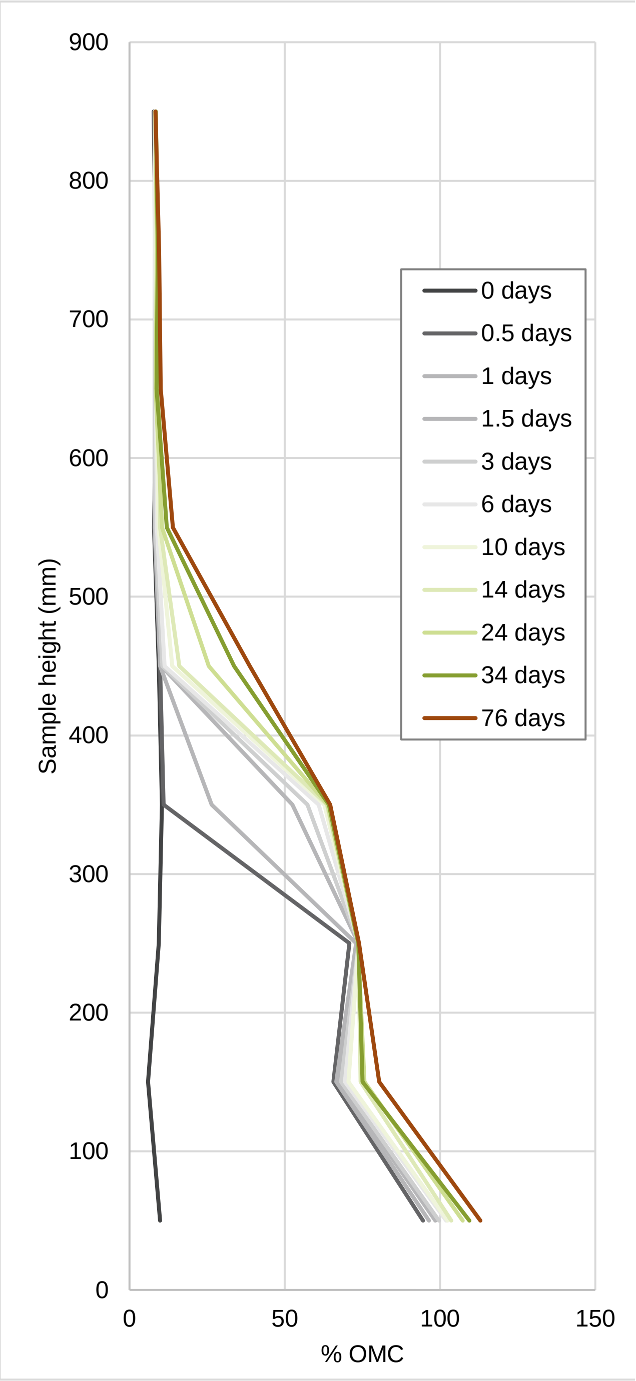


Figure 7.5 Moisture sensor time plot – Tamala sand sample 2, 60% OMC

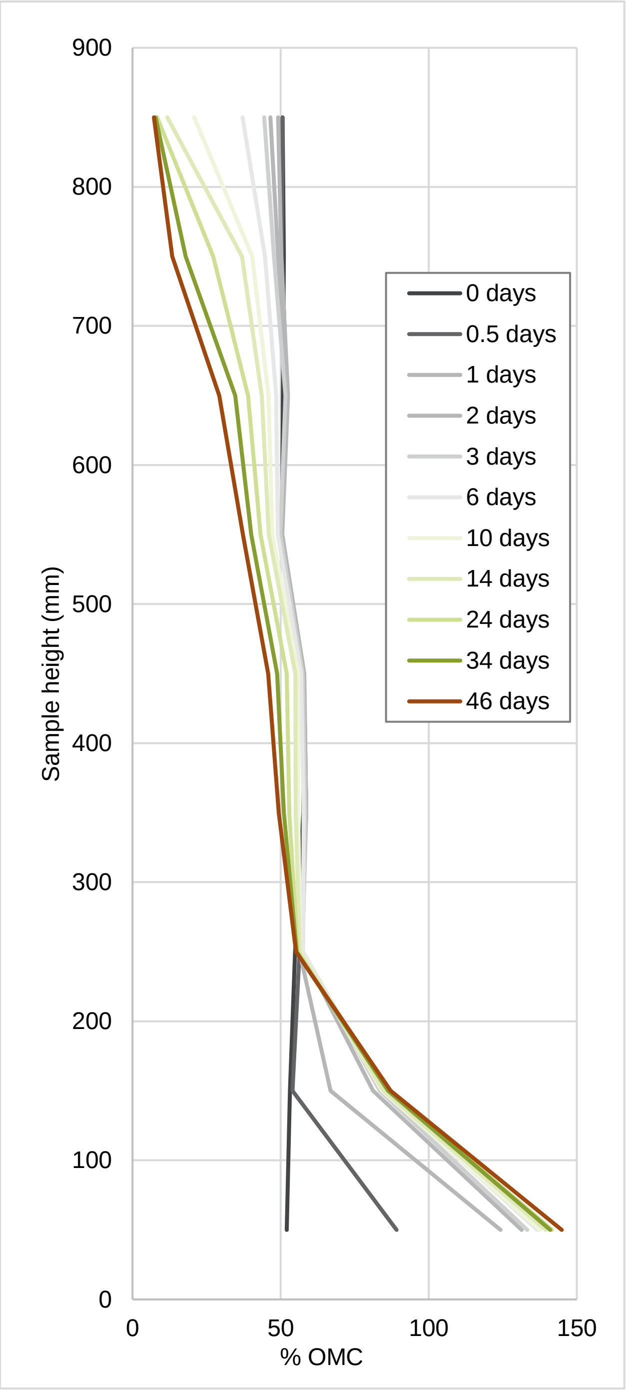


Figure 7.6 Moisture sensor time plot – Tamala sand sample 10, 80% OMC

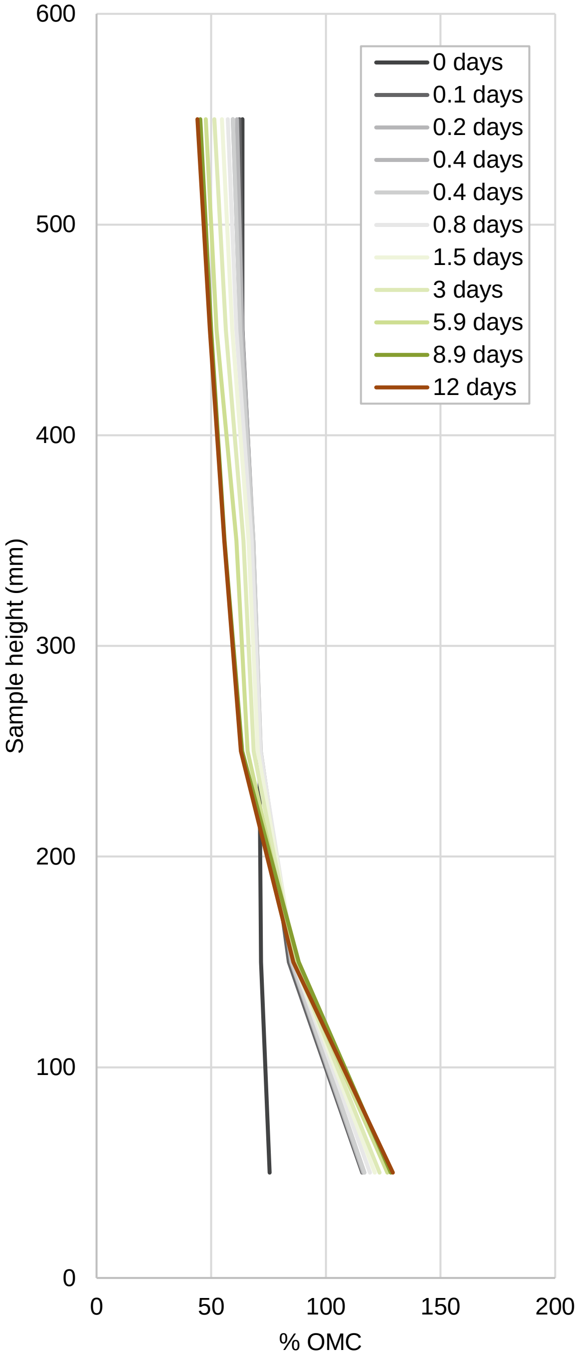
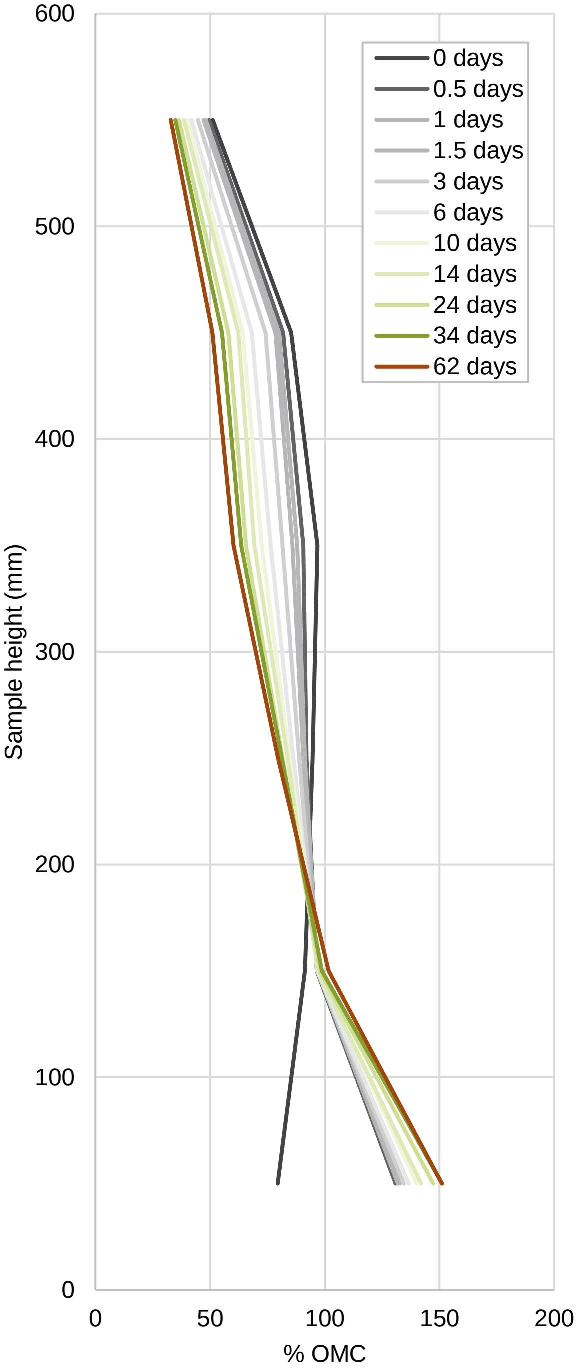


Figure 7.7 Moisture sensor time plot – Tamala sand sample 5, 100% OMC



7.5 TEST METHOD TEST CONDITIONS

7.5.1 MOISTURE AND DENSITY

There are significant advantages is preparing the test sample at optimum moisture content as it attributes to the least amount of compactive effort needed to prepare the sample and it simulates the likely approach during the construction of the earthworks. Due to the height of the sample and minimal drying area, being the top face of the sample, any procedure to dry back the test sample to a target dry back condition is difficult to achieve and a significant moisture gradient will be created.

It was observed (section 6.4) in the laboratory that the moisture content at the start of the test did not affect the final capillary rise height. Conversely it was observed that a change in dry density may affect capillary rise height, with higher compaction density causing higher capillary rise.

Allowing density to be chosen based on the application will enable representative results of capillary rise to be obtained. As moisture content does not affect the capillary rise result, and to reduce inconsistencies with sample preparation and dryback, the test moisture content has been set as 100% modified OMC.

Based on these observations the test conditions for the Test Method are recommended as follows:

- Density can be varied based on the application to ensure a representative condition of the in-service material.
- Moisture content should be set as equal to modified optimum moisture continent (OMC).

7.5.2 SAMPLE HEIGHT

Sample heights are shown in Table 7.4. For sand samples with the moisture condition > 60% OMC, the capillary rise was typically less than 300 mm where the material was clean with < 5% passing the 0.075 mm sieve. For material with higher fines content capillary rise was typically less than 500 mm. A sample height of 600 mm and 900 mm would be suitable for clean sands and higher fines content sand respectively.

As discussed in Section 0, it is likely that the height of limestone capillary rise at moisture condition > 60% OMC is approximately 800 mm. A sample height of 1500 mm would be suitable for this type of material.

Table 7.4: Laboratory summary of measured capillary rise

Sample ID	Material type	Sample height (mm)	Measured capillary rise (mm)
1*	Tamala sand 1	900	230
2		900	230
3		1500	230
4		900	580
5*		600	230
6*		600	230
10*		600	230
8	Tamala sand 2	600	320
9		600	280
7	Clayey sand	900	430
11		900	680
12	Crushed limestone	900	880
13		900	880

1. *Compacted at 100% modified OMC and dried back to 0%.*
2. *Compacted at 0% modified OMC using a vibrating table.*
3. *Compacted at 80% modified OMC and dried back to 0%.*

Note:

* *Tested with a cap on.*

7.5.3 TEST DURATION

Figure 7.8 presents the change in degree of saturation (DOS) of Tamala sand samples with a moisture condition > 60% OMC throughout the duration of the capillary rise test at a height of 150 mm above the base of the sample. All of these samples had a measured capillary rise in the vicinity of 230 mm. Sensors were places at 100 mm intervals starting at 50 mm from the base of the sample. The next sensor after the 150 mm sensor was at a height of 250 mm and therefore was unlikely to provide insight into the required test duration as the moisture horizon may not be captured by the sensor.

For the Tamala sand, sample 1 demonstrated the slowest development toward a stable DOS, reaching this at approximately 10 days after the test start.

Figure 7.8 Tamala sand - change in degree of saturation at 150 mm height

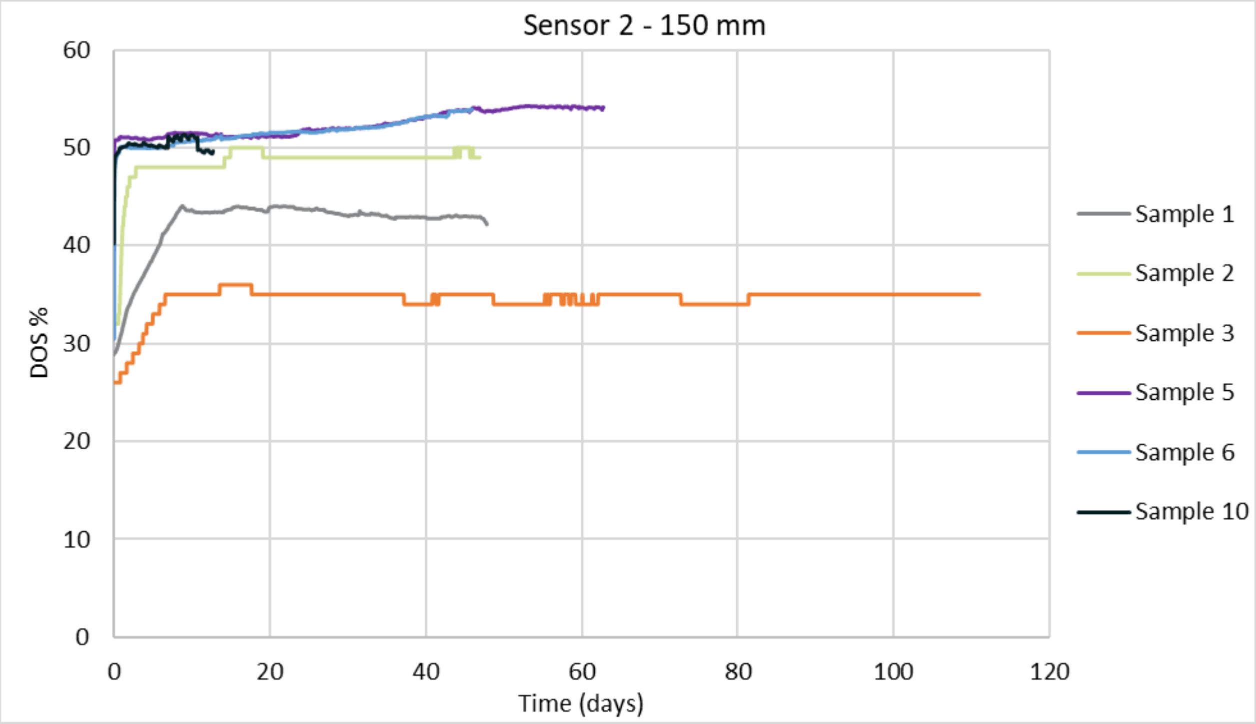
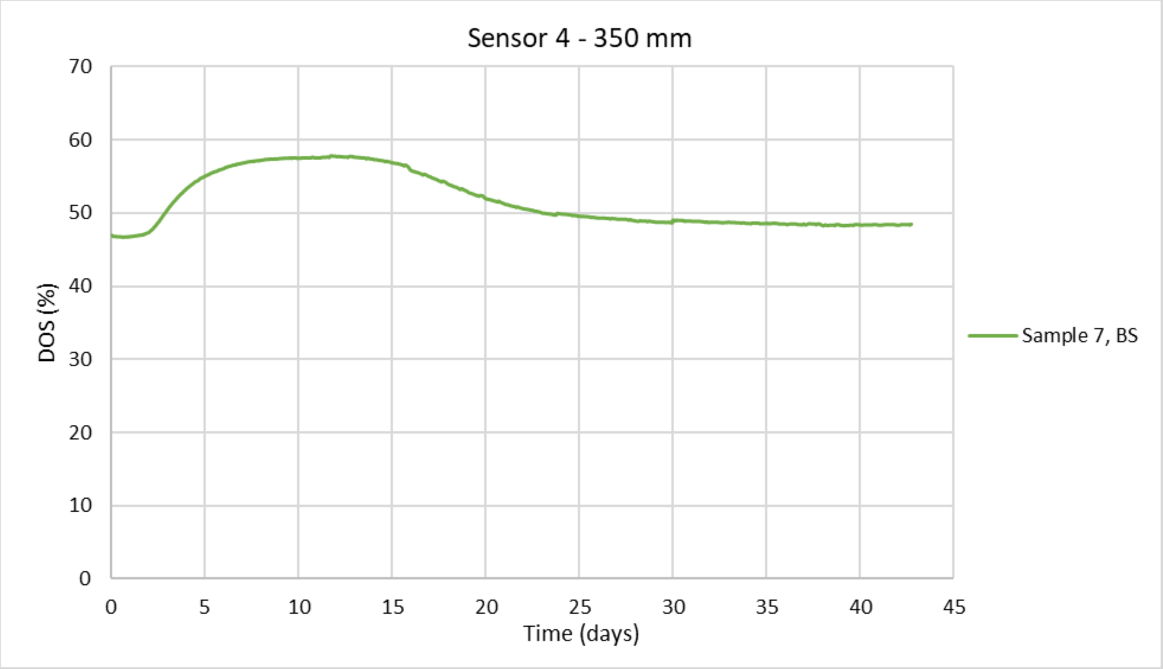


Figure 7.9 presents the change in degree of saturation (DOS) of the clayey sand sample with a moisture condition > 60% OMC throughout the duration of the capillary rise test at a height of 350 mm above the base of the sample. This sample had a measured capillary rise in the vicinity of 430 mm.

For the clayey sand, sample 7 reached a stable DOS, at approximately 10 days after the test start. Evaporation was evident after this time.

Figure 7.9 Clayey sand - change in degree of saturation at 350 mm height



7.6 CAPILLARY RISE DEFINITION AND TEST METHOD OUTPUT

Table 7.5 demonstrates the measured moisture content at the start of each laboratory test in terms of % OMC and degree of saturation (DOS). The degree of saturation at the end of each test for 50 mm increments of the sample height has been calculated using the final oven moisture results obtained in accordance with WA 110.1. These are shown in Table 7.6.

Using linear interpolation, the height within the sample where the final DOS equals the initial DOS has been predicted for comparison with the measured capillary rise.

In most cases the predicted capillary rise height was slightly higher than the measured height. For samples 5 and 10 the capillary rise height was slightly lower than the measured height.

The samples which were dried back to 0% moisture or compacted at 0% moisture had significantly higher predicted capillary rise than was measured. This is likely due to the very dry samples absorbing moisture from the atmosphere effectively moving the capillary rise height to the top of the sample. All of these samples were tested with the cap off further supporting this hypothesis.

All other samples (moisture > 60% OMC) suggested there was no influence on capillary rise height if the sample was tested with a cap on or cap off.

The capillary rise of the material determined by the Test Method has therefore been defined as the height of material above a constant source of water (phreatic line) where the moisture content is equal to the moisture content at the start of the test, which in the case of the test method is 100% modified OMC. The capillary rise height was obtained by plotting moisture content versus height at the end of the test. The capillary rise of the specimen was the height where the measured moisture content crossed the specimen 100% OMC line on the plot.

Table 7.5: Capillary rise height and moisture levels

Sample ID	Material type	Measured capillary rise (mm)	% OMC at compaction	Degree of saturation at t=0 (%)	Predicted capillary rise height at dos, t=0 (mm)
1*	Tamala sand 1	230	60	34	235
2		230	62	36	239
3		230	59	35	250
4		580	0[1]	0	950
5*		230	94	56	224
6*		230	58	34	243
10*		230	78	46	208
8	Tamala sand 2	320	0[2]	0	750
9		280	0[2]	0	717
7	Clayey sand	430	79	49	404
11		680	0[3]	0	875
12	Crushed limestone	880	0[3]	0	3400
13		880	0[3]	0	2550

1. *Compacted at 100% modified OMC and dried back to 0%.*
2. *Compacted at 0% modified OMC using a vibrating table.*
3. *Compacted at 80% modified OMC and dried back to 0%.*

Note:

* *Tested with a cap on.*

Table 7.6: Measured degree of saturation versus specimen height

Sample ID	Material	Measured degree of saturation (%) at sample height (mm)														
		50	150	250	350	450	550	650	750	850	950	1050	1150	1250	1350	1450
1*	Tamala sand 1	76	50	31	28	27	25	24	23	21						
2		78	56	33	29	27	16	17	8	4						
3		75	58	35	31	27	26	26	25	23	21	18	14	9	6	4
4		79	52	31	19	11	3	1	1	0.4						
5*		80	70	51	33	27	22									
6*		79	54	32	28	25	23									
10*		71	56	39	32	28	24									
8	Tamala sand 2	82	64	21	4	1	1									
9		67	43	10	1	1	0									
7	Clayey sand	87	86	66	53	45	42	40	38	34						
11		93	70	53	35	30	27	6	3							
12	Crushed limestone	79	83	77	61	47	40	38	36	35						
13		83	76	77	59	45	36	33	32	30						

Note:

* *Tested with a cap on.*

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 STAGE ONE

This report includes an overview of the capillary rise phenomenon, as well as how it is considered in pavement design procedures in Australia and internationally. A list of equations to estimate capillary rise of non-cohesive soils based on soil properties is presented, along with a comparison between estimated capillary rise heights for WA soils and laboratory or field measurements. The report also summarises national and international test methods for determining capillary height. Finally, a draft test method is proposed.

The literature review indicates that there are no clear national or international methods where capillary rise height is quantitatively considered in pavement design. There are some references to consideration of capillary rise in the form of assuming a soaked subgrade condition, a minimum required distance between the groundwater and the pavement, or reference to the use of drainage systems.

The available field and laboratory measurements of capillary rise height for WA non-cohesive materials were compared to estimated values using published equations. None of the equations were found to accurately predict the height of capillary rise. It was noted, however, that the laboratory measurements were obtained using different test methodologies, which may have contributed to the inconsistencies between estimated and measured values.

A review of the available national and international laboratory test methods indicates that none of the published standards is applicable to the measurement of capillary rise on non-cohesive soils. Some Australian standard methods for measurement of capillary rise exist, but they are not applicable to testing of non-cohesive materials.

Li (2018) from UWA proposed a more relevant test method, however, shortcomings were identified. To overcome those, modifications to the UWA test method have been proposed.

8.2 STAGE TWO

Capillary rise tests of four WA non-cohesive soils were undertaken to develop a standard test method. The proposed test is a simplification of the method described in section 5.5 (omitting the use of moisture sensors).

The following four materials were tested: two sources of Tamala sand, clayey sand and crushed limestone.

The following conclusions have been drawn from the analysis of the laboratory data:

- The capillary rise was influenced by material type.
- The capillary rise of a sample was not influenced by the moisture condition of the sample at the start of the test, unless the moisture condition at the start of the test was close to 0%.
- The capillary rise of a sample which had been dried back close to 0% OMC or compacted at 0% OMC was much higher than those compacted at higher levels of moisture. This may change if the test apparatus is sealed.
- The capillary rise of a sample was influenced by the dry density condition of the sample at the start of the test, with higher density increasing the capillary rise.
- The capillary rise of a sample was not influenced by sealing the test apparatus with a top cap, unless the moisture condition at the start of the test was close to 0% OMC.
- The capillary rise of a sample was defined as the height where a moisture horizon is present. Below this horizon the moisture was higher than the initial moisture content prior to testing. Above this height, the moisture content was the same as that at the test start.

The following is recommended for inclusion in the test method:

- The proposed test method is suitable for a range of non-cohesive soils.
- The test specimen should be prepared at 100% modified OMC.
- Test specimens should be prepared at a dry density that reflects the value in-service.
- The test duration should be 10 days for sand.
- The specimen height should be 600 mm for clean sands (< 5% passing the 0.075 mm sieve), 900 mm for sands with fines (< 12% passing the 0.075 mm sieve) and 1500 mm for calcareous sand gravel mixtures and sand gravel mixtures.
- Capillary rise as determined by the test method; is the height of material above a constant source of water (phreatic line) where the moisture content at the end of the test is the initial moisture content prior to testing.
- It is recommended that a factor of 1.5 is applied to the capillary rise value when applying the test result to the design of drainage layers.

A copy of the proposed standardised test method has been included in Appendix B with all the recommendations detailed above included.

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APPENDIX A MOISTURE SENSOR TIME PLOTS

Figure 8.1 Moisture sensor time plot - Sample 1 Yellow Sand, 96% MMDD, 60% OMC, cap on

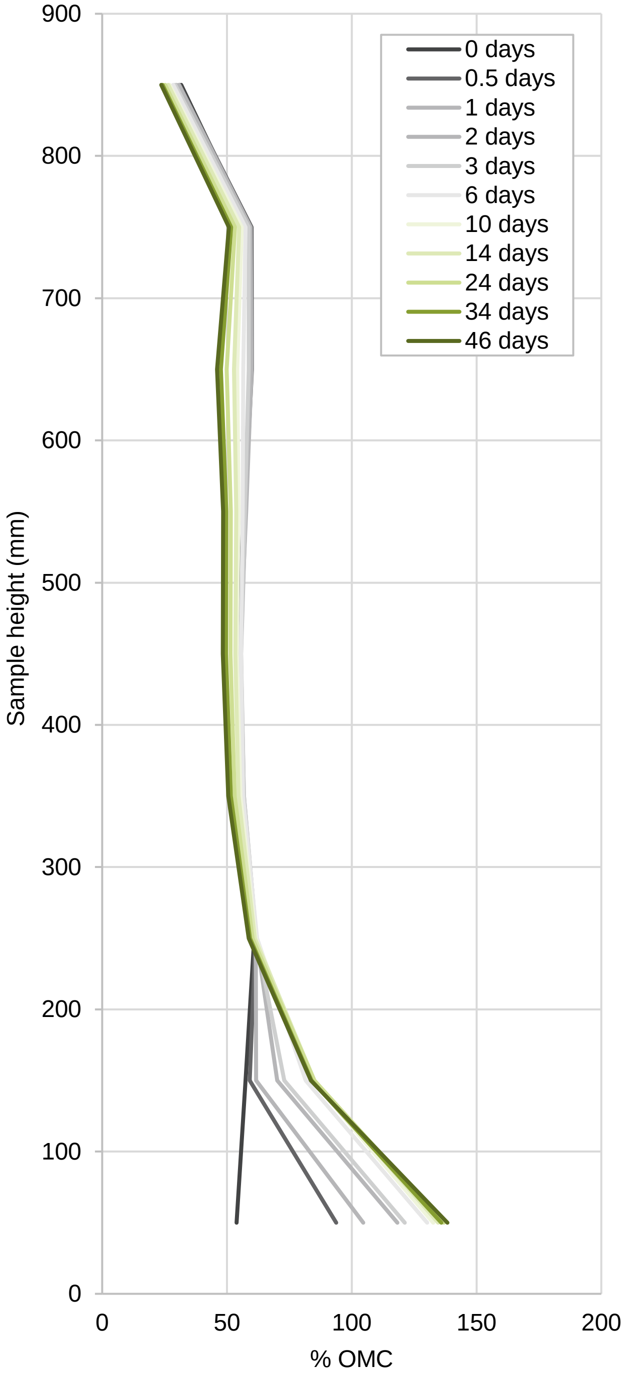


Figure 8.2 Moisture sensor time plot - Sample 3 Yellow Sand, 96% MMDD, 60% OMC, cap off

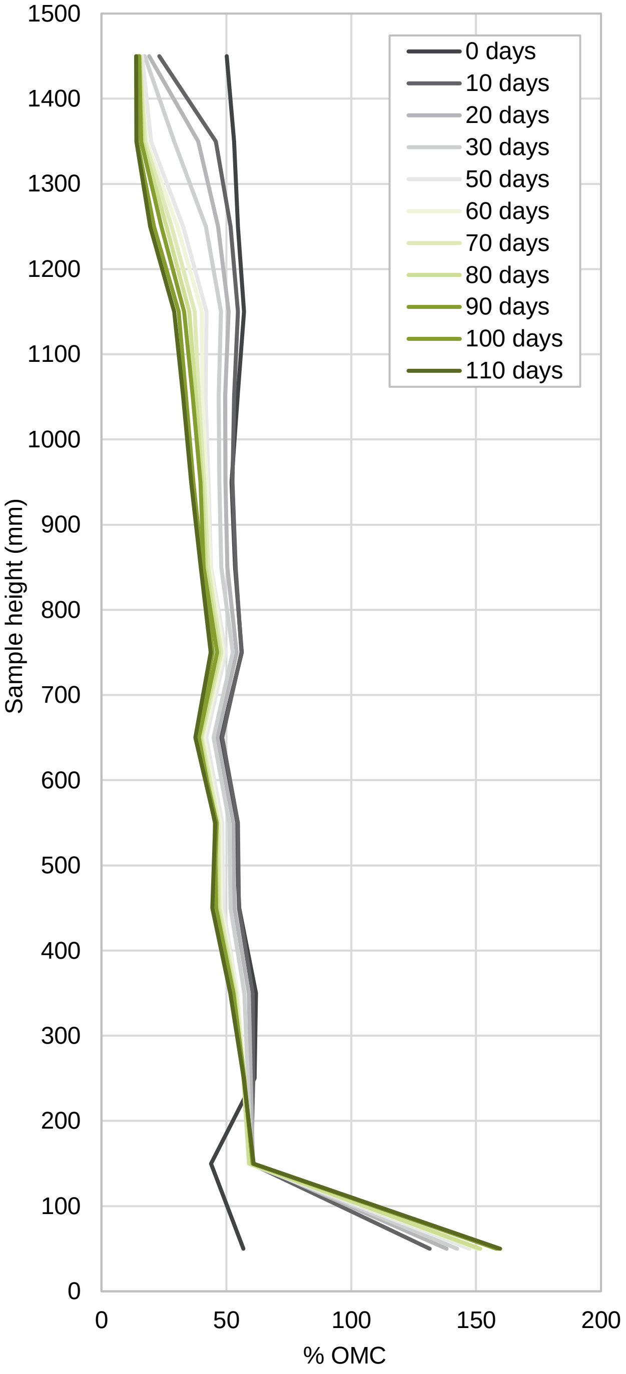


Figure 8.3 Moisture sensor time plot - Sample 4 Yellow sand, 96% MMDD, 0% OMC, cap off

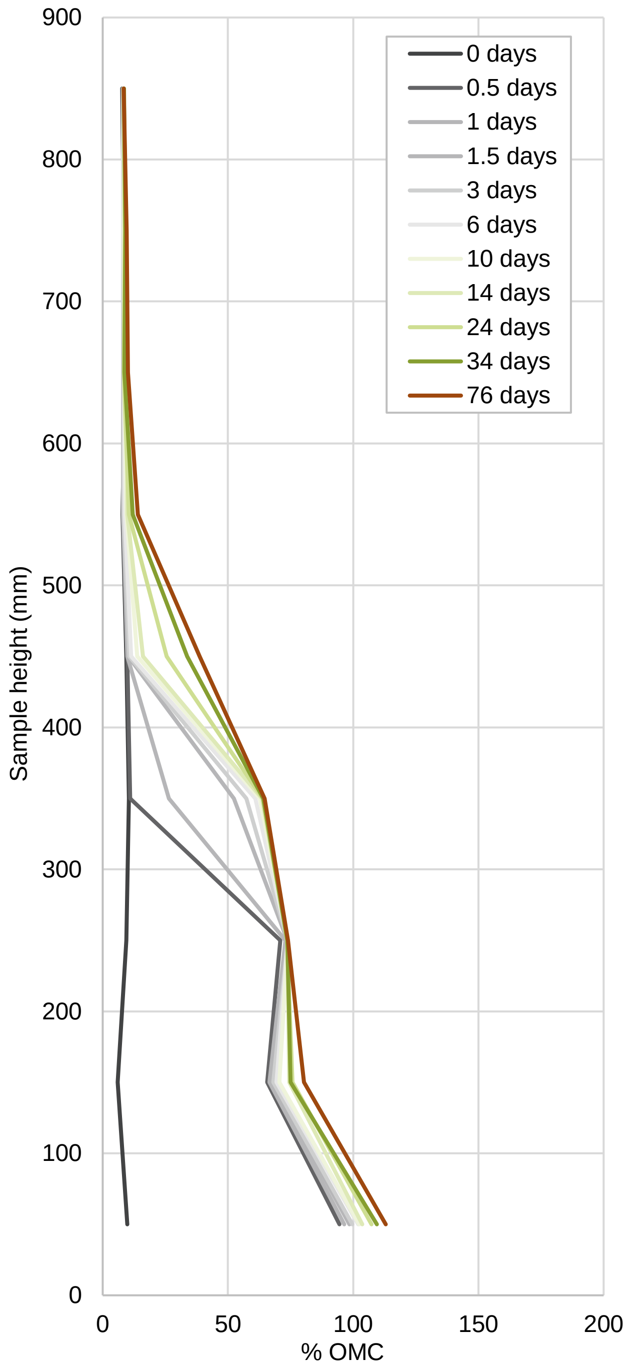


Figure 8.4 Moisture sensor time plot - Sample 5 Yellow sand, 96% MMDD, 100% OMC

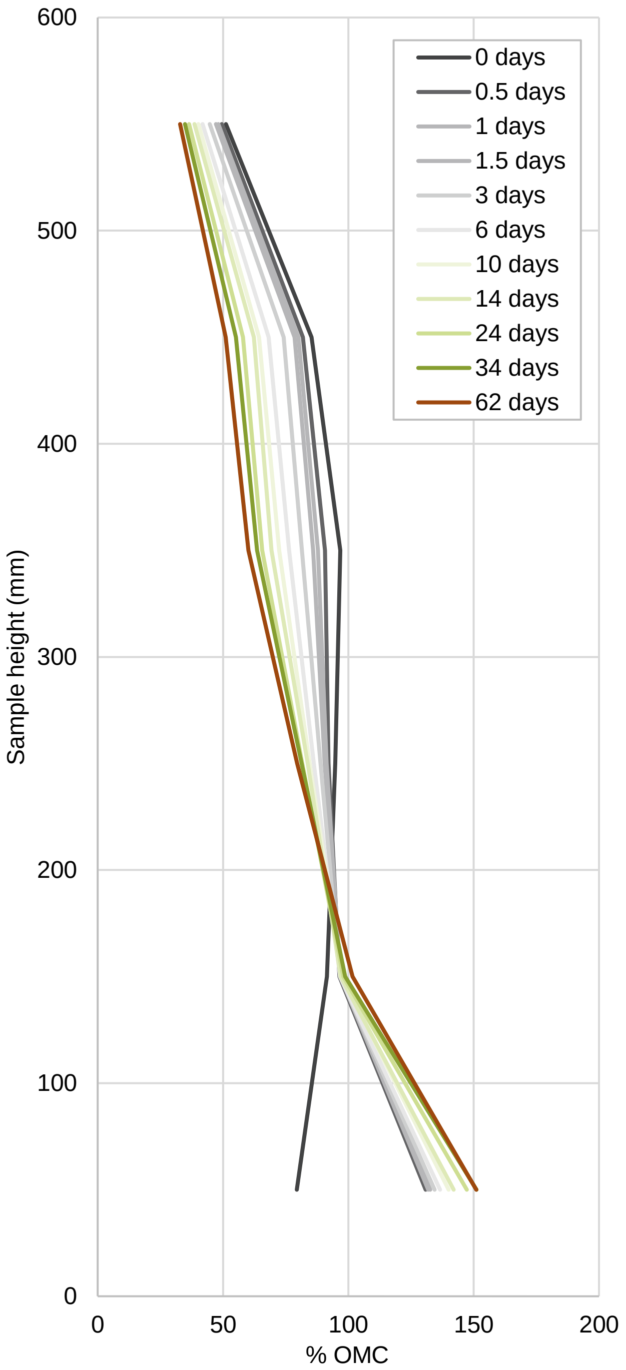


Figure 8.5 Moisture sensor time plot - Sample 6 Yellow sand, 96% MMDD, 60% OMC

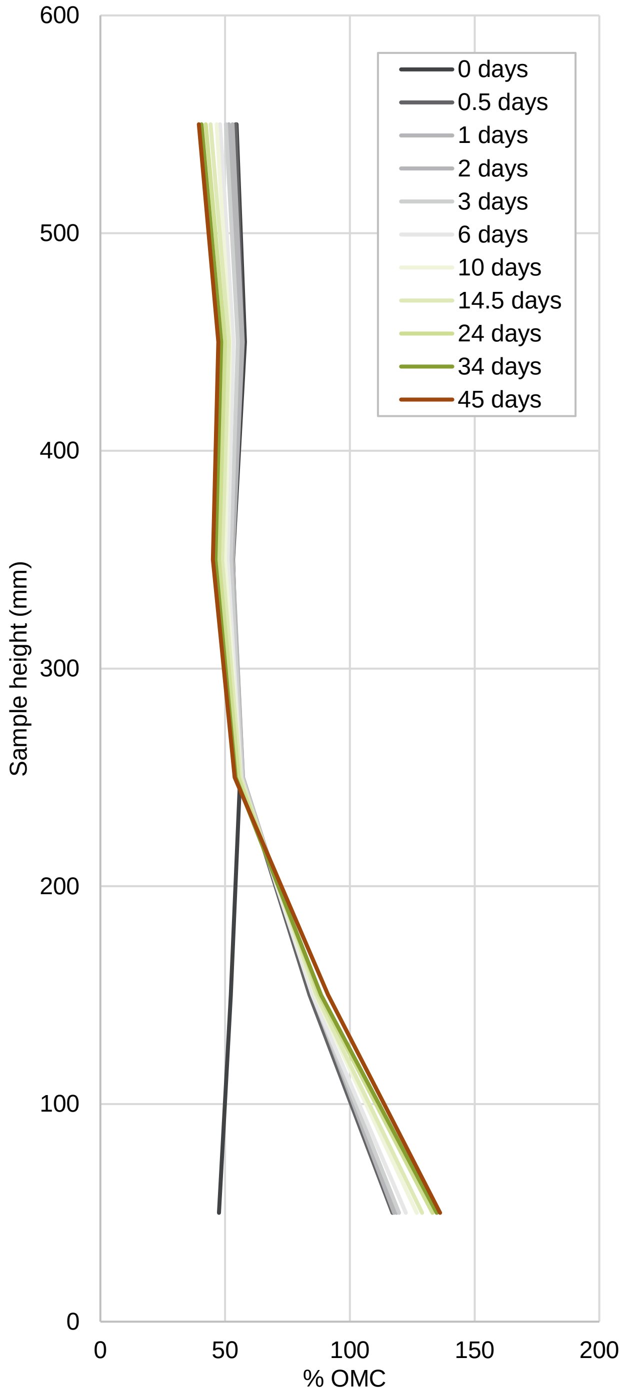


Figure 8.6 Moisture sensor time plot - Sample 7 Clayey sand, 94% MMDD, 80% OMC

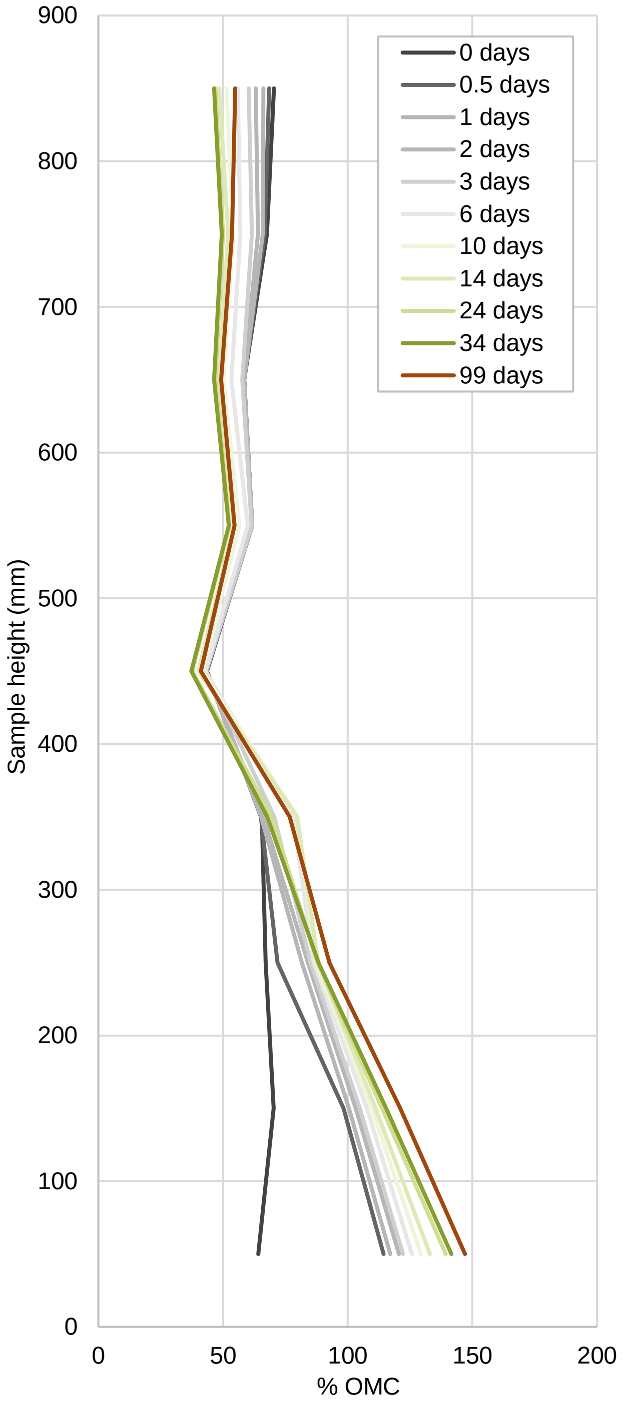


Figure 8.7 Moisture sensor time plot - Sample 8 Yellow Sand, 100% MMDD, 0% OMC

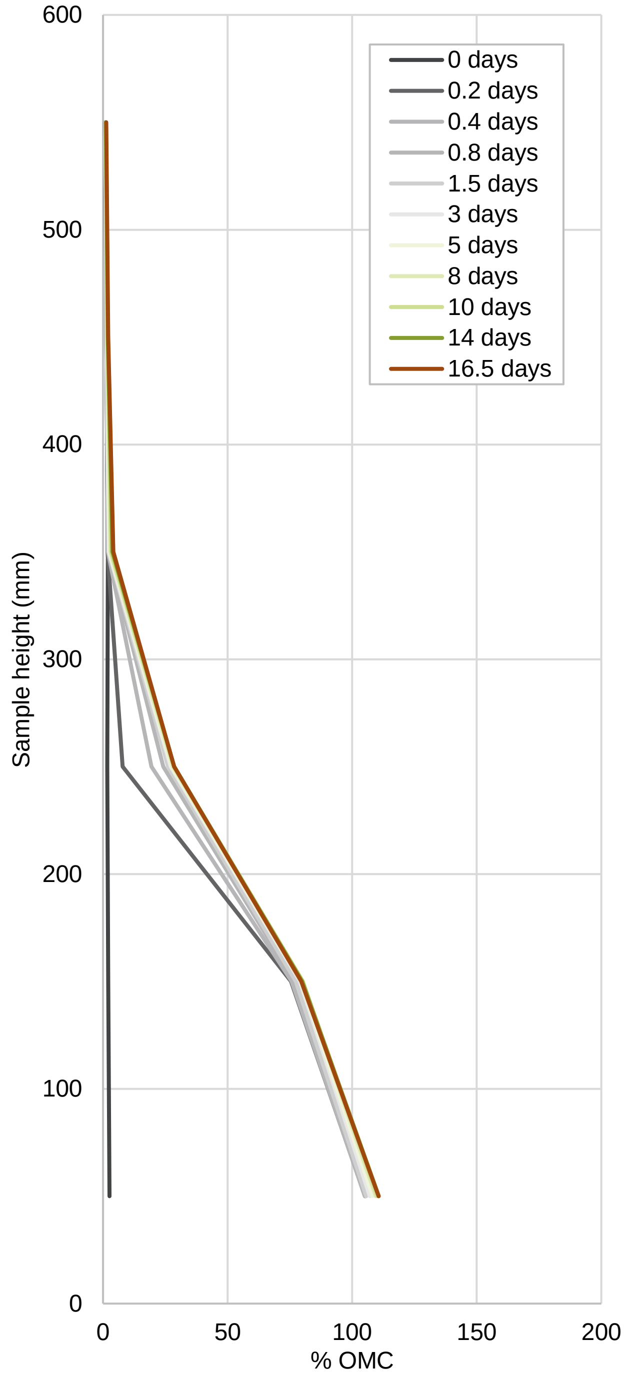


Figure 8.8 Moisture sensor time plot - Sample 9 Yellow sand, 90% MMDD, 0% OMC

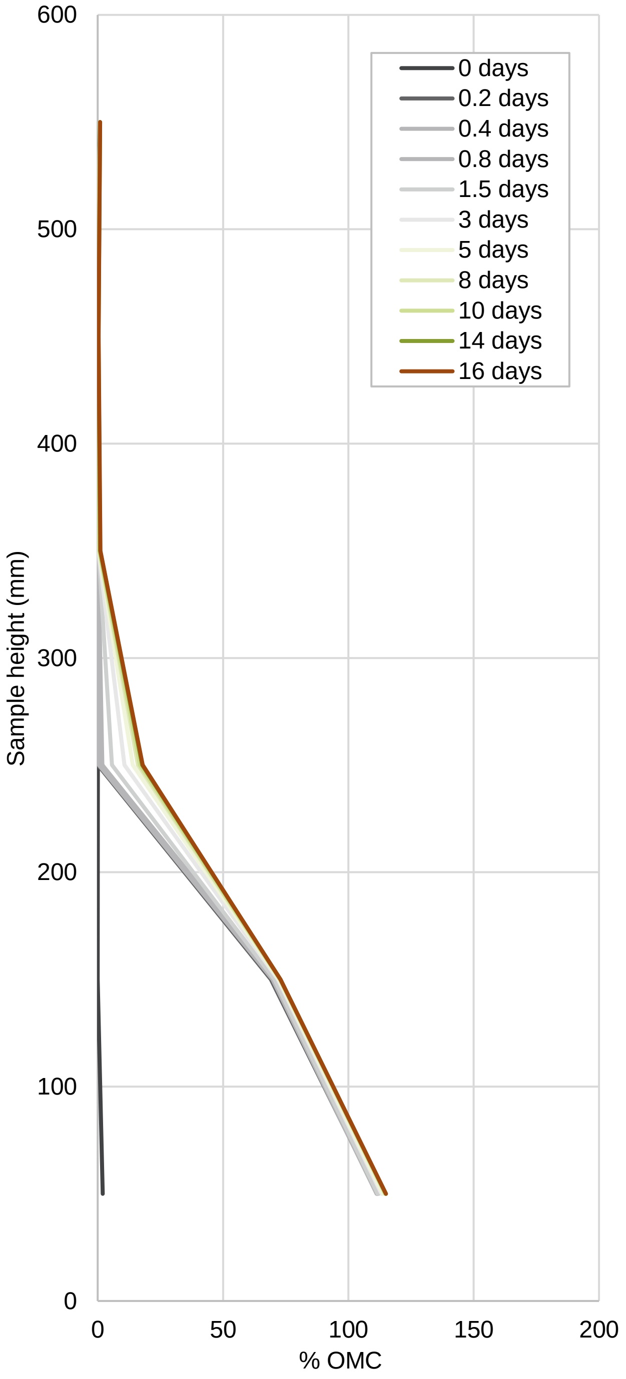


Figure 8.9 Moisture sensor time plot - Sample 10 Yellow sand, 96% MMDD, 80% OMC

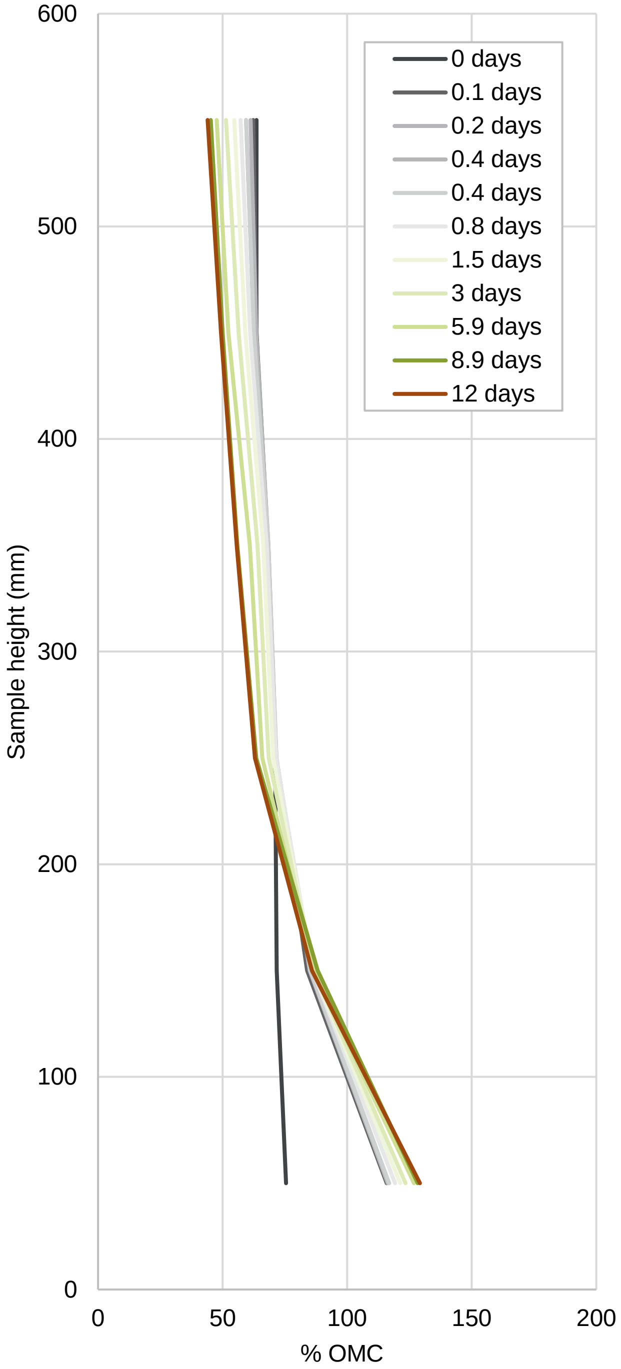


Figure 8.10 Moisture sensor time plot - Sample 11 Clayey sand, 94% MMDD, 0% OMC

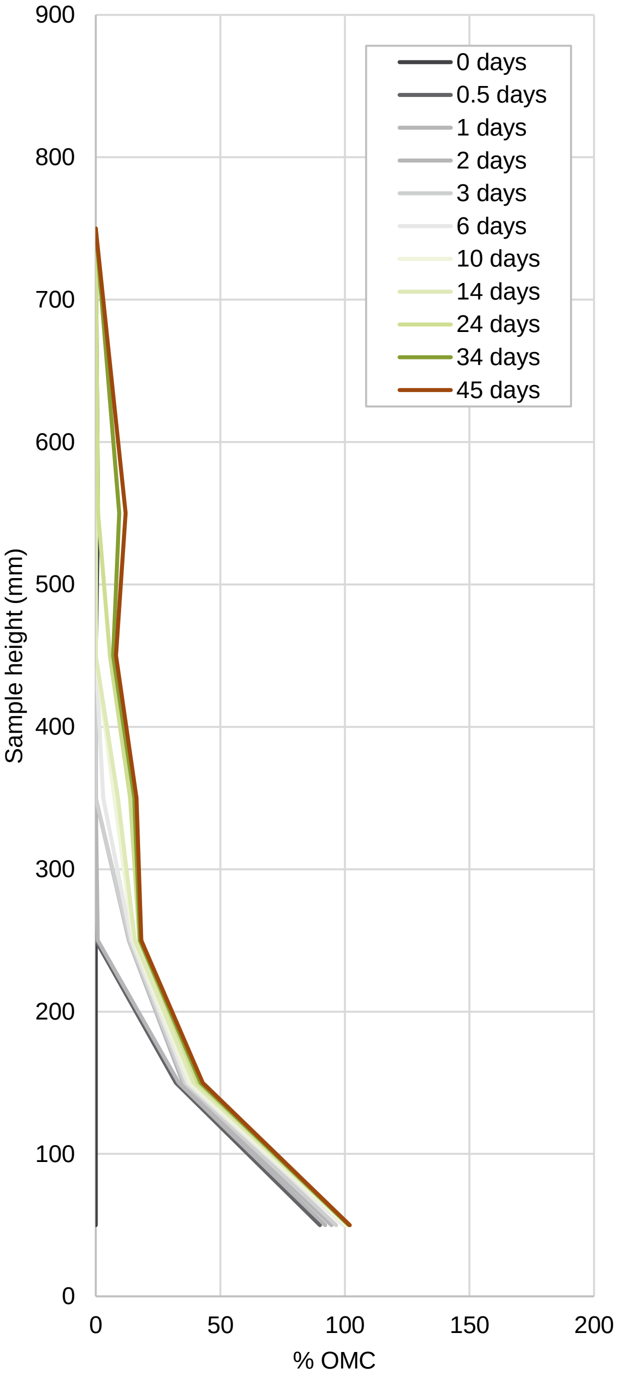


Figure 8.11 Moisture sensor time plot - Sample 12
Limestone sub base, 92% MMDD, 0% OMC

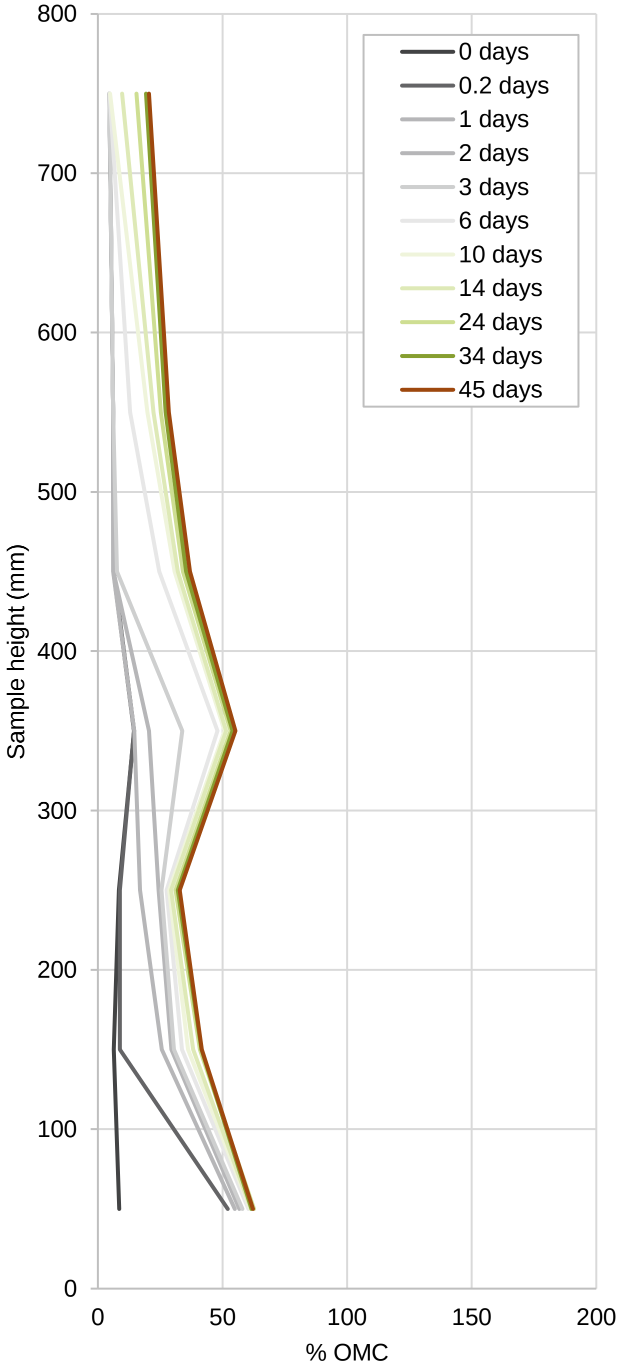
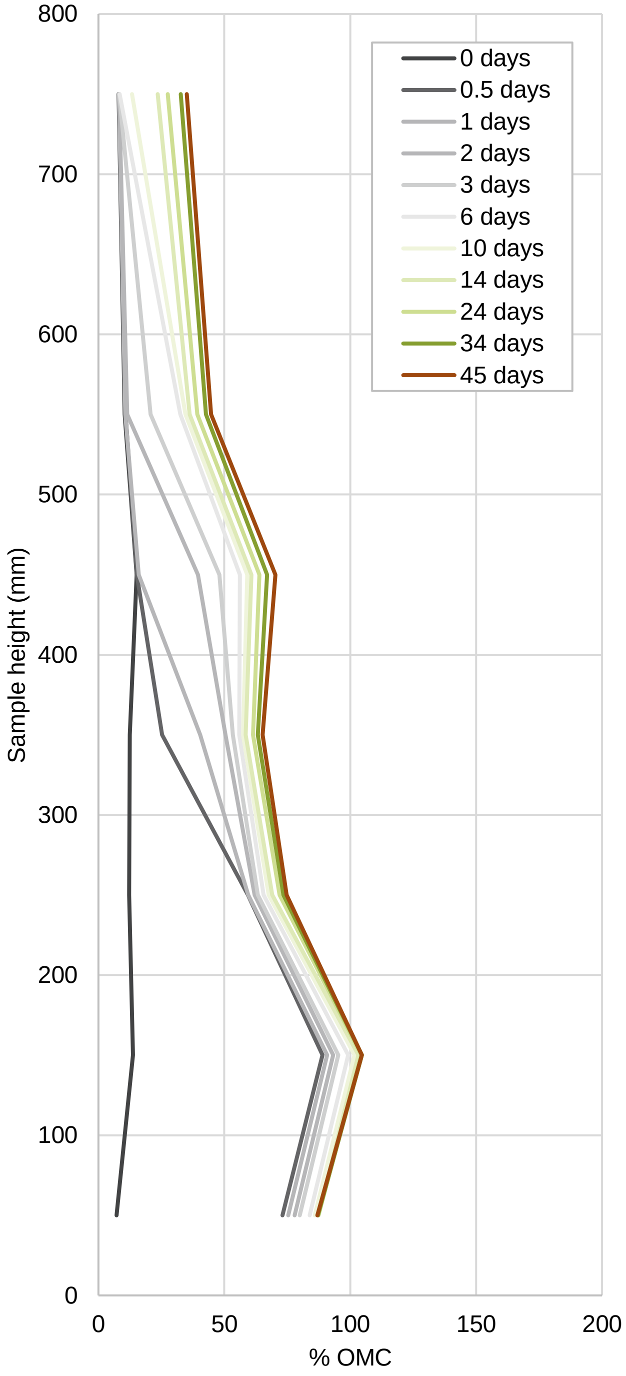


Figure 8.12 Moisture sensor time plot - Sample 13
Limestone sub base, 88% MMDD, 0% OMC



APPENDIX B PROPOSED TEST METHOD FOR MEASURING CAPILLARY RISE IN NON-COHESIVE SOILS

B.1 SCOPE

This method describes the procedure for the determination of the capillary rise of granular soils with less than 12% passing the 0.075 mm sieve.

This test method is not suitable for materials that have a capillary rise of greater than 1.0 m.

B.2 SAFETY

This method does not attempt to address the safety concerns, if any, associated with the test method. It is the responsibility of the user of this method to establish appropriate occupational health and safety practices that meet statutory regulations.

B.3 REFERENCED METHODS AUSTRALIAN STANDARDS

Australian Standard

AS 1152	Specification for test sieves

WA Test Methods

WA 105.1	Preparation of Disturbed Soil and Granular Pavement Material Samples for Testing.
WA 110.1	Soil and Granular Pavement Material Moisture Content: Convection Oven Method.
WA 115.1	Particle Size Distribution: Sieving and Decantation Method
WA 115.2	Particle Size Distribution: Abbreviated Method for Coarse Materials
WA 132.1	Dry Density/Moisture Content Relationship: Standard Compaction. Fine and Medium Grained Soils
WA 133.1	Dry Density/Moisture Content Relationship: Modified Compaction. Fine and Medium Grained Soils
WA 134.1	Dry Density Ratio (Percent)
WA 136.1	Moisture Ratio (Percent)

B.4 DEFINITIONS

a. **Laboratory density ratio** – the ratio of the dry density of the specimen to the maximum dry density of the material as determined on material prepared in accordance with Procedure 7(c), expressed as a percentage.

b. **Laboratory moisture ratio** – the ratio of the moisture content of the specimen to the optimum moisture content of the material as determined on material prepared in accordance with Procedure 7(d), expressed as a percentage.

c. **Capillarity** enables a soil to draw water above the phreatic line as a result of surface tension between the water and the soil particles.

d. **Capillary Rise** as determined by this test method; is the height of material above a constant source of water (phreatic line) where the moisture content is greater than the optimum moisture content at the end of the test.
e. **Capillary Fall** is when there is insufficient surface tension between the pore water and the soil particles allowing the moisture to drain due to gravity. Note there are no surface tension forces with a soil that is completely saturated and water will drain away until the forces of gravity equal the surface tension forces between the water and the soil.
f. **Evaporation** is the process of soil moisture changing from a liquid to a vapour and leaving the sample.

B.5 APPARATUS

a. Sufficient cylindrical moulds of known volume with an internal diameter 150 mm ± 5 mm. Moulds are typically 300 mm high steel or plastic concrete UCS moulds or CBR moulds with a joiner to allow multiple moulds to be stacked to achieve the required sample length and suitable restraining rods or straps to stabilise the moulds during the compaction process. The moulds must have sufficient strength to contain the soil sample during compaction using a steel rammer described below.
b. Cylindrical joiners to secure the moulds together to achieve the required sample length.
c. A porous/perforated base plate attachable to the first mould. Base plate perforations shall be no less than the requirements for WA 141.1 *Determination of the California Bearing Ratio of a Soil: Standard Laboratory Method for a Remoulded Specimen*, refer Figure 1 of WA 141.1.
d. Mould compaction collar and tie down rods to prevent damage to the upper edge of the moulds and secure the moulds and joiners during compaction of the test sample.
e. Water tank or container capable of maintaining a constant head of water 20 mm ± 5 mm above the base plate of the prepared specimen. The constant head water tank should have a minimum supply capacity of at least 4 L per day to allow for water drawn into the specimen and evaporation.
f. If necessary a sealing compound to seal the joints of completed moulds.
g. A steel rammer, having essential dimensions complying with Table B.1, and whose energy delivered per blow has been calibrated.
h. Thermostatically controlled oven with good air ventilation capable of maintaining a temperature within the range of 105 ºC to 110 ºC.
i. Sieve, 19 mm.
j. Drying cabinet 45 – 50 °C.
k. Balance of at least 30 kg capacity, readable to 1 g.
l. Temperature-controlled room (23 ± 5 °C).
m. Jack, lever, frame or suitably constructed split moulds or other suitable device, which may be used for extruding specimens from the moulds in 50 mm increments.
n. Other apparatus and supplies such as distilled water, mixing bowls, straightedge, filter paper and dishes.

Table B.1: Dimensions and tolerances for compaction apparatus

Apparatus	Value	Working tolerance

MOULD		
Individual internal diameter, mm	150.0	±1.0
Average internal diameter, mm	150.0	±0.5 (1)
Height, mm	300.0	±0.5 (1)
Calculated volume, cm^3	5250	±35 (1)
RAMMER		
Diameter, mm	50.0	±0.4
Drop, mm	300.0 (Standard compaction) 450.0 (Modified compaction)	±2.0 (2) ±2.0 (2)
Mass, kg	2.70 (Standard compaction) 4.90 (Modified compaction)	±0.01 (2) ±0.01 (2)
Energy delivered per blow, J	7.94 (Standard compaction) 21.62 (Modified compaction)	±0.08 ±0.08
Number of layers	5	-
Number of blows per layer	25 (varies according to compaction effort)	-
Thickness of each layer	60 (Standard compaction) 60 (Modified compaction)	±0.5 ±0.5
Energy input, kJ/m^3	187 (Standard compaction) 510 (Modified compaction)	±14 ±60

1. *Either but not both of the tolerances may be exceeded provided that the appropriate tolerance of volume is not exceeded.*
2. *Either but not both of the tolerances may be exceeded provided that the appropriate tolerance of energy blow is not exceeded.*

B.6 PROCEDURE

B.6.1 SOIL SPECIMEN CHARACTERISATION

Undertake a soil particle distribution in accordance with WA 115.1 *Particle Size Distribution: Sieving and Decantation Method*.

Undertake a dry density/moisture content relationship: modified compaction test in accordance with WA 133.1 *Dry Density/Moisture Content Relationship: Modified Compaction. Fine and Medium Grained Soils.*

B.6.2 CALCULATION OF THE REQUIRED SPECIMEN HEIGHT

The specimen height shall be no less than 150% of the capillary rise as determined by this test method. This may require the test to be repeated with a longer specimen if the measured capillary rise is greater than two-thirds of the specimen length. Table B.2 provides a guide for known soil types.

This test method is not suitable for materials that have a capillary rise of greater than 1 m where a specimen length of over 1.5 m would be required.

Table B.2: Recommended sample height and minimum test time in days for various non-cohesive materials

Soil description	Recommended sample height (mm)	Minimum test time (days)	Initial moisture content
Clean cohesionless sands with <5% passing 0.075 mm sieve	600	10	OMC
Silty sands with <12% passing 0.075 mm sieve	900	10	OMC
Clayey sands with <12% passing 0.075 mm sieve	900	10	OMC
Clean sand gravel mixtures <5% passing 0.075 mm sieve	900	10	OMC

Sand gravel mixtures <12% passing 0.075 mm sieve	1500	20	OMC
Calcareous sand gravel mixtures	1500	20	OMC
Soils with PI > 7 or > 12% passing 0.075 mm sieve	Test method unsuitable		

Notes:

- *Generally capillary rise is low for poorly graded sands and very low for poorly graded gravels.*
- *The capillary rise effect within well graded sands and sand gravel mixtures can be high as the small pore size between the particles creates a suitable structure to allow the surface tension forces to pull the water into the sample.*
- *The test specimen sample density should equal the expected density condition in the field to ensure the pore spaces with the specimen are similar.*
- *This capillary rise test method is unsuitable for fine grained soils such as clays and silts due to additional complex forces between the soil and the water.*

B.6.3 PREPARATION OF THE TEST INCREMENT

a. Using the 19 mm sieve, sieve a representative sample of the soil prepared in accordance with the procedure described in Test Method WA 105.1. Determine the percentage of material retained on the sieve. Only the material passing the 19 mm sieve is to be used for the test.

NOTES:

Where it is obvious that all material passes the 19.0 mm sieve, testing by WA 115.1 or WA 115.2 is not necessary. It is sufficient to record that the material passes the 19.0 mm sieve by visual assessment.

Material, which has been compacted previously in the laboratory, should not be re-used, as breakdown of the material during compaction can lead to misleading results.

b. Determine the dry density/moisture relationship on a representative sample passing the 19 mm sieve in accordance with Test Method WA 133.1.

c. Obtain a representative test increment. Determine the hygroscopic moisture content (w_h) in accordance with Test Method WA 110.1.

d. Select the dry density (ρ_d) /moisture content (w_c) condition at which the test increments are to be moulded.

e. Calculate the dry mass (DM_{TI}) of the test increment using the equation:

$$DM_{TI} = \frac{WM_{TI} \times 100}{100 + w_h}$$

where

DM_{TI} = dry mass of test increment in grams

WM_{TI} = wet mass of test increment in grams

w_h = hygroscopic moisture content as a percentage

f. Calculate the mass of water (m_{WR}) to be added to bring the test increment to the desired moisture content using the equation:

$$m_{WR} = \frac{(w_c - w_H)DM_{TI}}{100}$$

where

m_{WR} = mass of water to be added to the test increment in grams

w_c = moisture content (%) condition at which the test increments are to be moulded

w_H = hygroscopic moisture content (%) of the test increment

g. Cure the test increment for 12 hours or more depending upon the soil type. Record the duration of curing.

NOTES:

It is important that the water is thoroughly mixed into and uniformly distributed through the soil since inadequate mixing gives rise to variable results. It is desirable to keep the soil in a sealed container to allow the water to become more uniformly distributed through the soil before compaction. For materials of low plasticity and high permeability prepared in a moist condition close to optimum moisture content, little or no curing is required, but if the soil is dry and contains heavy clay, up to 7 days curing prior to compaction may be required. The more cohesive a soil, the more time required for moisture to infiltrate and equilibrate. All soils should be cured for a minimum of 12 hours.

B.6.4 PREPARATION OF THE TEST SPECIMEN

a. Calculate the desired wet density of the test specimen using the following equation:

$$\rho_w = \frac{\rho_d \times (100 + w_c)}{100}$$

where

ρ_w = desired wet density of test specimen in t/m^3

= desired dry density of test specimen in t/m^3

w_c = moulding moisture content of the test specimen as a percentage

b. Calculate the desired wet mass of the test specimen using the following equation:

$$m_{TS} = \rho_w \times V_1$$

where

m_{TS} = desired wet mass of the test specimen in grams

ρ_w = desired wet density of test specimen in t/m^3

V_1 = volume of the mould in cm^3

c. Calculate the wet mass of each layer that is to be compacted in the mould using the equation:

$$m_L = \frac{m_{TS}}{l}$$

where

m_L = wet mass of soil per layer in grams

m_{TS} = wet mass of test specimen in grams.

$l =$ = number of layers (for Tamala sand, compact in 5 x 60 mm layers per mould)

d. Determine the mass of the moulds, collar, rods and perforated baseplate (m_1).

e. Place filter paper on the perforated base of the baseplate. If necessary coat the inside of the mould with a thin layer of Vaseline or similar to assist with specimen extraction.

f. Place the mould with the collar attached and clamp to the rods to secure mould for compaction.

g. Immediately prior to compaction thoroughly mix the cured soil and determine the moisture content (w_1) of a representative fraction of the test portion in accordance with Test Method WA 110.1. This will be used to compare achieved against desired moisture ratio. The laboratory moisture ratio shall be within 5% of the specified moisture ratio.

h. Compact each layer uniformly into the mould, using a modified or standard compaction rammer, to the specified laboratory density. If the height of the layer approaches the top of the mould and an additional mould is required, determine the mass of the additional mould prior to attachment. The joint between the moulds should be made impermeable by application of Vaseline or silicone. Discard specimens that do not meet the above requirements.
i. Ensure the last compacted layer of the specimen is levelled off using a straight edge or a similar tool. Once the desired height of the specimen has been achieved, remove the collar and rods. If preferred, replace the rods with rachet straps and eye bolts to secure the specimen prior to commencement of the capillary test.
j. Obtain the weight of the specimen after compaction (m_2) in order to compare achieved against desired specimen density. The laboratory density ratio shall be within 1% of the specified density ratio.

B.6.5 CAPILLARY RISE TEST

a. Prepare a specimen to the required length and moisture content, refer to Table B.2
b. Place the completed specimen inside the dry water bath.
c. Allow the top surface of the specimen to be exposed to the air permitting evaporation from the uppermost surface.
d. Using distilled water, fill the water bath to 20 mm above the base of the specimen and record the time when the water is placed in the water bath (t_0).
e. Using distilled water, set the constant water level device to maintain the water level 20 mm above the base of the specimen.
f. Leave the specimen to soak for the prescribed time shown in Table B.2 in a temperature-controlled room.
g. At the completion of the soaking time, remove the mould(s) from the water and promptly remove the specimen from the moulds in 50 mm increments recording the position the increment was removed from the specimen.
h. Determine the hygroscopic moisture content for each specimen increment collected in accordance with Test Method WA 110.1.

NOTE:
The test should be carried out in a temperature-controlled room (23 ± 5 °C).

B.7 CALCULATIONS

a. Calculate the mass of dry soil in the specimen from the following equation:

$$m_5 = \frac{m_2 - m_1}{\left(1 + \frac{w_1}{100}\right)}$$

where

m_5 = mass of dry soil in the specimen, in grams

m_2 = mass of mould plus moisture sensors plus compacted soil, in grams

m_1 = mass of mould plus moisture sensors, in grams

w_1 = moisture content of the soil immediately prior to compaction, in percent

b. Calculate the dry density of the specimen prior to testing

$$\rho_d = \frac{1}{V_1} \times m_5$$

where

ρ_d = dry density of test specimen in grams per cubic centimetre

V_1 = volume of the mould in cm^3

m_5 = mass of dry soil in the specimen, in grams

c. Calculate laboratory density ratio (LDR) of the specimen prior to testing

$$LDR = \frac{\rho_d}{MDD} \times 100$$

where

LDR = laboratory density ratio, in percent

ρ_d = dry density of the specimen, in grams per cubic centimetre

MDD = maximum dry density of the soil, in grams per cubic centimetre

d. Calculate the laboratory moisture ratio (LMR) of the specimen prior to testing

$$LMR = \frac{w_1}{OMC} \times 100$$

where

LMR = laboratory moisture ratio, in percent

w_1 = moisture content of the soil immediately prior to compaction, in percent

OMC = optimum moisture content of the soil, in percent

e. Convert moisture content by mass obtained from Test Method WA110.1 to % of OMC for plotting on the graph:

$$w\%\ of\ OMC = \frac{w_2}{OMC} \times 100$$

where

w_2 = final moisture content of the soil as obtained from Test Method WA110.1

OMC = optimum moisture content of the soil, in percent

f. If using this test to determine the capillary rise of drainage layers, the following factor shall be applied:

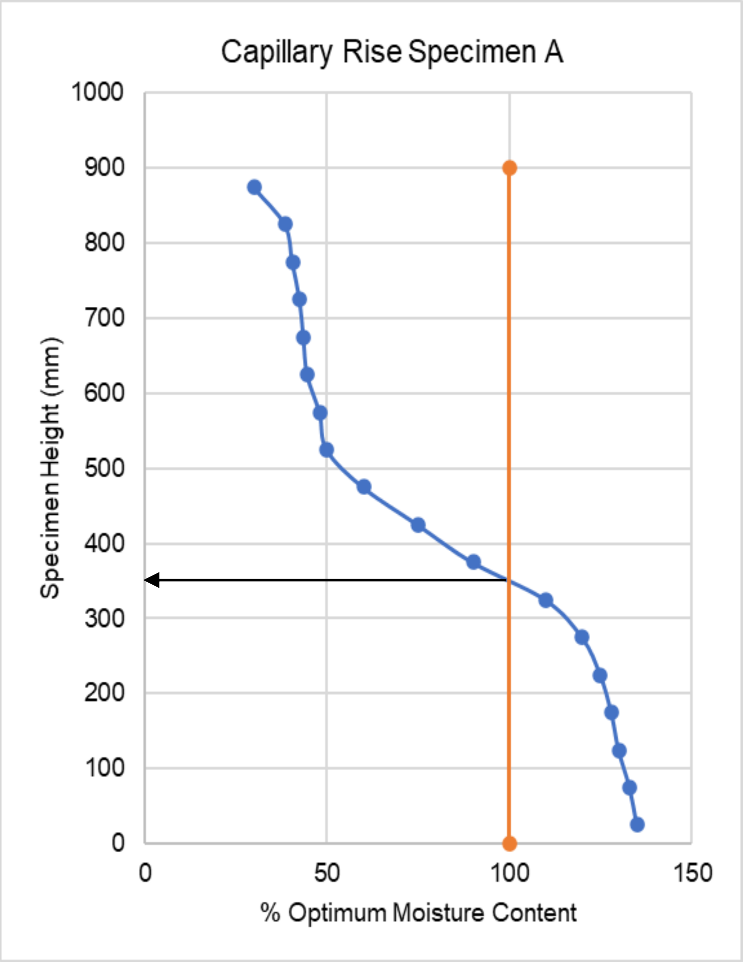
Table B.3: Recommended factor for capillary rise based on material purpose

Material purpose	Multiplication factor

Structural layer	1.0
Drainage layer	1.5

B.8 REPORTING

a. Identification and description of the sample
b. The percentage by mass retained on the 19 mm sieve
c. Laboratory moisture content (w_1) and moisture ratio (LMR) at which the specimen was compacted, to the nearest 0.1%
d. Desired moisture ratio to the nearest 0.1% at which the specimen was to be moulded
e. Laboratory dry density (ρ_d) and dry density ratio (LDR), at which the specimen was compacted to the nearest 0.001 t/m^3 and 0.1% respectively.
f. The desired dry density ratio to the nearest 0.1% at which the specimen was to be moulded.
g. Maximum dry density to the nearest 0.001 t/m^3 and the optimum moisture content of the specimen to the nearest 0.1%.
h. The compactive effort used to compact the specimen in terms of the number of layers, the number of blows per layer and the mass of the rammer.
i. Plot each increment moisture content versus average increment height (mm) at the end of testing, as obtained from B.5 and B.6
j. Prepare a table and chart of the specimen moisture content versus height and draw a line showing the specimen OMC.
k. The capillary rise of the specimen is the height where the measured moisture content crosses the specimen OMC line, refer example below for Specimen A.
l. The capillary rise of a specimen which is intended to be used as a drainage materials is the height where the measured moisture content crosses the specimen OMC line multiplied by the appropriate factor as per Table B.3.


Capillary Rise Specimen A
Specimen Height (mm)
1000
900
800
700
600
500
400
300
200
100
0
0
50
100
150
% Optimum Moisture Content