P2R2C2

Soil wetting-drying study

Report Nr 4

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Deliverable Nr 4 – Soil wetting-drying study

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1 Introduction

High subgrade water content, with the resulting decrease in subgrade strength and stiffness, is detrimental to roadway pavement response. In fact, typically, an increase in subgrade water content results in a decreased resilient modulus, which leads to increased deflections in the pavement subgrade. Increased subgrade deflection generally leads to decreased pavement design life (Elliot and Thornton 1988). Pavement subgrades usually experience seasonal variations in water content (Guinnee 1958; Marks and Haliburton 1969; Rada et al. 1994). The resilient modulus of subgrade soils, an important parameter of flexible pavement design, changes seasonally with variations in subgrade water content, besides changing with other environmental factors such as temperature.

Subgrade moisture content near the ground surface depends on a variety of climatic and physical factors including soil type, temperature, precipitation, vegetation, and others. Because of the variability of all those parameters, the prediction of subgrade moisture content is complicated. The most reliable method for determining subgrade moisture variations is the direct measurement over an extended time period.

In general, the major factors that affect subgrade moisture content are divided into external factors and internal factors. External factors include precipitation, temperature, groundwater table location, time and pavement factors - such as pavement condition, shoulder condition, and pavement drain ability. Internal factors could include soil type, compaction/density, depth, and soil suction properties.

Soil is a highly variable material. The interrelationship of soil texture, density, moisture content, and strength is complex, and in particular, behaviour under repeated loads is difficult to evaluate. Also, subgrades are generally constructed in the surface soil, which is usually subject to large moisture content variations and is strongly influenced by surrounding climatic conditions. It is widely known that pavement subgrade soils not only experience temporary (seasonal) changes in moisture content but also undergo changes in their long-term average annual moisture content.

Seasonal variations in pavement subgrade water content and the environmental factors affecting the water content have been investigated as important parameters of pavement response for at least 40 years (Guinnee 1958; Marks and Haliburton 1969; Russam 1970; Vaswani 1975; Rada et al. 1994; Baran 1994; Jin et al. 1994). Early research (Guinee 1958) relied on extensive coring to periodically extract subgrade samples and to determine water content and density in the laboratory. Later research relied on a variety of methods, including gypsum blocks, tensiometers, and neutron probes to measure soil water (Marks and Haliburton 1969; Russam 1970; Vaswani 1975). Soil temperature and meteorological data were usually collected to determine the factors influencing the subgrade moisture. Although the variation in subgrade water content and the effects on pavement response have been investigated for some time, the magnitude of these variations and the relationships involved are not yet well understood (Rada et al. 1994).

The effect of precipitation on measured or observed subgrade moisture content is not well defined. While some studies have suggested that precipitation has a considerable influence on subgrade moisture, others could not establish a firm relationship. The effects of seasonal and temperature variations on moisture contents seem to be better defined. Many studies have demonstrated minimum subgrade moisture in the early fall, followed by a gradual build-up over the winter months resulting in maximum moisture levels in the spring.

Strong relationships have been found between the location of the groundwater table and the observed subgrade moisture content. However, as with any complex system, a single factor such as the location of the groundwater table is interrelated with other factors such as precipitation and seasonal/temperature variations. It is interesting that subgrade moisture content has been observed to stabilize over time, approaching some equilibrium level in the years after pavement construction.

Pavement conditions can have a marked effect on subgrade moisture levels. As might be expected, subgrades underlying relatively impervious pavements show little variation in moisture content compared to subgrades under pavements in poorer conditions. In addition, subgrade moisture variations are reduced when pavements are constructed using well-draining materials for the base and sub base. A major pavement factor related to subgrade moisture is the type and condition of the pavement shoulders and edges. Many studies have reported higher moisture contents in the subgrade under the edges of a pavement than at the centre, and this situation is directly attributable to the condition of the pavement shoulder.

The density or level of compaction of the subgrade has been found to significantly influence the moisture content of the subgrade soil. In addition, the moisture content of the subgrade soil at the time of subgrade preparation can have an effect on subsequent moisture levels and moisture variation in the subgrade. Subgrade soils placed at moisture contents similar to their natural moisture content and lower than the plastic limit have shown reduced variability compared with soils placed at higher moisture levels. Moisture contents also vary with depth. A general increase in moisture content with depth has been noted. Greater variations in moisture content are generally observed at shallower depths of subgrade soil. Soil type, as quantified by plasticity and soil textural classification, can also have an impact on observed subgrade moisture content.

When one reviews the literature concerned with subgrade moisture content and its primary factors, it becomes obvious that the subject is incredibly complex. No single factor or group of factors can be said to control moisture levels in subgrade soils. Most of the factors mentioned are interrelated and can act on a given subgrade simultaneously or at given intervals over time.

In the next chapters some results of different test field will be presented. The emphasis is on determining the connection between precipitations and subgrade water content.

2 Data collection

2.1 Blount County, McNairy County and Sumner County test site

The tests performed on the site consisted of monitoring subgrade water content and temperature, pavement water content and temperature, infiltration into the pavement base layer and the meteorological conditions. Test fields are installed in US, in the state of Tennessee (Rainwater et al., 1999). Multiple-segment probes based on domain reflectometry technology TDR were placed horizontally in the soil subgrade, in the stone subgrade, and in the asphalt stabilized base, and single-segment probes were placed in the asphalt concrete of the roadway sections. Test site descriptions are summarized in Table 2.1. The typical roadway cross section with TDR probe placement is presented in fig. 2.1

Table 2.1 Test site descriptions

Detail	Blount County test site	Sumner County test site	McNairy County test site
Location	Alcoa, I-141	Gallatin, State Route 109	near Henderson, US-45
Surface layer (SL)	0.03 m	0.03 m	Future
Binder layer (BL)	0.04 m	0.03 m	Future
Asphalted concrete (AC)	0.08 m	0.08 m	0.10 m
Asphalt stabilized base (AS base)	0.06 m	0.07 m	0.08 m
Prime coat (bituminous material)	not applied on roadway project	applied on roadway project but omitted in vicinity of test site	removed over pan lysimeters, left in place over probes
Stone base (SB)	0.25 m	0.25 m	0.25 m
Lime stabilization	No	Top 0.15 m of SS	No
Soil subgrade (SS)	AASHTO: A-7-5(20)	not available	AASHTO: A-4(1)
EN classification	Si		Cl-Si
Water table depth below surface	>7.60 m	unknown	55.85 m—2/3/9

2.1.1 Results of measurements

The top probe in the soil subgrade of Blount County test site has not indicated significant changes in water content correlating with rainfall events but has shown a gradual 1.5% gravimetric water content increase over the five months following the 2% gravimetric water content increase in the bottom of the stone base (Fig. 2.2) The horizontal permeability in the stone base is greater than the vertical permeability of the soil subgrade. Thus, water perching above the soil subgrade will tend to move laterally toward the edge drain while a portion of the water will slowly move downward into the subgrade, resulting in a time lag in subgrade water content response.

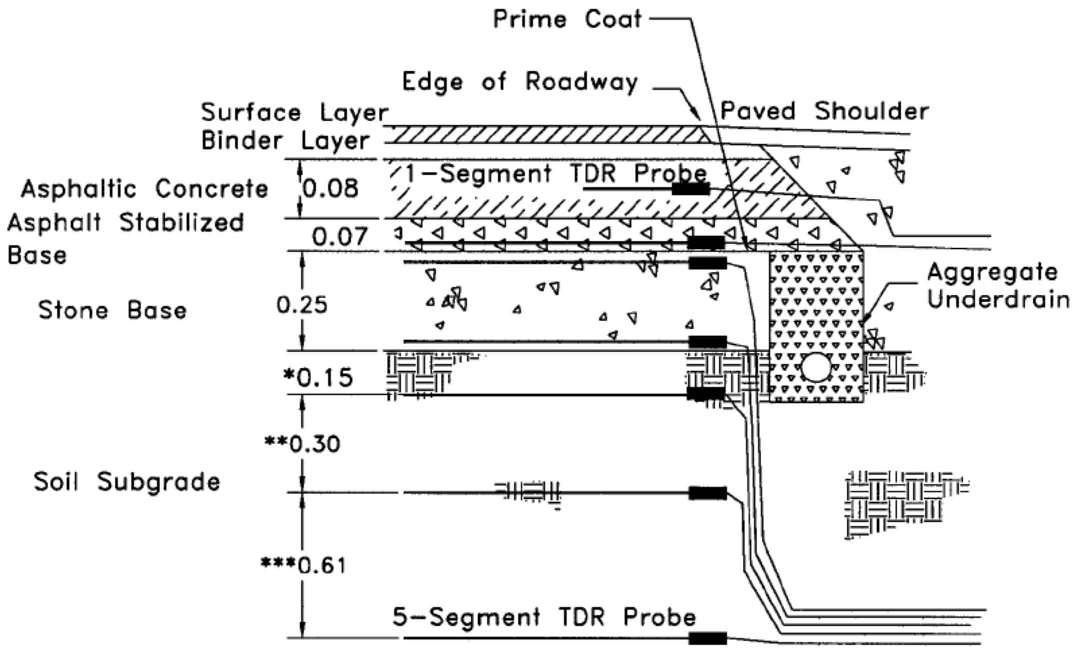


Figure 2.1 Typical roadway cross section

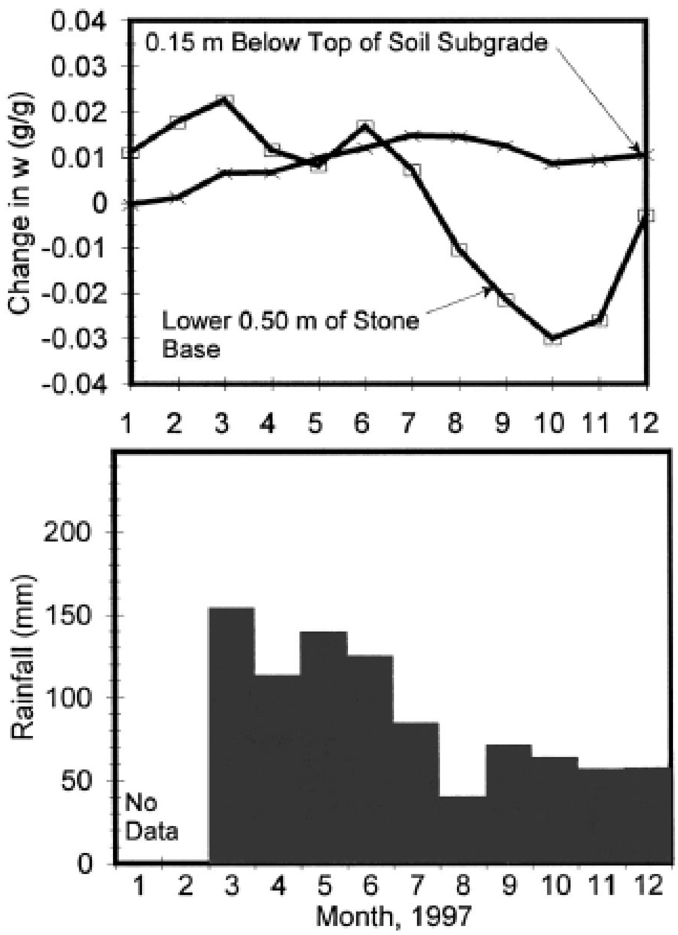


Figure 2.2 Seasonal Change in Stone Base Water Content and Soil Subgrade Water Content at Blount County Test Site during 1997

At the McNairy County Site, the dense, impermeable surface layer and binder layer are not in place. Data from the soil subgrade probes indicate less than 1% change in gravimetric water content during the first nine months of data collection. This may have reduced the water content changes in the subgrade.

Data collection began in October 1997 at the Sumner County Site. Data from the soil subgrade probes indicated a 2 to 3% water content decrease during November and December, then a small increase in January 1998 (Fig. 2.3). Although not documented with existing data, it is suspected that the soil subgrade water content increased significantly after compaction and prior to sensor installation because of several rainfall events that occurred prior to the placement of the stone base and the asphalt material. If so, covering the subgrade reduced further infiltration and allowed drainage of excess water.

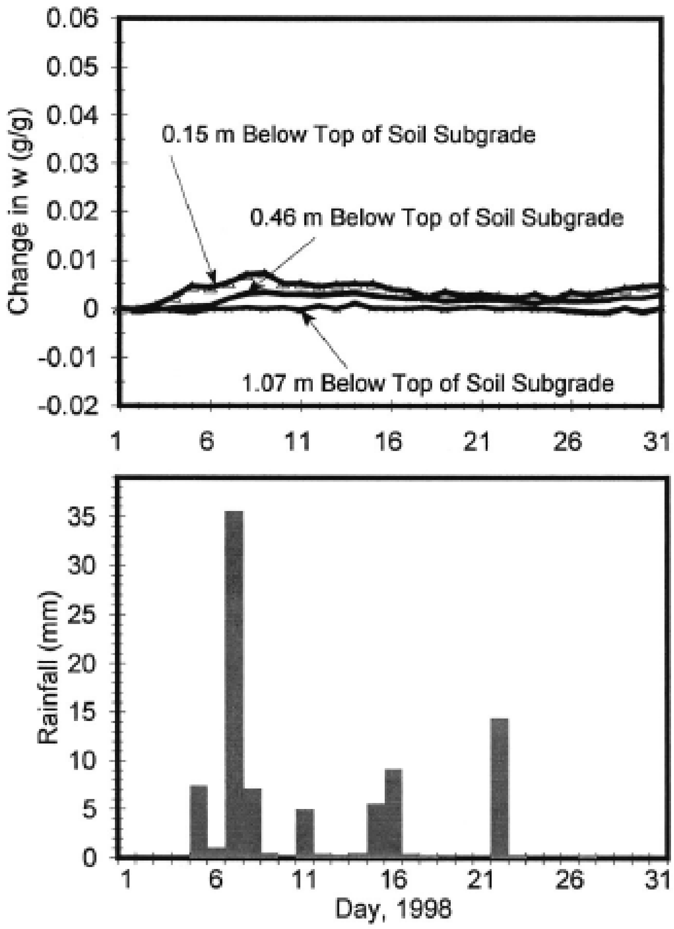


Figure 2.3 Change in Daily Average Water Content in Soil Subgrade and Total Daily Rainfall at Sumner County Test Site during January 1998

2.1.2 Conclusions

The comprehensive monitoring systems detect small changes in subgrade water content.

Data suggest that water moves readily through the AS base and into the stone base of the pavement subgrade in some roadways. It seems likely that repeated increases in stone base water content will eventually result in increased soil subgrade water content as water perched over the soil subgrade slowly infiltrates into the compacted material. Thus, changes in water content will occur very slowly; they will most likely either be seasonal or vary with unusually wet or dry years. The Blount County soil is a fine-grained soil that exhibits a high soil-water tension, resulting in very slow drainage. It is possible that fine-grained subgrade similar to thee Blount County Site will progressively increase in water content and equilibrate some years after construction. Coarser-textured subgrade similar to those at the McNairy County site, with higher permeability and lower water retention forces, may eventually show some seasonal water content changes. Also it is clear the importance of keeping the lower layers of soil and base not in contact with rainfall and other water sources before the surface layer is placed.

2.2 Lantz Corners, Meadville, Washington, State College, Wilkes Bare

Field test sites were selected throughout Pennsylvania (Cumberledge, 1974). Pits 3 ft (0.91 m) wide, 4 ft (1.21 m) long and 5 ft (1.52 m) deep were opened in the centre of one of the travel lanes for the purpose of installing thermocouples and moisture cells (Fig 2.4). Properties of the different subgrades met are presented in Table 2.2.

Table 2.2 Properties of test sites

	Corrected deflection	Moisture Content	Depth of Pavement Section	Engineering Properties of Subgrade Soils				Subgrade
				Density	Liquid	Plasticity	Percent Passing No. 200	
Site	(mils)	(percent)	(in.)	(Pef)	Limit	Index	Sieve	Classification
Lantz Corners'	-	-	17.0	112	25	2	65.1	A-4 (Cl-Si)
Meadville	0.62	15.0	12.0	110	24	3	66.2	A-4 (Cl-Si)
State College	0.59	18.1	18.0	100	55	20	74.9	A-7-5 (Cl-Si)
Washington	0.53	21.7	15.0	105	37	11	85.9	A-6; (Cl)
Wilkes-Barre	0.47	12.2	24.0	127	16	NP	29.2	A-2; (siGr)

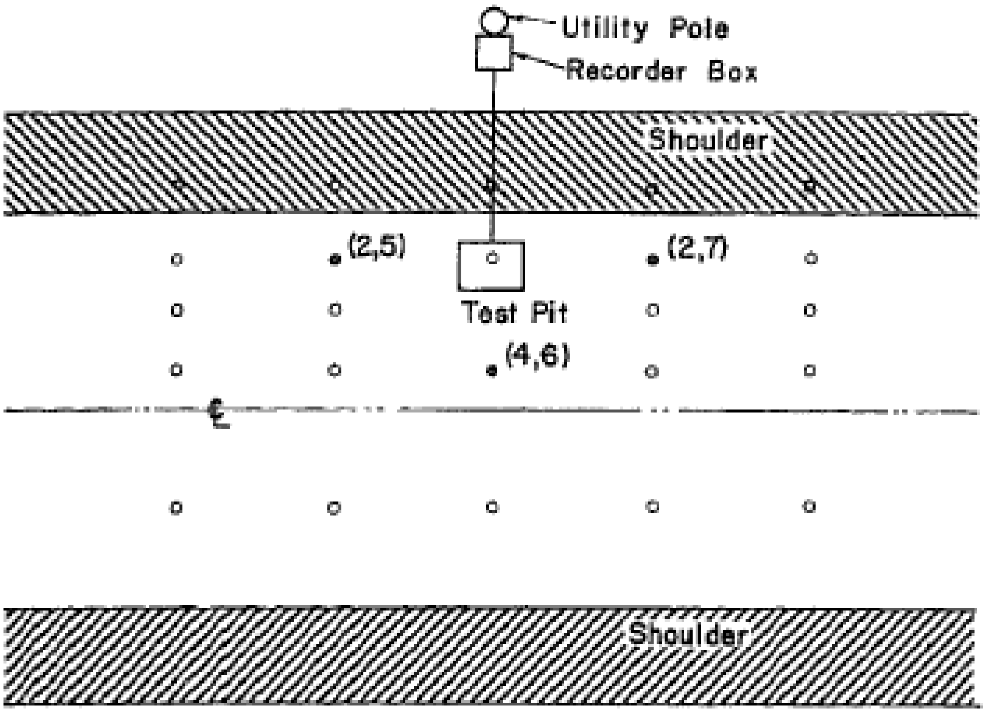


Figure 2.4 Plan view of test site

2.2.1 Results of measurements

Figures 2.5 - 2.9 show the average change in actual subgrade moisture content for the interval between 1970 and 1973. The sand curve is comprised of data from the Wilkes Barre sites, which have an A-2-4 subgrade soil classification(silt). Data from the Lantz Corners and Meadville sites have an A-4 subgrade soil classification (silt). State College and Washington sites, which have an A-7 and A-6 subgrade soil respectively, provide data for the clay.

2.2.1 Conclusions

Field tests seem to indicate a seasonal influence of subgrade moisture. In some instances, points of maximum subgrade moisture are preceded by a few months by periods of high precipitation.

It can be readily seen that all three subgrade soil types experience the greatest increase in moisture content in March and April. The sand soils show the greatest increase in moisture (3 to 4 percent) as compared to increases of 2 to 3 percent for silt soils and only 1 percent for clay soils. As anticipated, the increased moisture content in the sands drops back to a base level at a faster rate than do the silts. All subgrade soil types perennially reach a base level or minimum moisture content by September and October. The subgrade moisture variation, which occurs throughout the entire instrumented depth of 5 ft (1.52 m), can be associated with lateral movement from the shoulders, fluctuation in the water table and capillary zone.

A comparison of monthly precipitation with moisture variation indicates erratic peaks and no definite increases in moisture due to periods of heavy rainfall. In some instances, however, points of maximum subgrade moisture are preceded by a few months by periods of high precipitation.

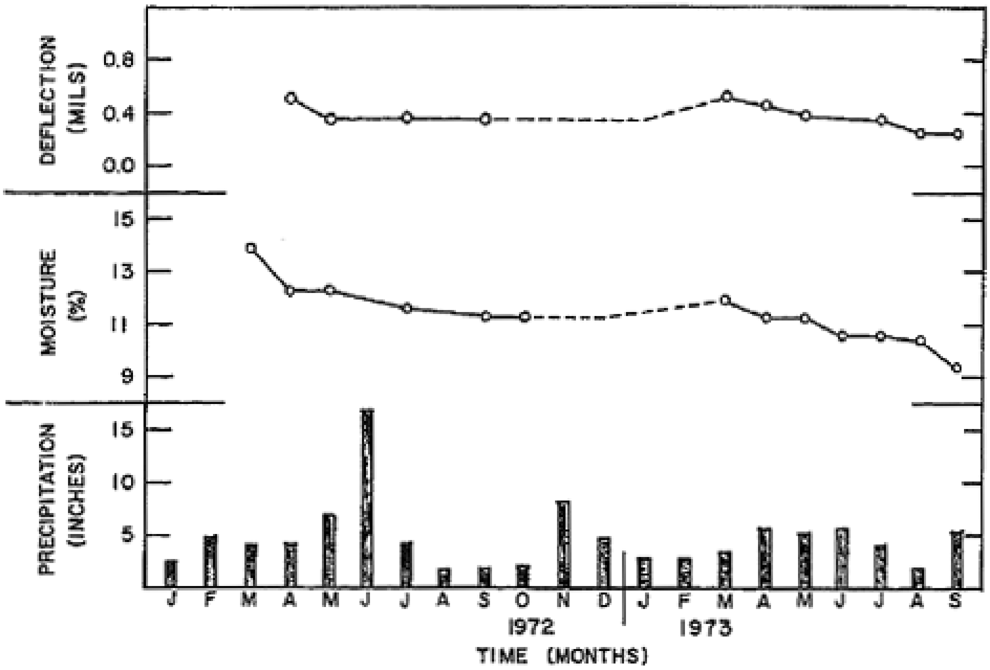


Figure 2.5 *Seasonal relationship of precipitation, subgrade moisture, and corrected surface deflection for Lantz Corners.*

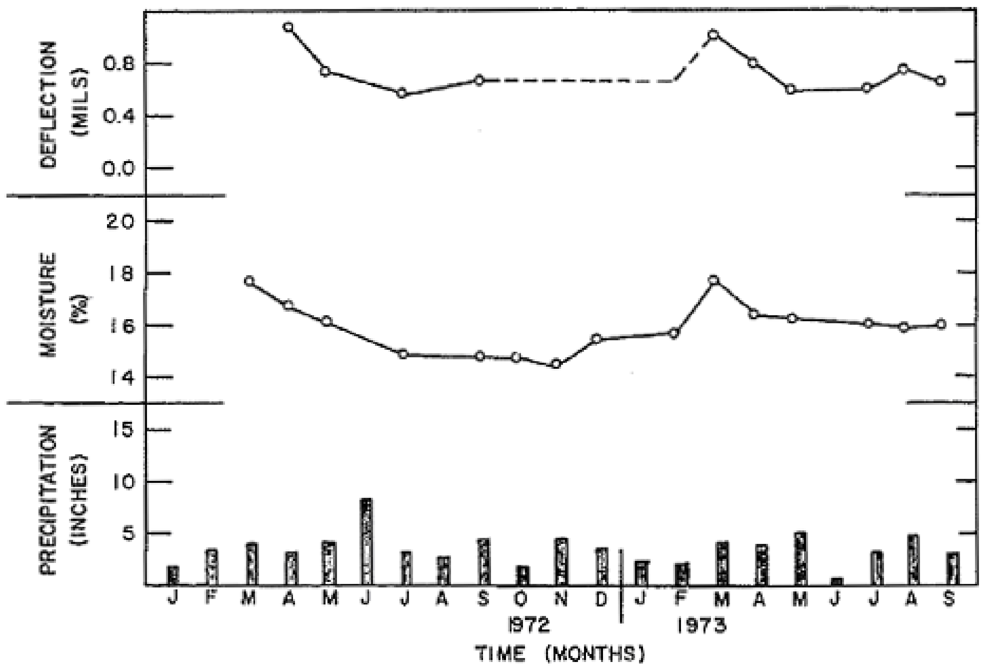


Figure 2.6 *Seasonal relationship of precipitation, subgrade moisture, and corrected surface deflection for Meadville.*

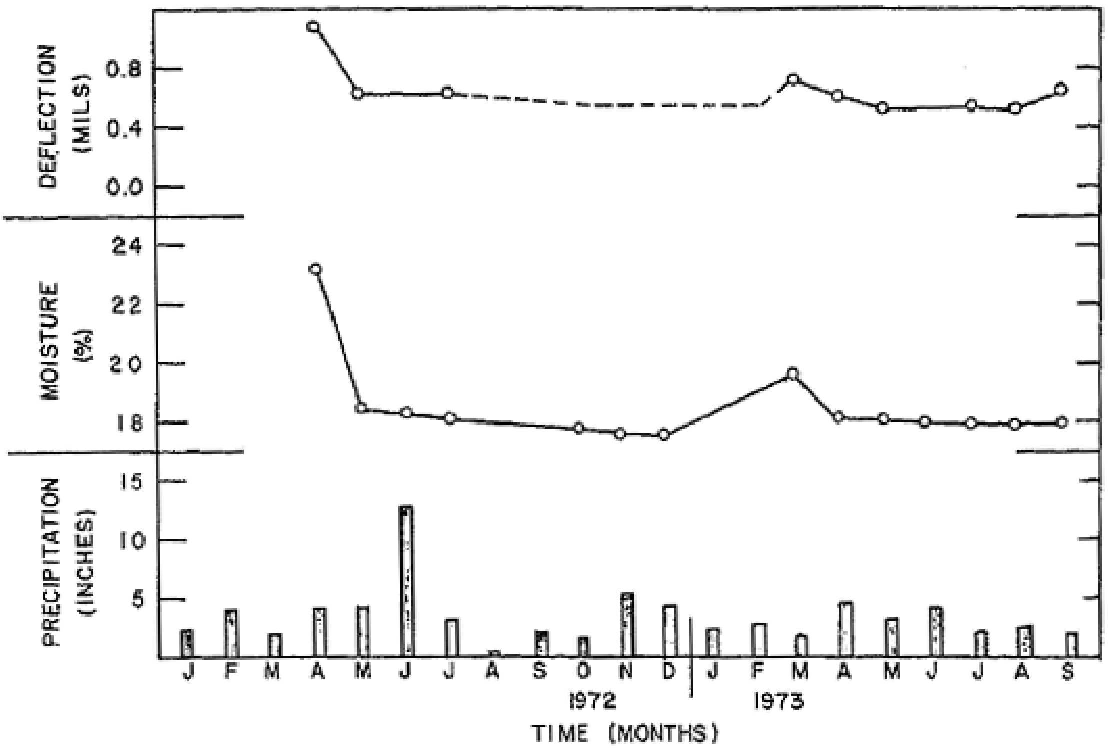


Figure 2.7 Seasonal relationship of precipitation, subgrade moisture, and corrected surface deflection for State College

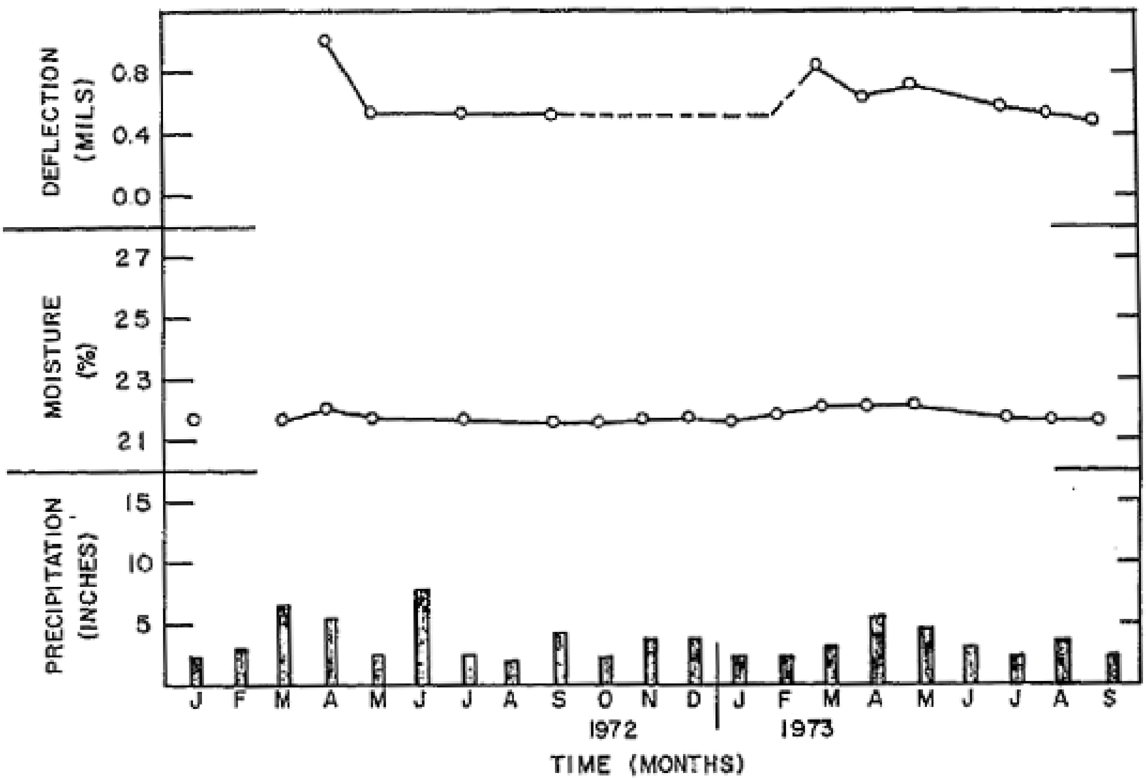


Figure 2.8 Seasonal relationship of precipitation, subgrade moisture, and corrected surface deflection for Washington.

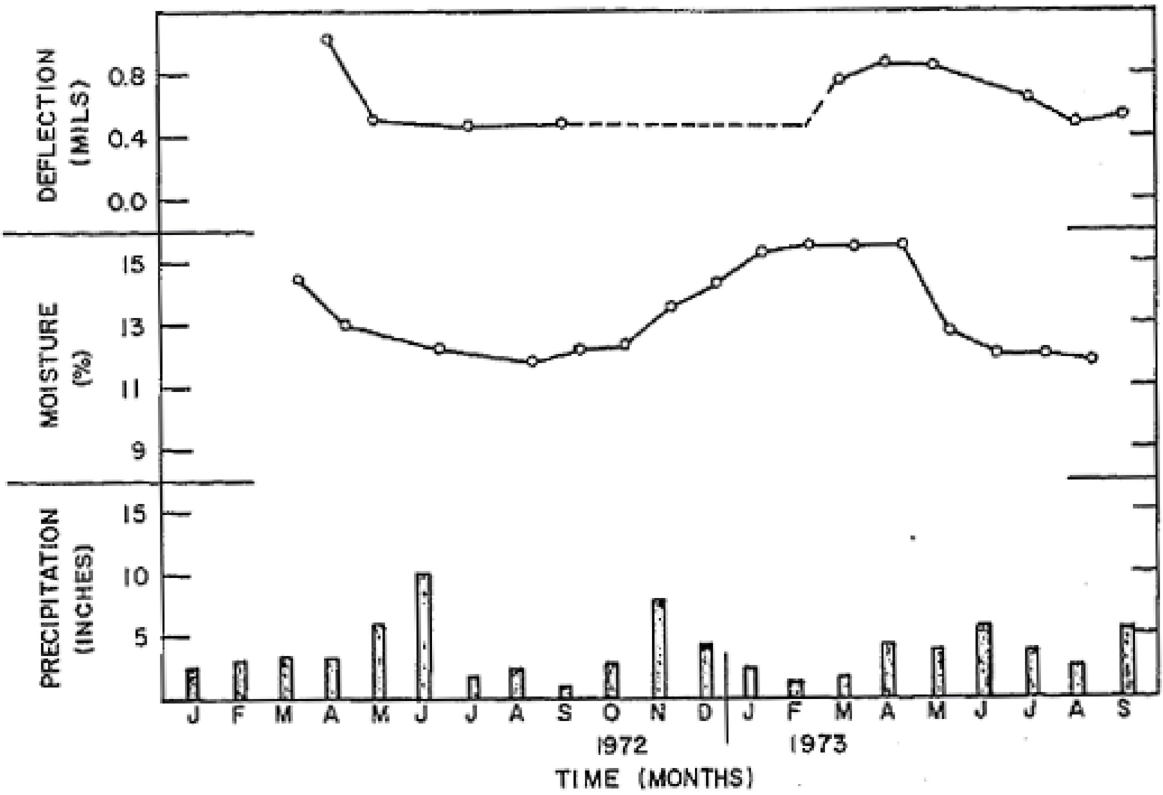


Figure 2.8 Seasonal relationship of precipitation, subgrade moisture, and corrected surface deflection for Wilkes Bare

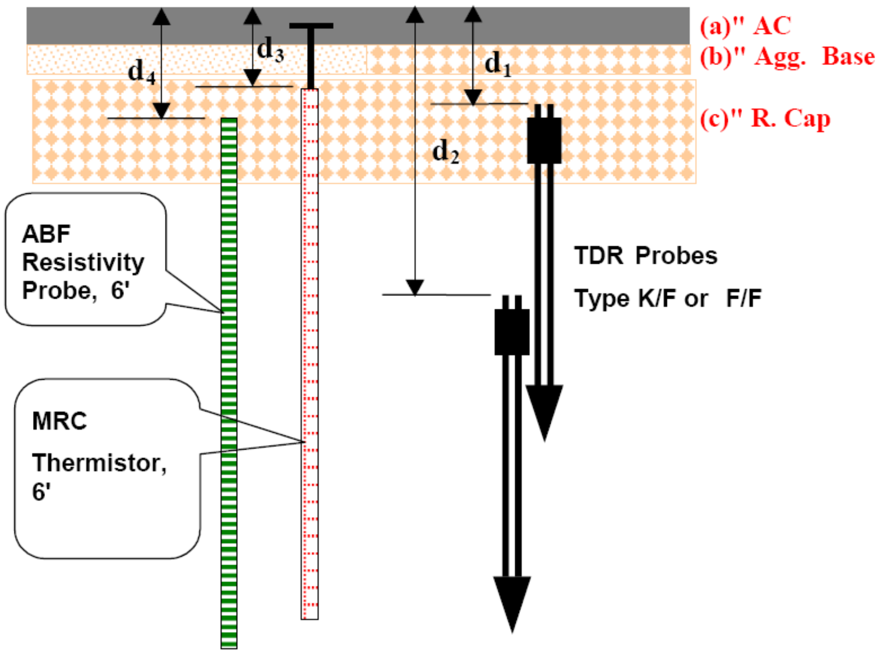


Figure 2.9 Schematic the probes installation for all sites

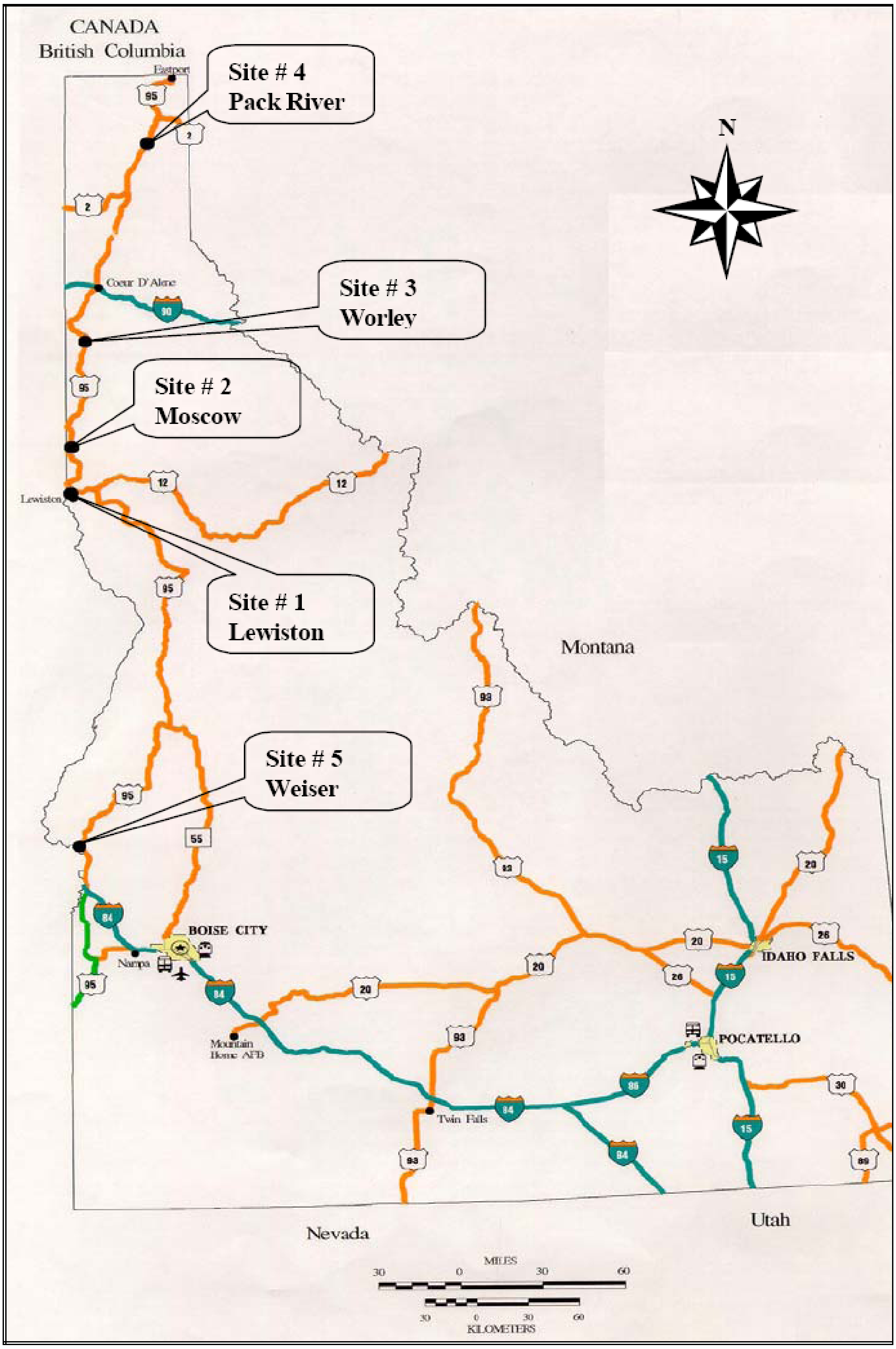


Figure 2.10 Idaho Site locations

2.3 Lewiston, Moscow, Worley, pack River and Weiser test site

In a study performed in Idaho (Bayomy, 2004) the variation of subgrade soil moisture was monitored by means of TDR (Time-Domain Reflectometry) moisture sensors, which measure the volumetric moisture content (Fig. 2.11). Layer properties of test sites are presented in Table 2.3 and location of probes in test fields in Fig. 2.10.

Table 2.3 Layers' Thickness & Subgrade Soil Characterization Tests, for Different Sites

Site Test	Lewiston	Moscow		Worley	Pack River		Weiser	
	1	2A	2B	3	4A (S)	4B (N)	5A	5B
Construction year	97	96	96	96	88	98	99	99
AC surface Thickness, in	6	4.8	4.8	7	6	12	6	6
Agg. Base Thick., in	-	6	27.6	-	-	-	6	12
Rock Cap, Thick., in	20	21.6	0	21	24 (river cap)	Undefined	6	0
Subgrade Type	Granular Fill (Si)	CL (Cl)	CL (Cl)	Clayey silt (siCl)	Lacustrine silt & silty gravel (Si,siGr)	Lacustrine silt (Si)	ML (Si)	ML (Si)
% Pass # 4	100	100	100	100	100	100	100	100
% Pass # 10	100	100	100	100	88	100	100	100
% Pass # 40	100	100	100	100	65	100	100	100
% Pass # 200	62	98	98	82	29.5	92	70	70
LL, %	25	30.3	30.3	40.2	NP	NP	39.8	39.8
PI, %	NP	8	8	18.4	NP	NP	9.6	9.6
AASHTO Class.	A-4	A-4	A-4	A-6	A-2-4	A-4	A-4	A-4
Unified Classif.	ML	CL	CL	CL	SM	ML	ML	ML

2.3.1 Results of measurements

The moisture content versus average monthly rainfall for all sites is shown in Figures 2.12-2.16. The figures indicate that the moisture content is highly related to the average monthly rainfall amounts in most of the sites (Lewiston, Moscow- A, Moscow -B and Pack River –A). For example, the moisture content at the Lewiston site increases when the average rainfall increases. However, when the rainfall drops (during July and August) the moisture content does not drop suddenly, because the soil is fine and has little permeability, therefore it continues to decrease gradually.

In order for the rock cap layer to show its effectiveness in draining the water out of the pavement system, it should be connected to a daylight drainage layer (open to a side ditch), as shown in Weiser sites. However, in a closed system like the one in Moscow, the water may seep vertically through the layer voids and cause an increase in subgrade moisture.

The change in subgrade moisture under base and rock cap is noticed only at shallow depths just below the base or rock cap layer.

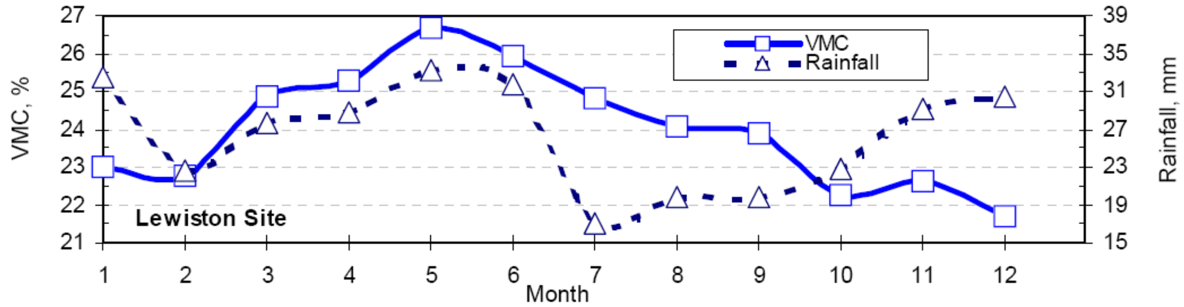
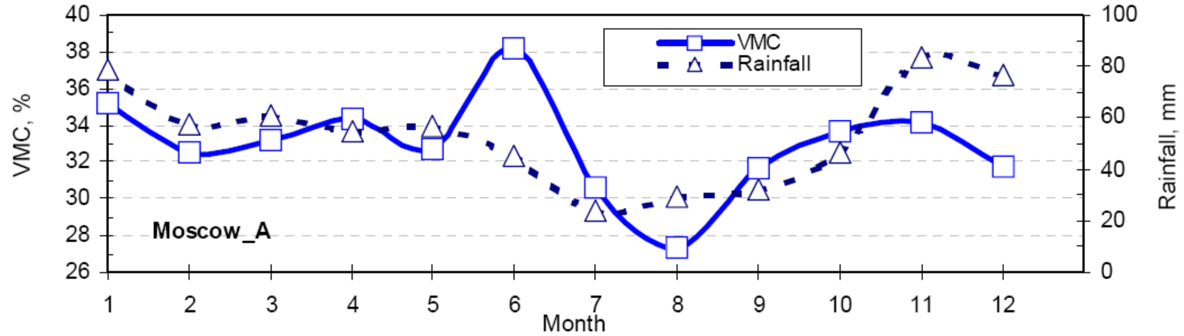


Figure 2.11 Moisture Content versus Rainfall for Lewiston Site



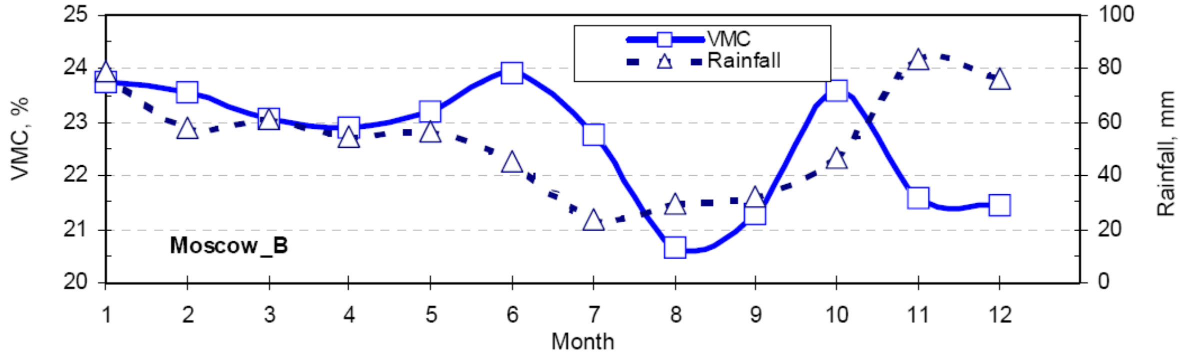


Figure 2.12 Moisture Content versus Rainfall for Moscow Sites

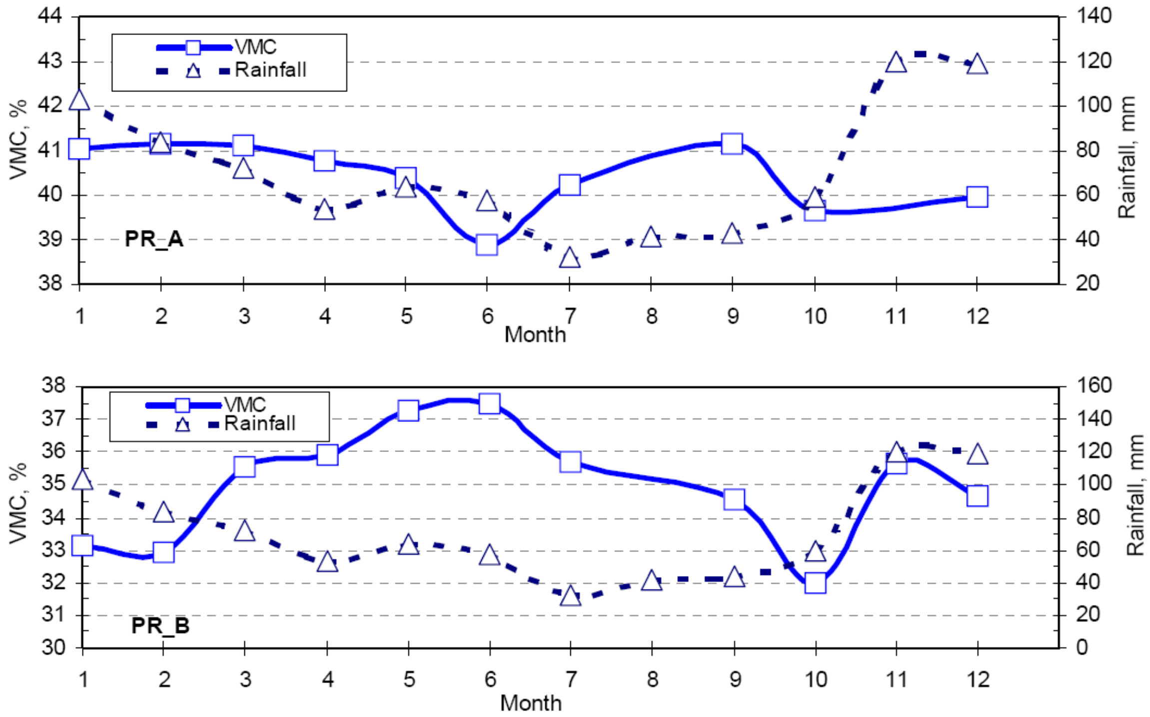


Figure 2.13 Moisture Content versus Rainfall for Pack River Sites

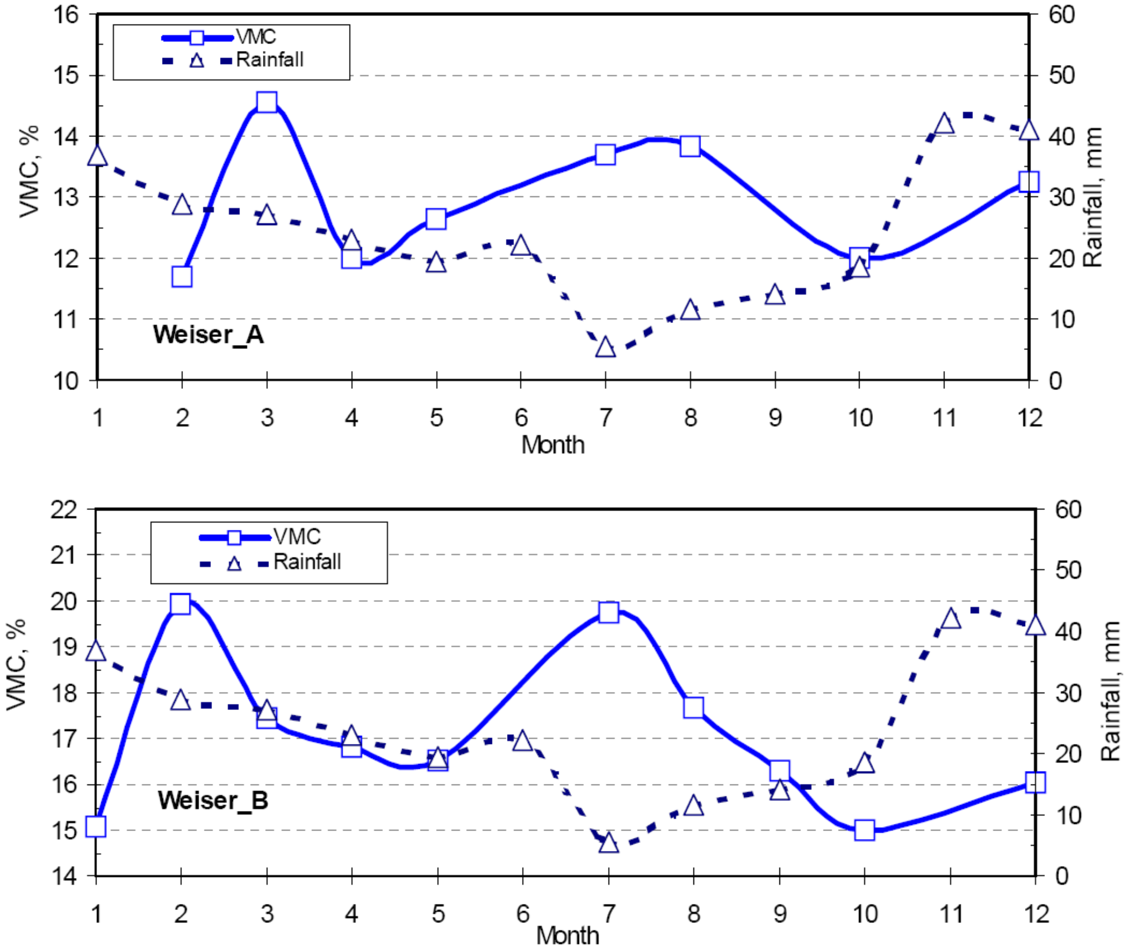


Figure 2.14 Moisture Content versus Rainfall for Weiser Sites

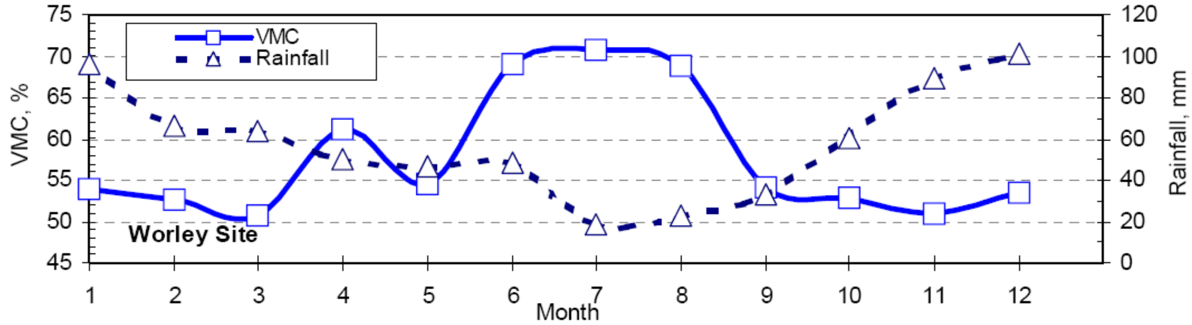


Figure 2.15 Moisture Content versus Rainfall for Worley Site

2.3.2 Conclusion

The findings are summarized in the following points:

The moisture contents measured at most of the Idaho sites showed long-term equilibrium with little seasonal fluctuation. The seasonal variation ranged from +/- 2 % to about +/- 10% from the average value.

The seasonal variation in subgrade moisture content could be related to the rainfall amount, the level of the ground water, and soil type (fine or coarse, plastic or non-plastic). The data presented showed that the soils that were more sensitive to moisture variations were the fine silty soil and the clay, while coarser soils, like clayey sand, were less sensitive to moisture variations.

2.4 U-283, U-160 test site

Four 150 meter long asphalt pavement sections were selected as test sites in an area that represents the average climatic condition for Kansas (Hossain, 1997). Table 2.4 lists the locations and characteristics of the sites.

Table 2.4 Location and Characteristics of the Sites Selected for the Study

County & Route	Layer Thick- ness (mm)	Shoulder Type	Soil Type (Unified)	LL (%)	PI (%)	% passing 75 pm sieve	Soil Perm-eability (mm/hr)
Clark, US-160	229	unpaved	CL-ML (Cl-Si)	26 25 26	6 7 6	59 58 55	15-51
Clark, US-283	305	unpaved	CL, CL- ML (Cl, Cl-Si)	27 27 29	9 7 9	51 50 52	15-51

2.4.1 Results of measurements

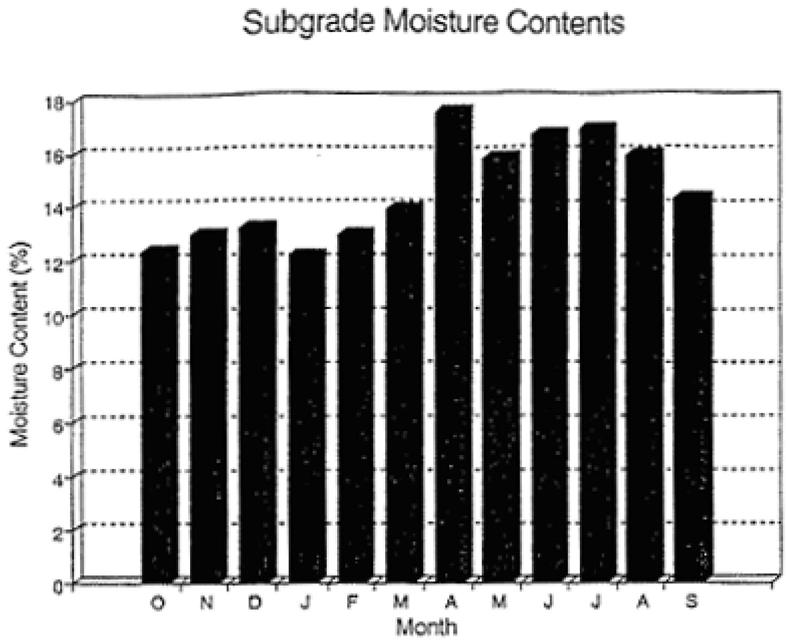
Both US-160 and US-283 were selected in the same climatic zone in south-western Kansas with the same precipitation history, but the variations of subgrade moisture contents on these routes are slightly different as shown in Figures 2.17 and 2.18, respectively. The highest subgrade moisture content for US-283 occurred in September, and for US-160, it happened in April. However, the moisture contents were reactively unchanged, varying between 13% and 18% for US-283 and 12% and 16% for US-160.

The results also indicate that for every 100 mm precipitation in south-western Kansas, the subgrade moisture contents under asphalt pavements tend to increase by only approximately

3%. Drainage of these pavements are provided by the cross-slopes and side-slopes on the shoulder. These measures seem to be adequate for the pavements in this climatic area.

2.4.2 Conclusion

The asphalt pavements in Kansas experience relatively constant moisture condition under paved surfaces during most of the year. Although some subgrade moisture content readings were constant over one year period, quite a few readings showed significant variation during short periods of time suggesting extremes for those sites. This may indicate the necessity for better drainage for the pavements in northeast Kansas.



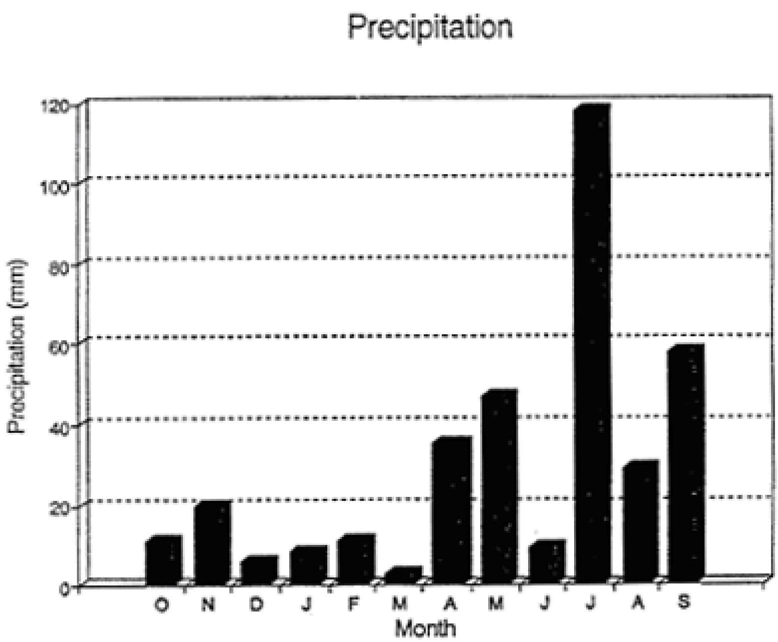


Figure 2.16 Monthly subgrade water content and precipitation at K160

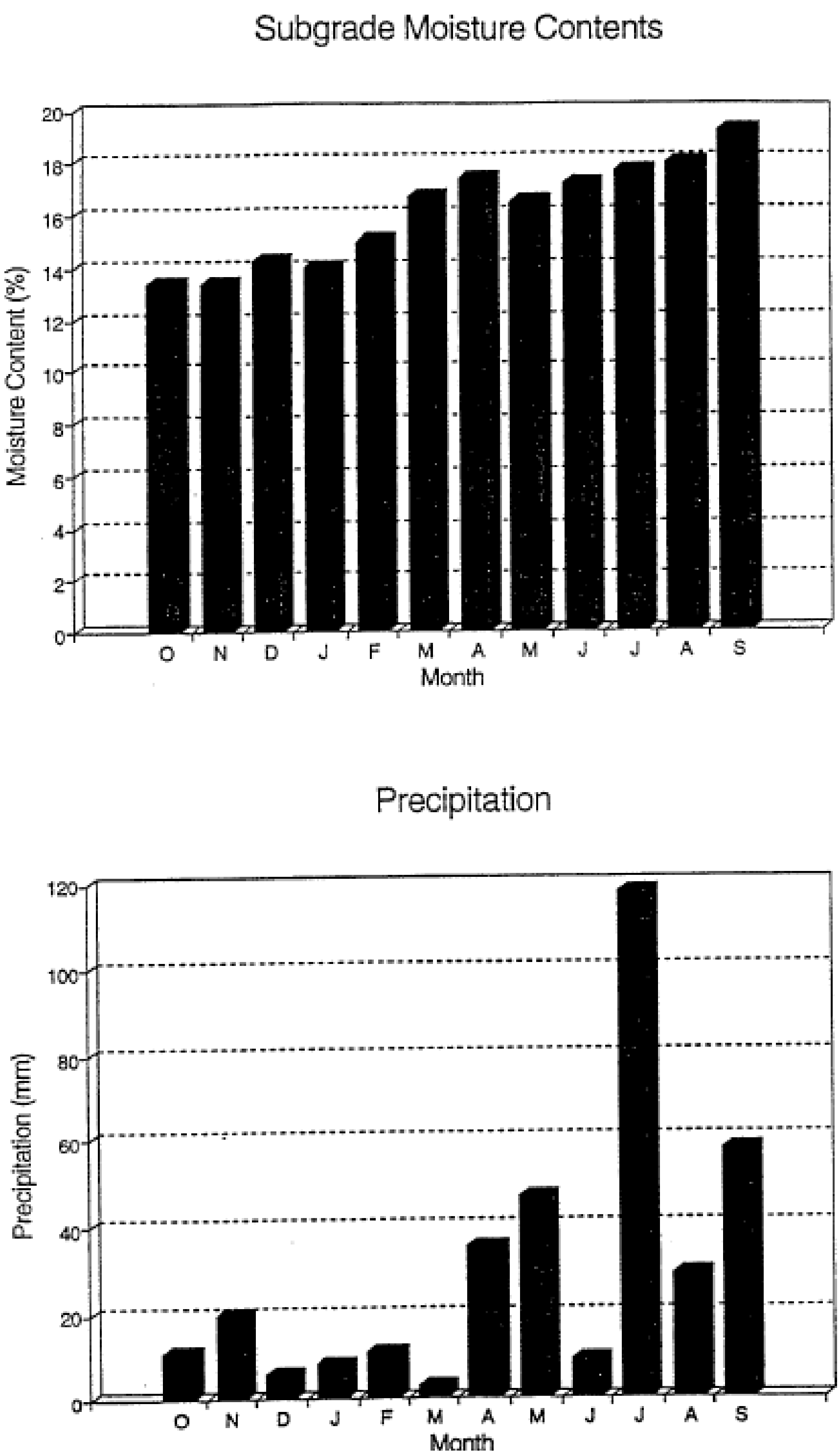


Figure 2.17 Monthly subgrade water content and precipitation at K283

Variation of subgrade moisture contents does not appear to depend on precipitation only. For pavements in south-western Kansas, moisture contents during months with higher precipitation exceeded moisture contents during spring thaw periods. This indicates that for Kansas condition, the subgrade structural response in summer may be lower than that in spring.

2.5 Rogla test site

The site location Rogla is located at R3 701, section 1430, Sand - Zreče, km 11 +500. It is a tourist mountain road (Petkovšek, 2003). The road was due to damage repaired in 1999, the following year in 2000 fissures occurred again on the road.

A typical cross-section of the road structure at this site is described in Table 2.5.

Table 2.5 A typical cross-section

Site:	**Rogla**
Layers:	8 cm new asphalt layer
	5 cm unbound layer
	8 cm old asphalt layer
	22 cm unbound layer

Five instruments for moisture measurement were installed (TDR), three in the unbound layer and two in the subgrade. The subgrade consists of perm carboniferous shale, weathered into a soil. Geomechanical properties are in the Table 2.6.

Table 2.6 Geomechanical properties of the subgrade

Classification	**Water content**	**Plastic and liquid limits**		**Plasticity index**	**Determination of particle size distribution**				**Density with isotopic probe**	**Water of content with isotopic probe**
	W	**W_p**	**W_l**	**I_p**	**C_u**	**C_c**	**<0,063**	**<0,02**	**ρ_d**	**W**
	%	%	%	%			%	%	kg/m^3	%
ML (Si)	24.1	29	39	9.8	293	0.3	26.3	16.2	1433	26.8

2.5.1 Results of measurements

Humidity was near 24% through the year of 2001, excepted for deviations during rainfall. In a winter time the water content of subgrade drops down for 5% (Fig.2.19). Consequently to a warming period at the end of January 2002, the average level of water content increased for 5 % and stayed the same for almost the whole year. The water content did not increase even on the wetter period in November. In the winter 2003, the water content dropped down again because of the partly frost road layers. It has to be noted that in the observed time, the winters were very warm.

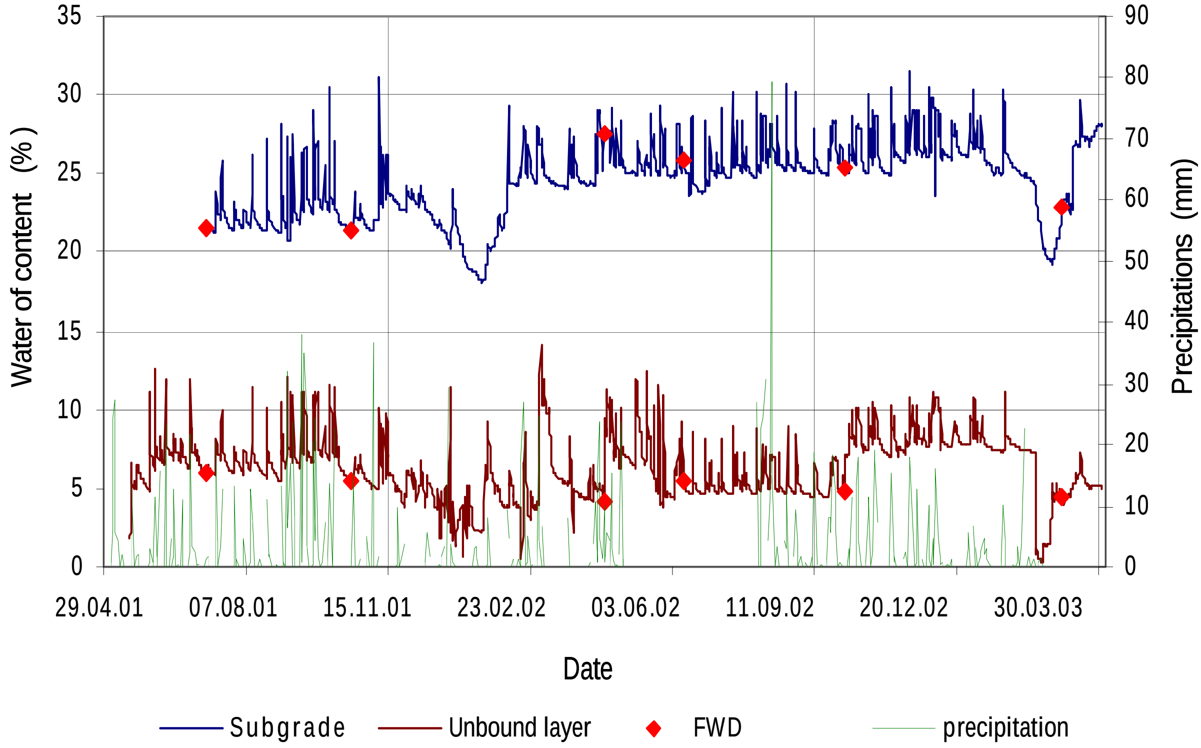


Figure 2.18 Water of content with precipitation

2.5.2 Conclusion

In the observed period of two years, winters were very warm. In winter time the water content of the subgrade dropped down to 10%, but increased in spring after thaw. The soil is highly weathered soft rock, and basically behaves as a silt (ML in table 3.2). It is assumed that condition of the pavement shoulders and edges were in bad condition because in the lens formation through the winter time.

2.6 Muljava test site

A section of national road Ivančna gorica – Muljava, which was at that time under reconstruction, was chosen for testing with crushed concrete rubble in an unbound layer. The test section is situated in a road that goes from Dolenjska lowland to Suha krajina, about 85 km south-east from Ljubljana, capital of Slovenia (Petkovšek, 2007). Due to the heavy traffic and influences of weather (infiltration of water, frost heave), the road was badly damaged and in need of reconstruction. During the reconstruction works, a test section was prepared and instrumented.

The test section consisted of two parts:

- A part with crushed concrete rubble as aggregate for unbound layer and
- A part with natural aggregate in unbound layer.

The road is constructed over a clay embankment overlaying sub base (Fig. 2.20). During reconstruction, a granular base layer, an unbound layer and an asphalt layer were rebuilt. In both parts of the test section is a sub base and embankment, consisting of clay of high plasticity, which was upgraded with granular base layer and unbound layer, followed by asphalt layers.

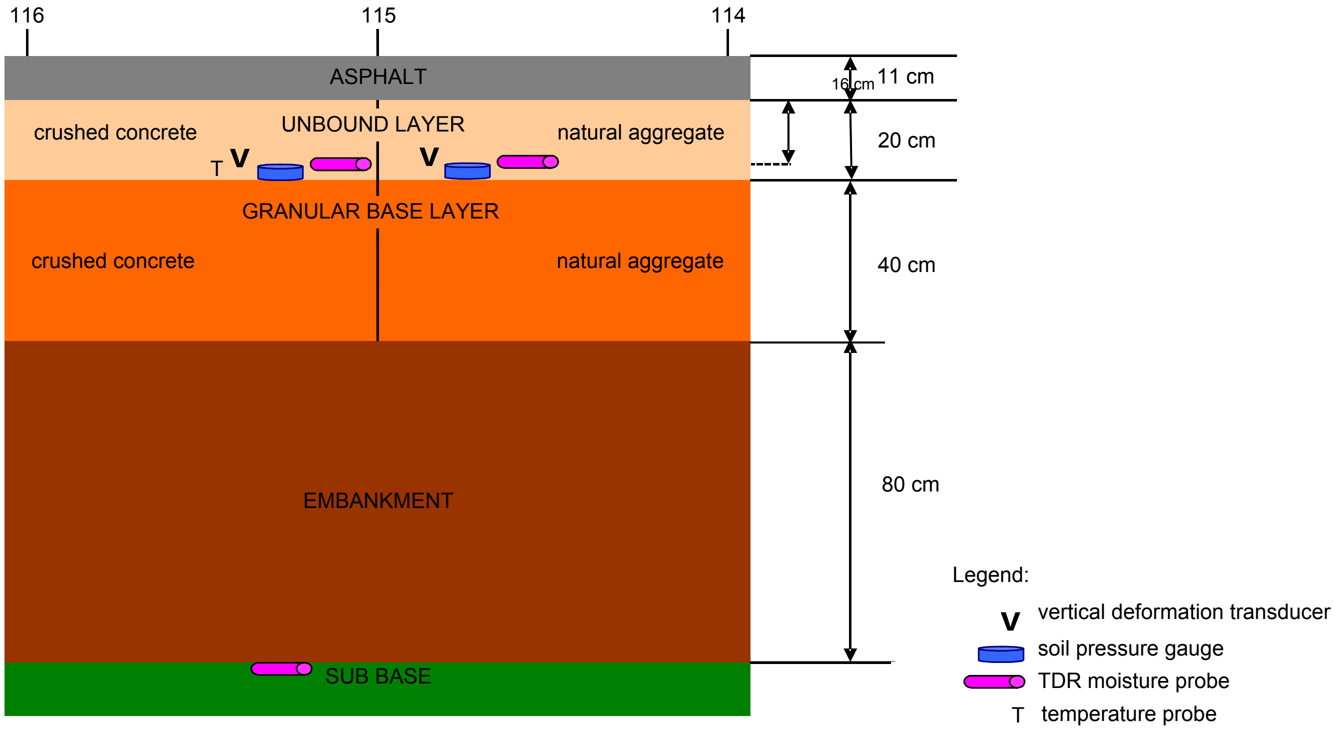


Figure 2.19 Schematic presentation of instrumented test section – cross section

2.6.1 Results of measurements

The water content of the soil sub base is higher in autumn and spring and lower in summer time. Between winters, the temperature and precipitation had a lower influence on the soil subbase.

2.6.2 Conclusion

Low bearing capacity of subgrade soil was compensated with quite thick embankment. The water content did not drop below the optimal moisture even in summer time. The change of water content through the year was no more then 2%

The time delay between rainfall and corresponding increase in water content in granular base layer is 2 days at most. The first maximum correlation for subgrade layer is 5 days and the second peak is 30-50 days after rainfall.

2.7 Raahe test site

As a part of the COURAGE Project (Suni, 1999), two moisture test sections were instrumented in the middle of Finland near the city of Raahe, about 500 km north of Helsinki, Finland`s capital. Raahe is situated on the eastern shore of the Gulf of Bothnia.

The test sections were on main road 8, which was undergoing rebuilding and widening work from April to August 1998. Two test sections were chosen to represent different moisture conditions, one on the embankment and the other on a cut. The subsoil and materials used in the construction work were analysed through laboratory tests.

The base and surface work of the road rebuilding were finished in June 1998, when the instruments were installed and material samples were taken. Follow-up measurements were launched immediately after surfacing, and they have continued until late autumn 1999.

Table 2.7 Basic properties of the test section materials

Properties	Unit	Unbound layer	Granular layer	Subgrade layer
USCS		GW (Gr)	GW-GM (Gr-siGr)	CL-SC (Cl-Si)
Water of content W_o	%	4,8	1,5	23,8
Plasticity				
Plastic limits W_p	%			35,0-40,5
Liquid limits W_l	%			18,0-21,6
I_p	%			17,0-18,9
I_c				0,65-0,9
Particle size				
<0,063		4,5	5,9	64,1
<0,02		2,4		40,8
C_u		17,3	32,6	14,7
C_c		2,1	2,8	0,7
Density				
ρ_s	t/m^3	2,73		2,69
ρ	t/m^3	2,396		1,93
ρ_d	t/m^3	2,265		1,56
Proctor				
W_{opt}	%	3,9	4,3	19,1
ρ_{dmax}	t/m^3	2,267	2,307	1,681

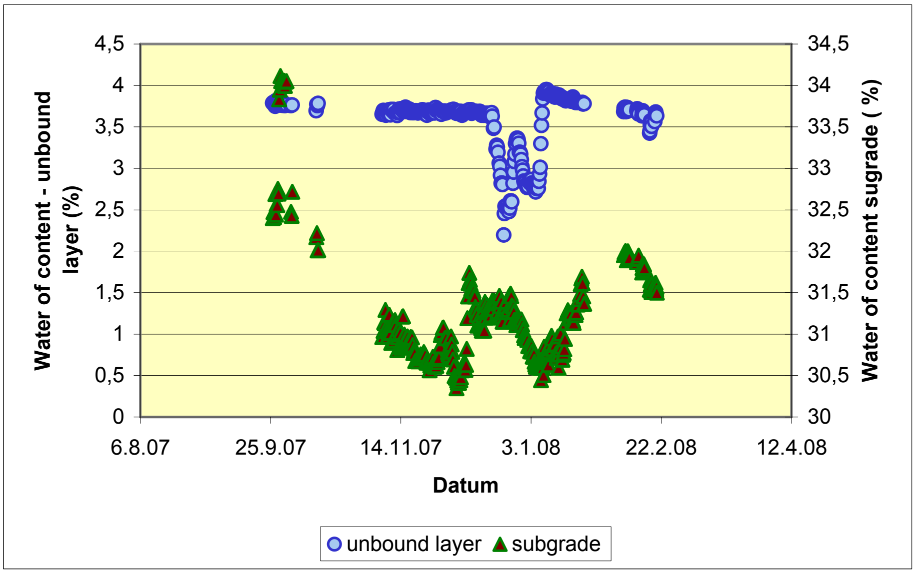


Figure 2.20 Moisture content of subgrade (sub base) and unbound layer

The main road 8 is an old road, and the previous significant improvement of the road structure was done in the beginning of the 1980s. At that time the road was rebuilt and widened to 8 m. The AADT at the test section is about 6500 vehicles / day, with a 9 % share of heavy traffic.

The layers of the road are shown in Table 2.8 and the instruments of test fields in fig.2.32.

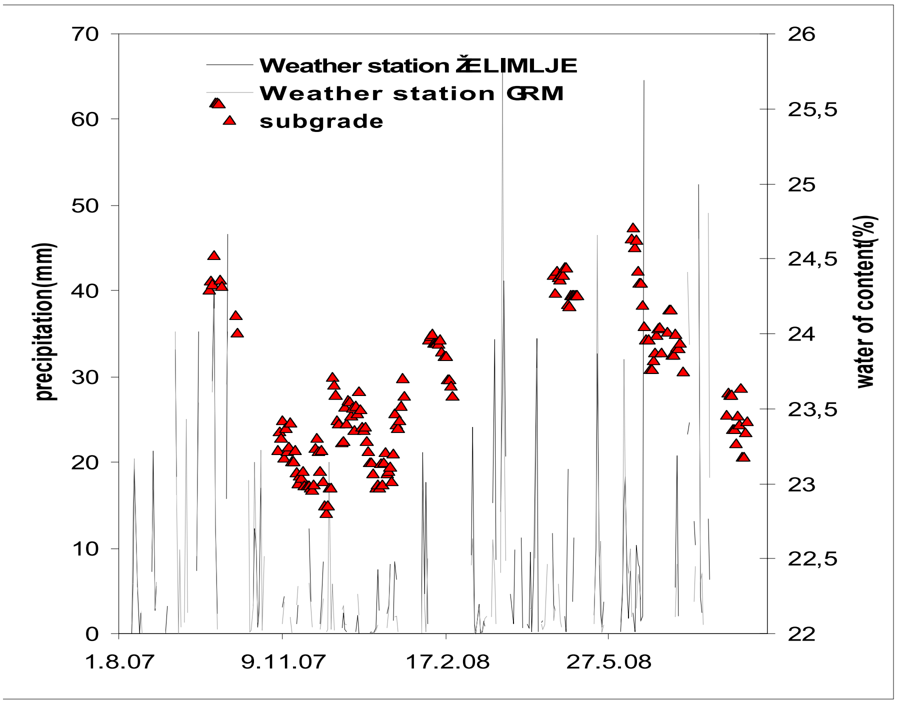


Figure 2.21 Water of content with precipitation

Table 2.8 Layers of test sections

Layer	Embankment profile	Cut profile
AC	18/20 kg/m^2, 50 mm	18/20 kg/m^2, 50 mm
AC	14/80 kg/m^2, 30 mm	14/80 kg/m^2, 30 mm
Base	0-64 mm crushed rock, 250 mm	0-64 mm crushed rock, 250 mm
Sub-base	0-64 mm crushed rock, 300 mm	0-64 mm crushed rock, 300 mm
Filter	0-16 mm sand, 300 mm	0-16 mm sand, 300 mm
Subsoil	old road structure	Moraine

The materials used were typical Finnish mineral materials, crushed rock and sand. The subsoil is rocky sand, typical for this area.

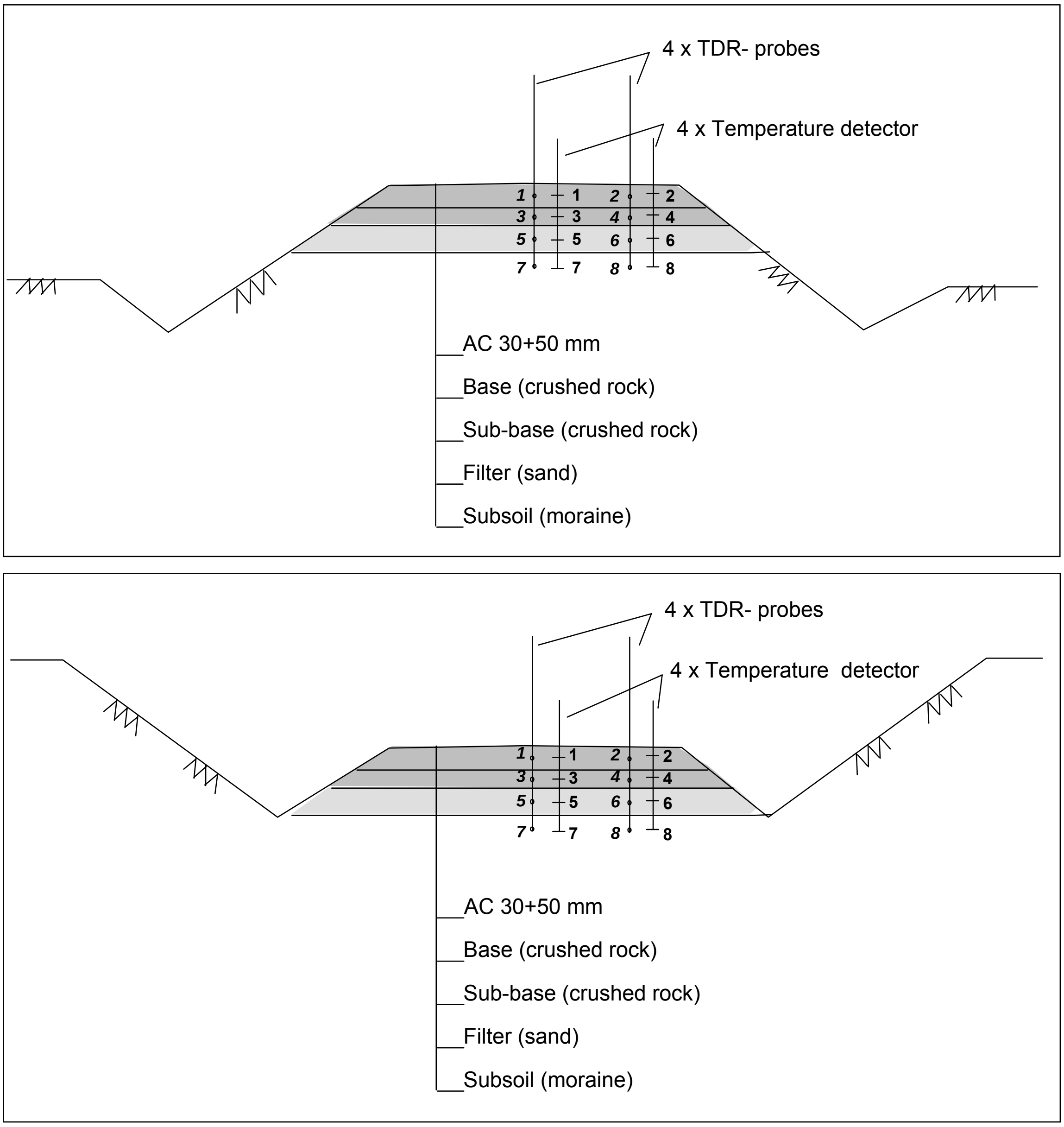


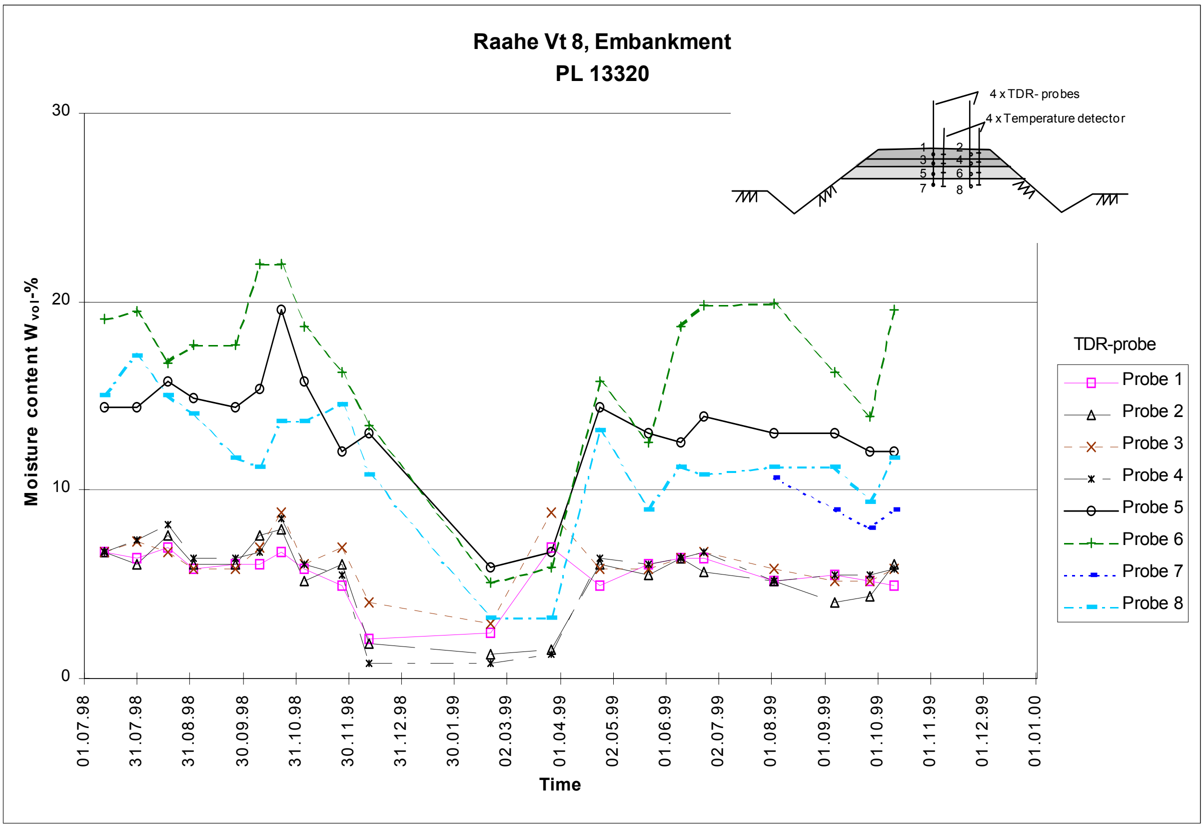
Figure 2.22 Instrumentation layout and sensor depth locations

2.7.1 Results of measurements

Embankment profile

In the subsoil the moisture content near the shoulder is higher than beneath the road. The moisture content varies in the unfrozen state near the shoulder between 11-18 %, and, in the middle part of the road, between 8-11 %. In the driest season the moisture content is the lowest (Fig. 2.25).

In the cut profile the subsoil the moisture content varies between 19 and 25 according to weather conditions (Fig. 2.25).



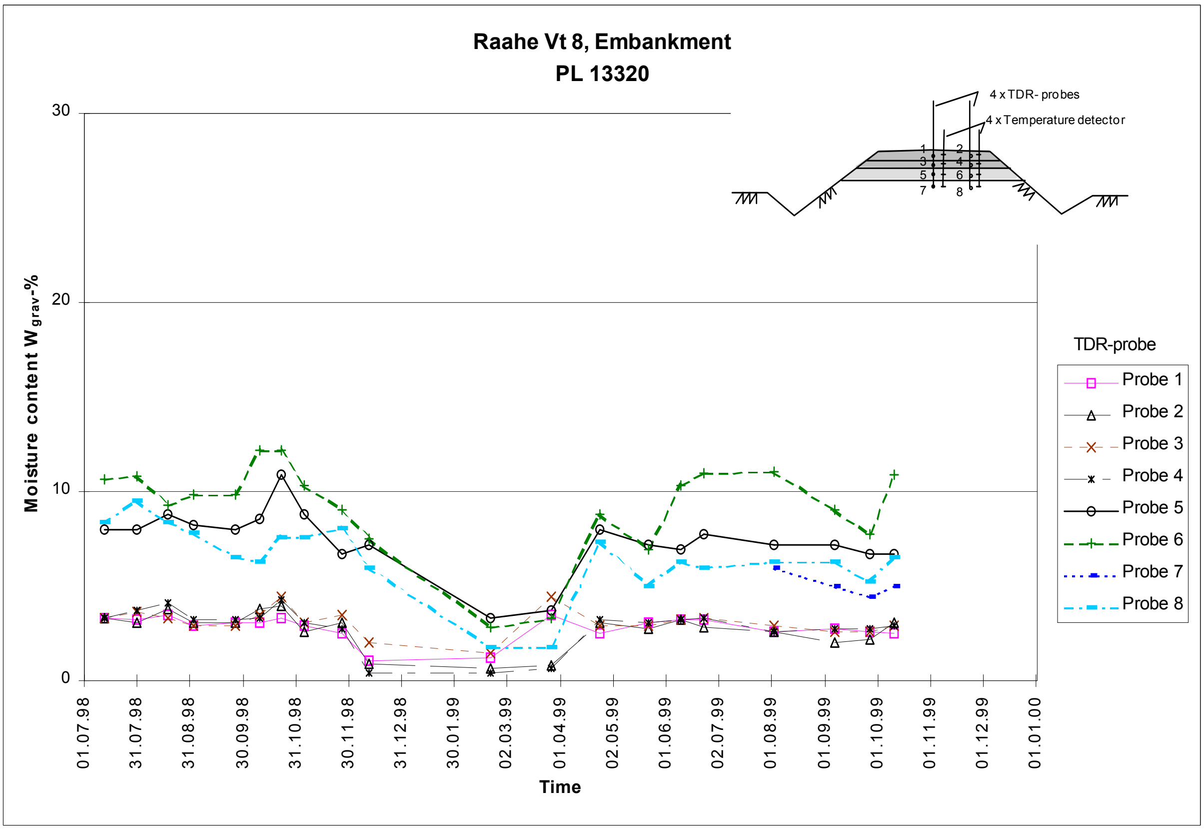
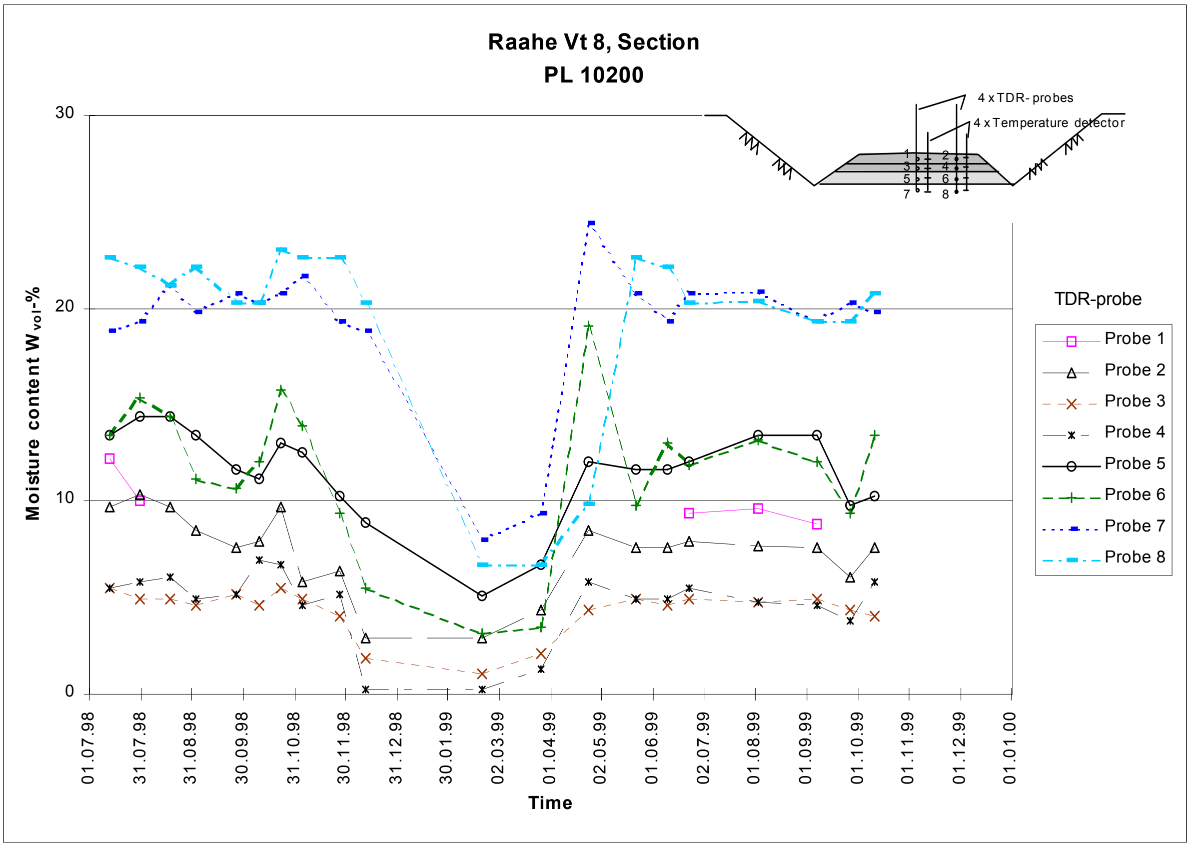


Figure 2.23 Variation of moisture with time. In Fig. 2.24a moisture content is in volumetric form and in Fig. 2.24b in gravimetric form.



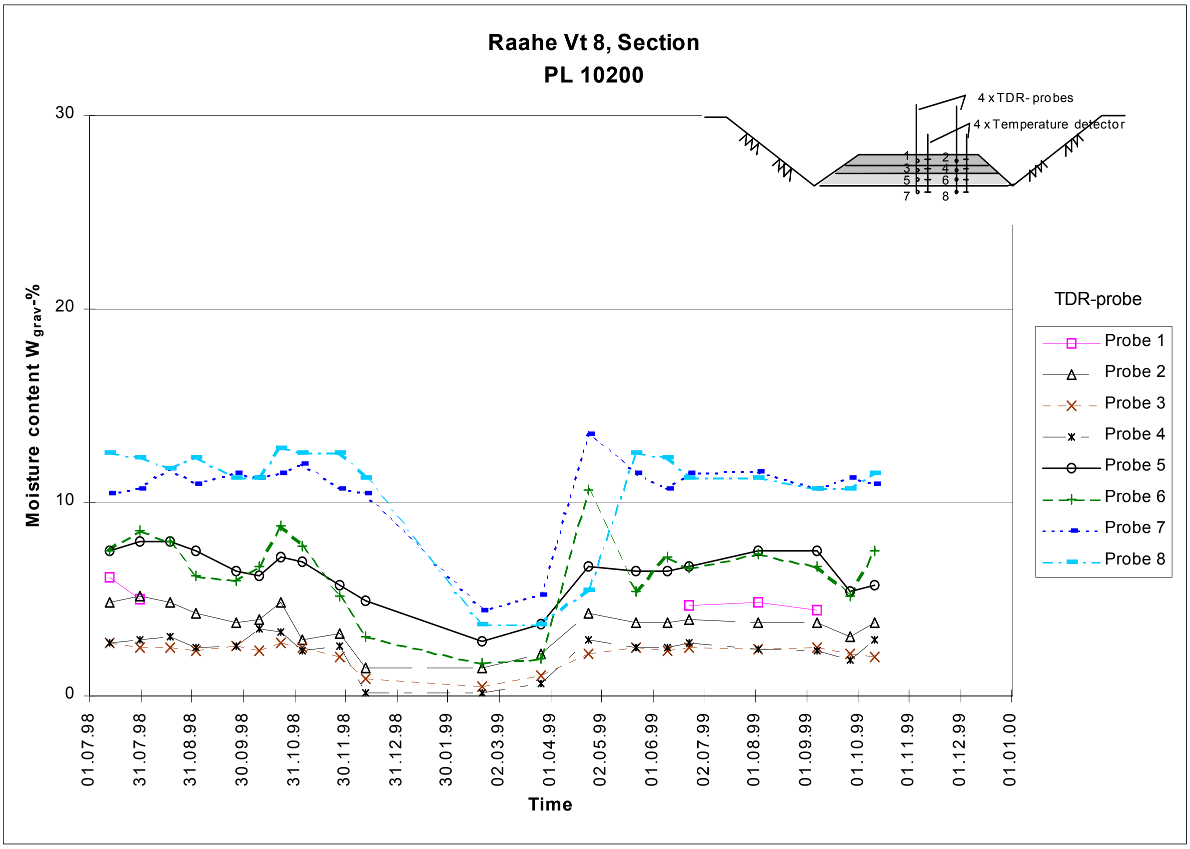


Figure 2.24 Variation of moisture with time. In Fig. 2.25a moisture content is in volumetric form and in Fig. 2.25b in gravimetric form.

2.7.2 Conclusion

Based on the moisture content and the FWD measurements during period 1998 – 1999 the following conclusions could be found:

- The variation in moisture content in all structural layers followed seasonal variations, with the moisture content being the highest in autumn and spring. The highest variation was in the filter layers and the subsoils. In the base and sub-base layers, the moisture content and variation were both lower. In the filter layer the volumetric moisture content varied between 10-23 %. In the base and sub-base layers the moisture content was 4-9 %, and for this reason the variation was also lower. In the cut structure the moisture content was slightly higher, but the variation was lower compared to the embankment structure. The TDR-method used in this research was very suitable for all material types.
- During the wintertime when structural layers were in a frozen state, the unfrozen water content was very low. The amount of water was, however, temperature dependent.

3 Data analysis

The precipitation changes the percent of water content in the subgrade. The higher water content has high influence on the bearing capacity and stability of the road construction. Because of this reason results of water content measurements and precipitation measurements (mm/month) were collected from literature from 19 test fields. Based on those data 5 soil types were defined:

Table 3.1 Types of soil

USCS classification	Classification EN ISO 14688-1:2004	Description
MH	Si (high compressibility)	silt, high compressibility
CL	Cl (low to medium compressibility	clay, low to medium compressibility
CL-ML	Cl-Si (low to medium compressibility)	Clay to silt, low to medium compressibility
ML	Si (to medium compressibility)	Silt, low to medium compressibility
G, S	Gr, Sa	Gravel, sand

More precise classification was not possible, because there were no data for other types of soil. From many test fields very low correlation between change of water content and precipitation was reported. For our project some simplifications were used, to get rough estimation of the influence of precipitation on subgrade layers.

- Natural moisture content can be, even for the same type of soil, very different. In order to interpret the results, the percentage of change of moisture content was calculated and compared with the natural one.
- For a given level of precipitation, the highest change of water content was used.
- Laboratory data were used to identify the natural water content of a soil; if they did not exist in the paper, the lowest measurement on the field was used.
- From the test fields only data that were not influenced on freezing were used.
- The influence of infiltration time was taken into account. Many times the influence of heavy rain was visible on results only after few weeks.
- There were not enough data to make an interpretation based on the different road construction.
- For every type of the soil, the minimum and maximum trend line was defined (pictures 1-5). In the pictures, 6-9 the trend line for the all data of one soil type was defined, but correlation is very low. For gravel and sand trend line is even negative.

Soil material as high compressibility silt (MH) and low to medium compressibility clay (CL) change with precipitation slowly and in a few percent (8-10 %).

The percent of change of water content is higher for mixed material of clay and silt (CL-ML) and silt (ML).

The highest change of water content is measured for gravel and sand (G, S). In that material, time of wetting and drying is very short, in comparison with clay where that process is very slow.

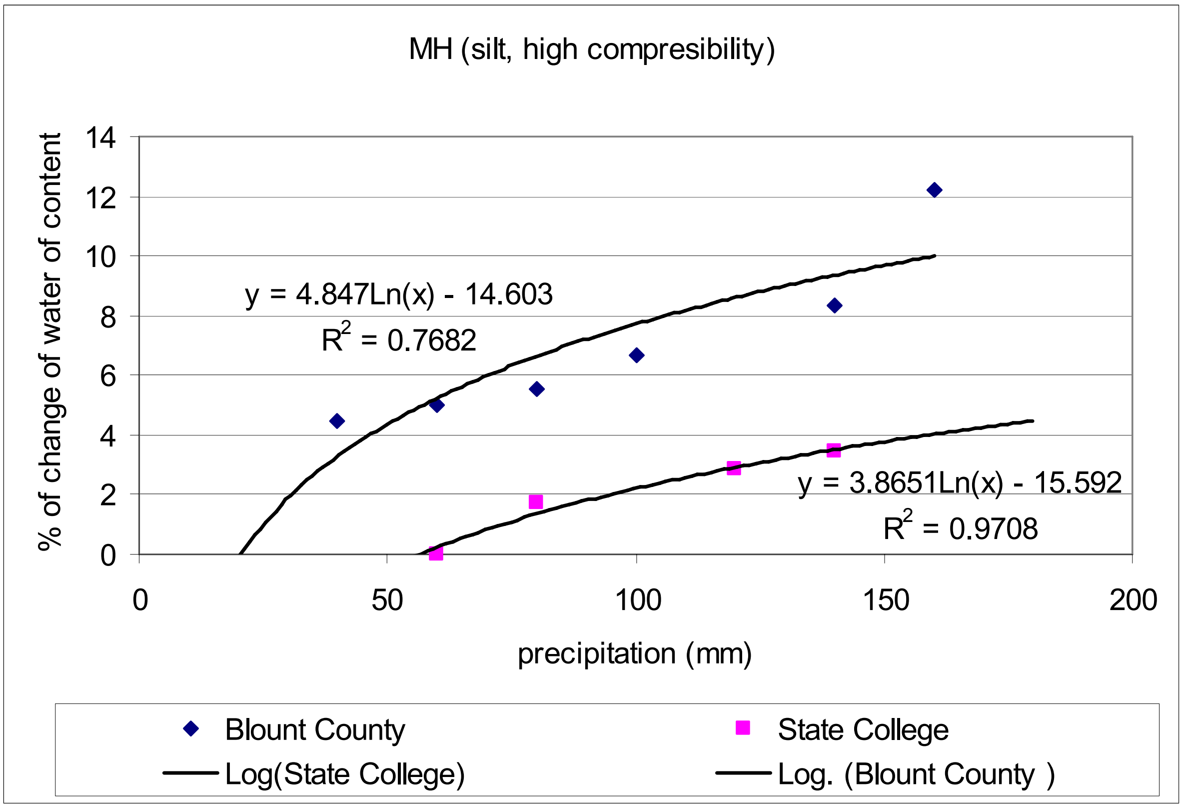


Figure 3.1 Trend lines for silt, high compressibility

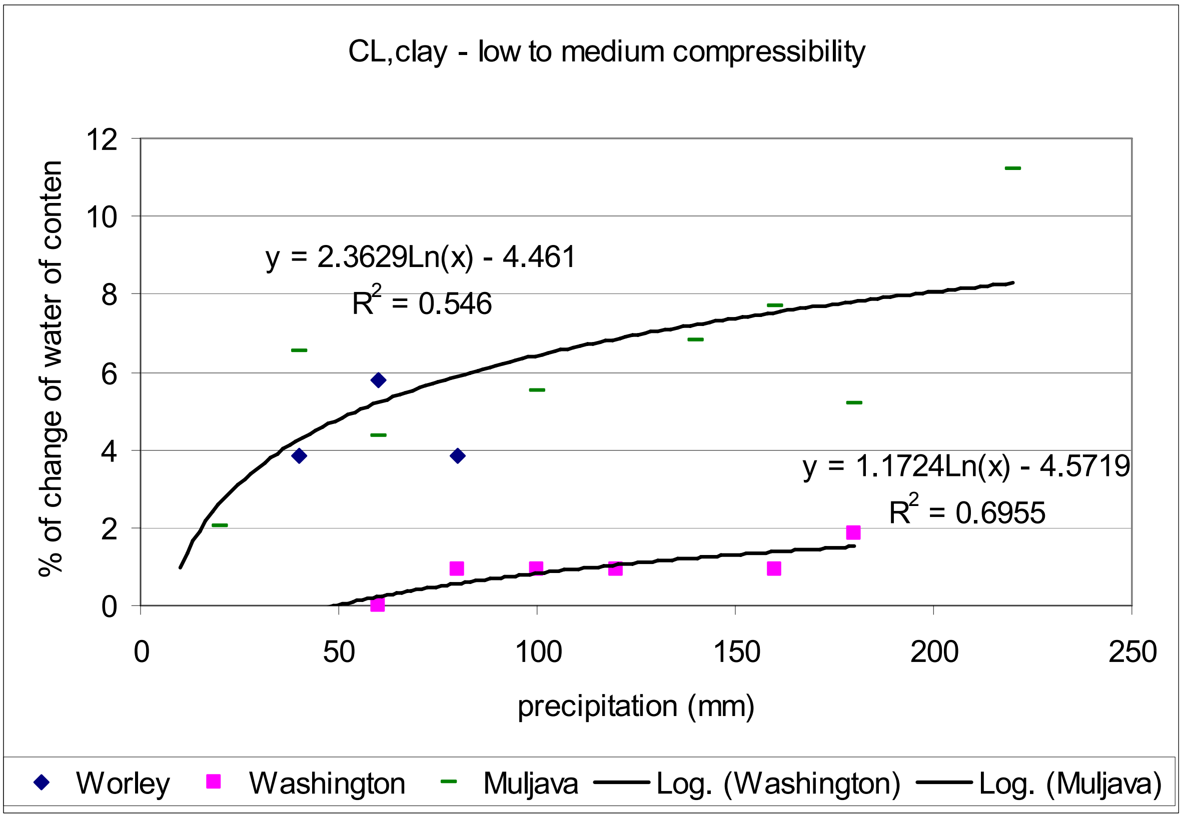


Figure 3.2 Trend lines for clay low to medium compressibility

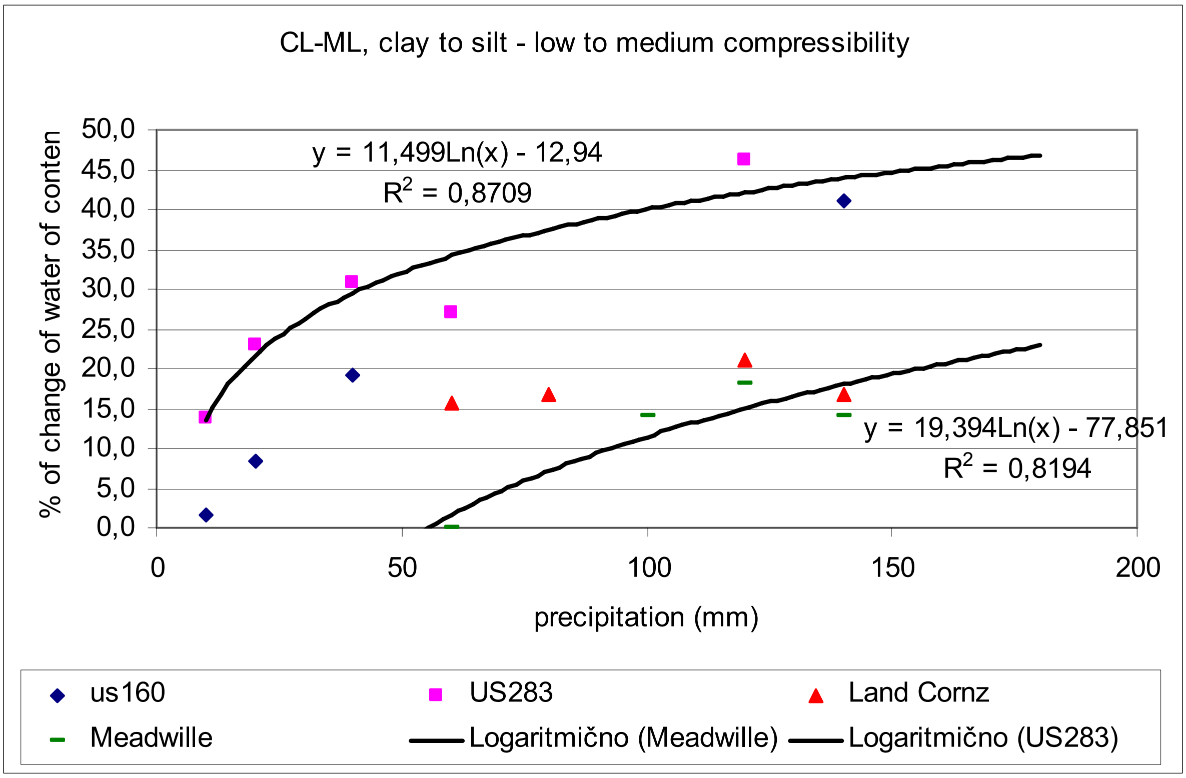


Figure 3.3 Trend lines for clay to silt, low to medium compressibility

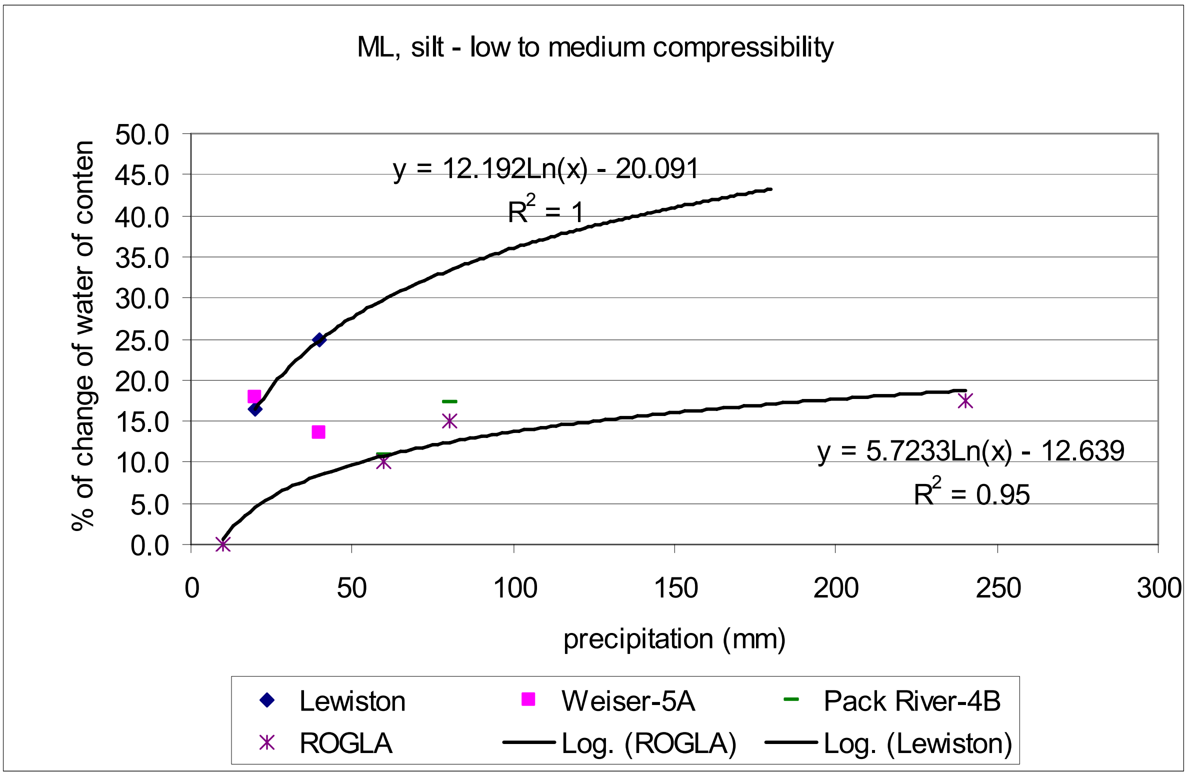


Figure 3.4 Trend lines for silt low to medium compressibility

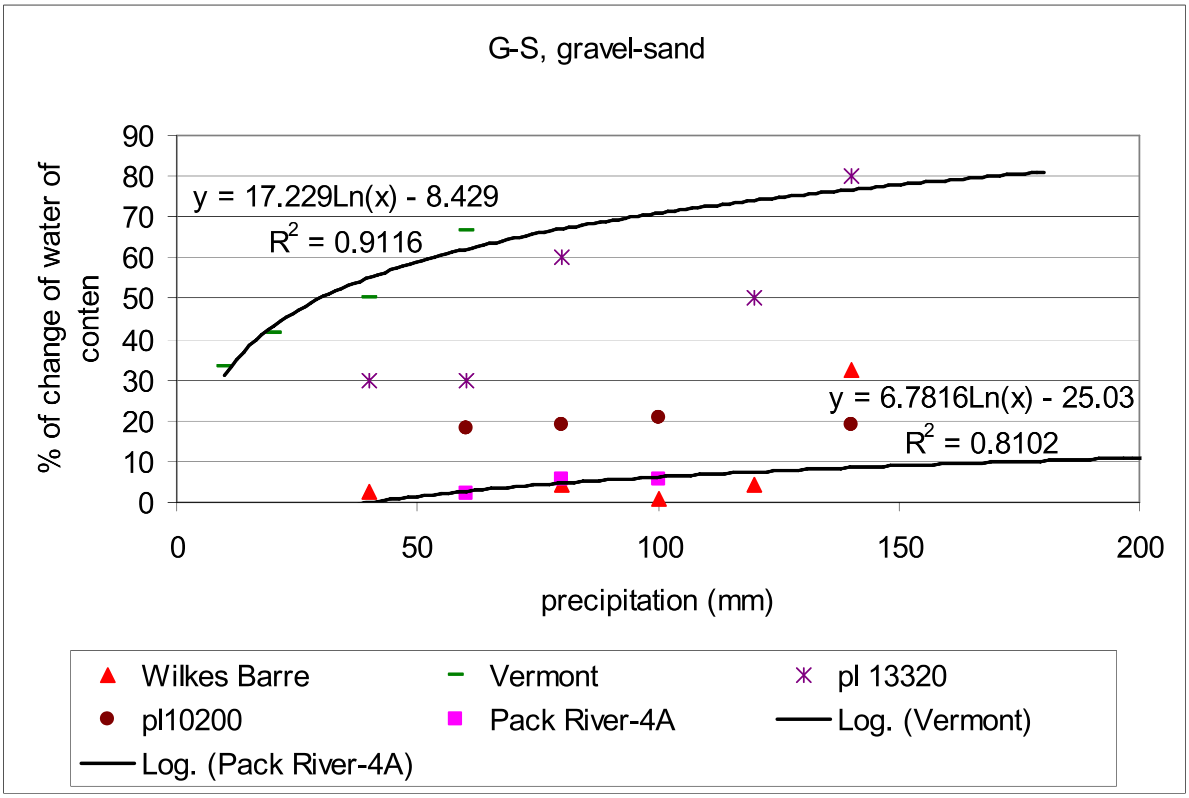


Figure 3.5 Trend lines for gravel and sand

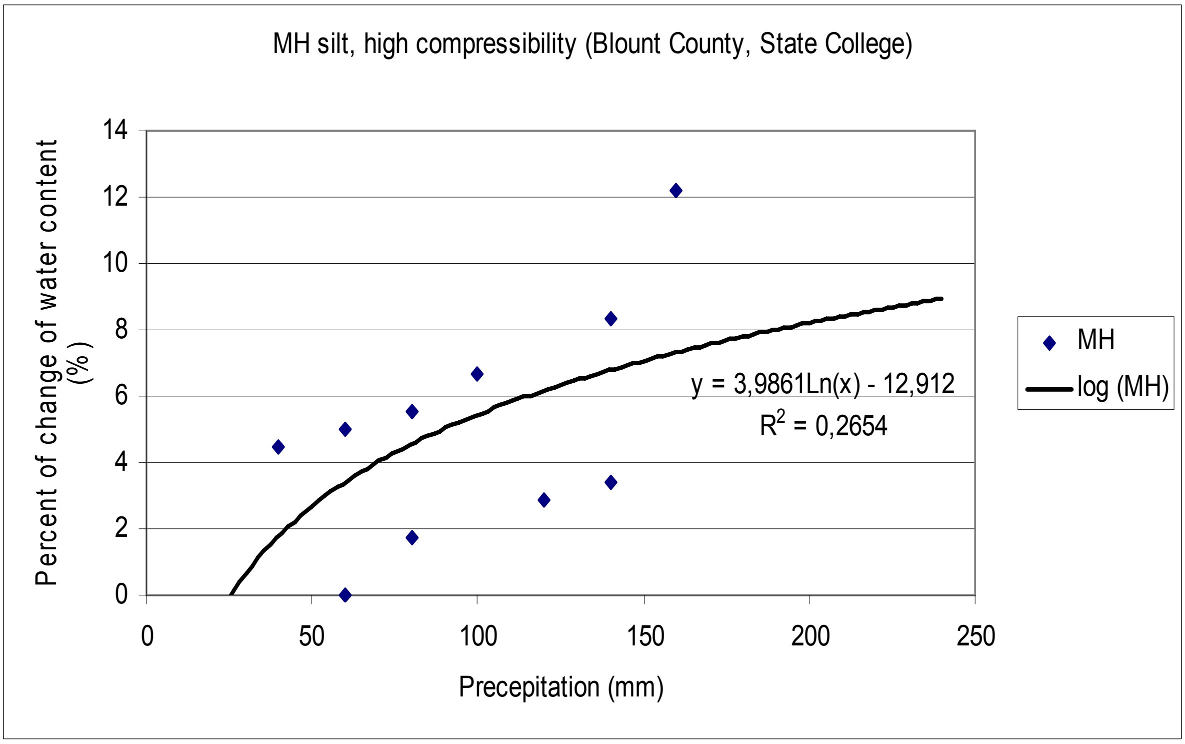


Figure 3.6 Trend line for silt, high compressibility (all data)

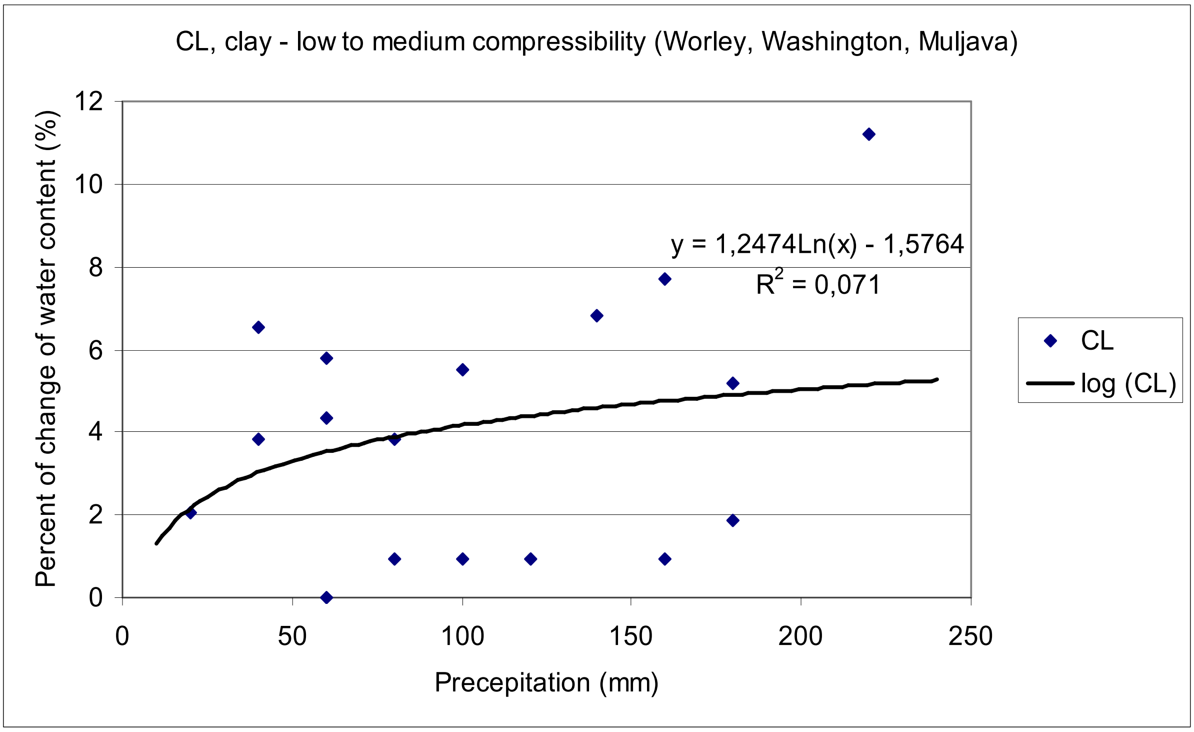


Figure 3.7 Trend line for clay low to medium compressibility (all data)

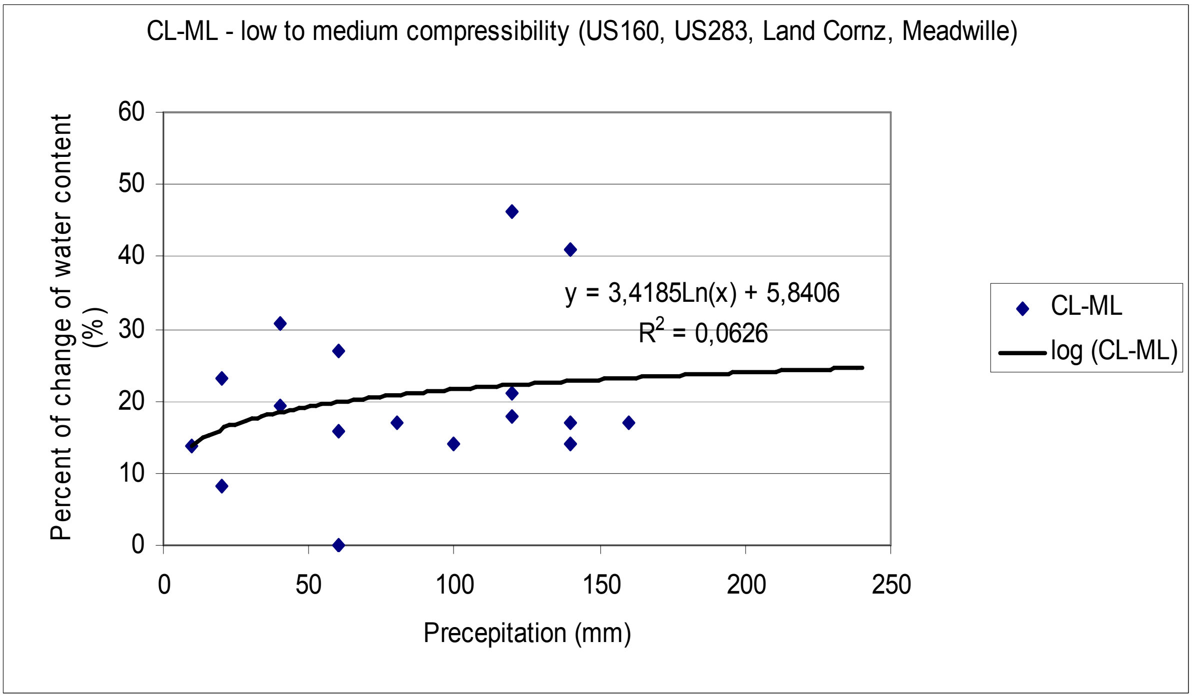


Figure 3.8 Trend line for clay to silt, low compressibility (all data)

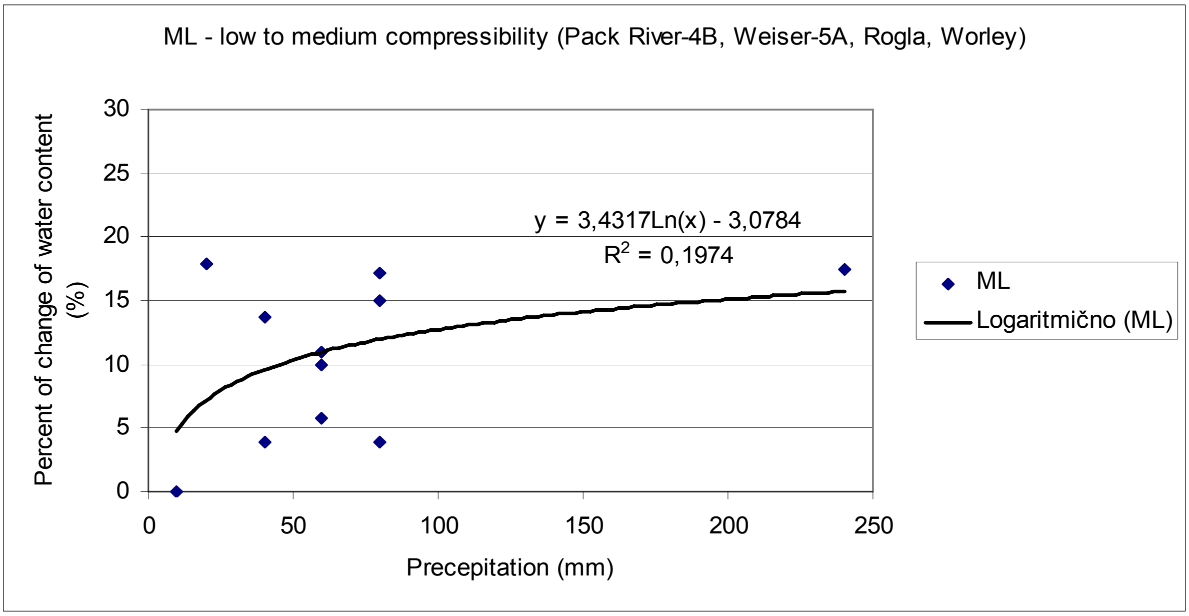


Figure 3.9 Trend line for silt, low compressibility (all data)

Table 3.2 Types of soil

Test field	Blount County	Lewiston	Worley	Pack River-4A	Pack River-4B	Weiser-5A	Weiser-5B	US 160	US 283	Land Cornz	Wilkes Barre	Washington	State College	Meadwille	Muljava	Vermont	ROGLA	PL 13320	PL 10200
Road construction		1																	
Asphalt layer	0.21	15.2	7.6	15.2	30.5	15.2	15.2									6.5	8	8	8
Stone base (SB)	0.25			0	0	15.2	30.5									46	35		850
Rock cap		50.8	53.3	61	no data	15.2	0												
Total high of road structure	0.46	66	60.9	76.2		45.6	45.7	22.9	30.5	43.2	60.9	38.1	45.7	30.4					
Soil subgrade (SS)																			
Classification USCS or geom. description	MH	ML	CL	silt&silty gravel	silt	ML	ML	CL-ML	CL, CL-ML	CL-ML	GM-SM	CL	MH	CL-ML	CL	SM-ML	ML	sand	sand
Classification EN ISO 14688-1:2004	Si (high compr.)	Si (low compr.)	Cl (low comp.)	Si, siGr	Si	Si (low compr.)	Si (low comp.)	Cl- Si (low compr.)	Cl, Cl- Si (low comp.)	Cl- Si (low comp.)	siGr-Sa	Cl (low comp.)	Si (high compr.)	Cl- Si (low compr.)	Cl (low comp.)	siSa-Si (low comp.)	Si (low comp.)	Sa	Sa
Water content																			
w_0 or $w_{min\ (gravimetric)}$	18							12	13	9.5	11.7	21.6	17.5	14.5	23		20.0	5.0	10.5
w_0 or $w_{min\ (vol)}$		21.3	52	38.9	32	11.7	15									12			
Precepitation (mm)	**Procent of change water content**																		
10.0								1.7	13.8							33.3	0.0		
20.0		16.4				17.9	42.7	8.3	23.1						2.0	41.7			
40.0	4.4	24.9	3.8			13.7	70.1	19.2	30.8		2.6				6.5	50.0		30.0	
60.0	5.0		5.8	2.3	10.9				26.9	15.8		0.0	0.0	0	4.3	66.7	10.0	30.0	18.1
80.0	5.6		3.8	5.7	17.2					16.8	4.3	0.9	1.7				15.0	60.0	19.0
100.0	6.7			5.7							0.9	0.9		14.0	5.5				21.0
120.0									46.2	21.1	4.3	0.9	2.9	18.0				50.0	
140.0	8.3							41.0		16.8	32.5		3.4	14.0	6.8			80.0	19.0
160.0	12.2									16.8		0.9			7.7				
180.0												1.9			5.2				
200.0																			
220.0															11.2				
240.0																	17.5		

4 Soil drying and wetting process

The soil undergoes processes of drying and wetting as a result of climatic changes. In the highway and highway environment, much of the road constructions are in a partially saturated condition. The effect of this partial saturation is to cause suctions to exist within the pores of the soils and aggregates.

It is important to know the nature of the soil-water characteristic curve of an unsaturated soil in order to predict the water content changes when the soil is subjected to drying or wetting. An unsaturated soil in the field is often subjected to more significant and frequent changes in matric suction, than in total stress.

Moisture changes in road construction have a big influence on behavior of pavement materials. While upper bound layers are little affected by pavement moisture, moisture plays a major role in behavior of unbound and subgrade materials. Mechanical performance of materials in lower unbound and soil layers depends on the frictional interaction developed between particles, while the pressure of water in the soil pores tries to push the particles apart.

Nevertheless, even if it were possible, a completely dry geotechnical material is not wanted, instead a partially-saturated condition is often desired. When soil or aggregate is kept relatively (but not totally) dry, matric suctions will develop in the pores due to meniscus effects at the water-air interfaces.

The soil water characteristic curve (SWCC) provides the relationship between the matric suction and water content for a given soil. In fact, calling the curve “characteristic” is something of a misnomer as the relationship is not solely a function of the soil type, but varies with (for example) temperature, pressure and pore water chemistry. Even at very high matric suctions (capillary pressures) all the water cannot be removed from the soil. The residual (or the irreducible) water content is the water content that is not removed in the soil even when a large amount of suction is applied.

For most soils the soil water characteristic curve (SWCC) shows hysteresis. The SWCC for drainage and wetting conditions differs and thus characteristics curves exhibit hysteresis between drying and wetting process.

Deterioration of pavement structures is caused not only by deformations induced by commercial vehicles, but also by the interaction of traffic and climate. Particularly during spring thaw, climatic effects may become critical. During this period the base, subbase, and subgrade may become water-saturated due to melting of excess ice, thereby substantially reducing bearing capacity. Such conditions may initiate large settlements and deformations. Inadequate drainage of surface and subsurface water can have significant impact on pavement behaviour and long-term maintenance costs. Subgrades and underlying foundation soils with high capillary rise and a relatively high water table, when subjected to repetitive wheel loads, can exude water into the base course. The combined effects of load repetitions, stress level, compressibility, availability of a sufficient quantity of capillary water, and the physical-chemical characteristics of the granular base course will determine whether the upper pavement structure is sufficiently weakened to cause distress.

For natural subgrade soils two special conditions have to be checked; the potential for swelling clays and the potential for collapsible silts. Those two types of soils are particularly sensitive to drying - wetting process in the ground.

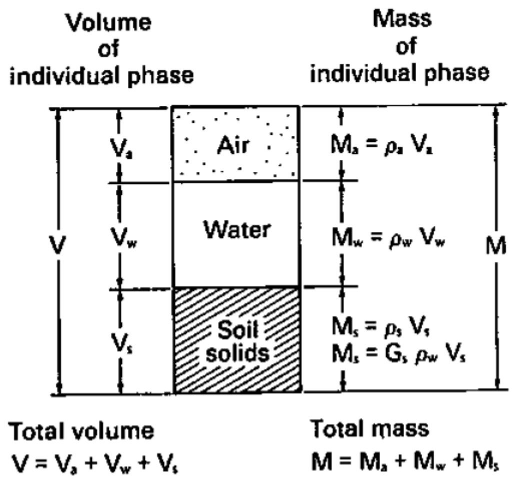
Swelling soils exhibit large changes in soil volume with changes in soil moisture. The potential for volumetric swell of a soil depends on the amount of clay, its relative density, its mineralogical composition, the compaction moisture, permeability, depth of the water table, presence of vegetation and trees and overburden stress.

Collapsible soils exhibit abrupt changes in strength at moisture contents approaching saturation. When the soil is dry or at low moisture content, collapsible soil is a stable deposit. At high moisture contents, these soils collapse and undergo sudden decreases in volume. Collapsible soils are found most commonly in loess deposits, which are composed of windblown silts. The collapsible state is characterized by a low relative density, a low unit weight, and a high void ratio.

Subgrades on these soil conditions require special design attention. By identifying such subgrade issues in the design stage, or even the potential for such problems along an alignment, alternative designs can be established. When these special subgrade conditions are not recognized in design, they are often identified during construction, usually resulting reconstruction of the pavement within the first few years of the pavement performance period.

4.1 Unsaturated soil

The zone between the ground surface and the water table is generally referred to as the unsaturated soil zone (Fig. 4.1). The entire zone subjected to negative pore–water pressures is commonly referred to as the unsaturated zone in geotechnical engineering. The unsaturated zone becomes the transition between the water in the atmosphere and the groundwater (i.e., positive pore – water pressure zone). The ground surface climate is a prime factor controlling the depth of the groundwater table and therefore, the thickness of the unsaturated soil zone.

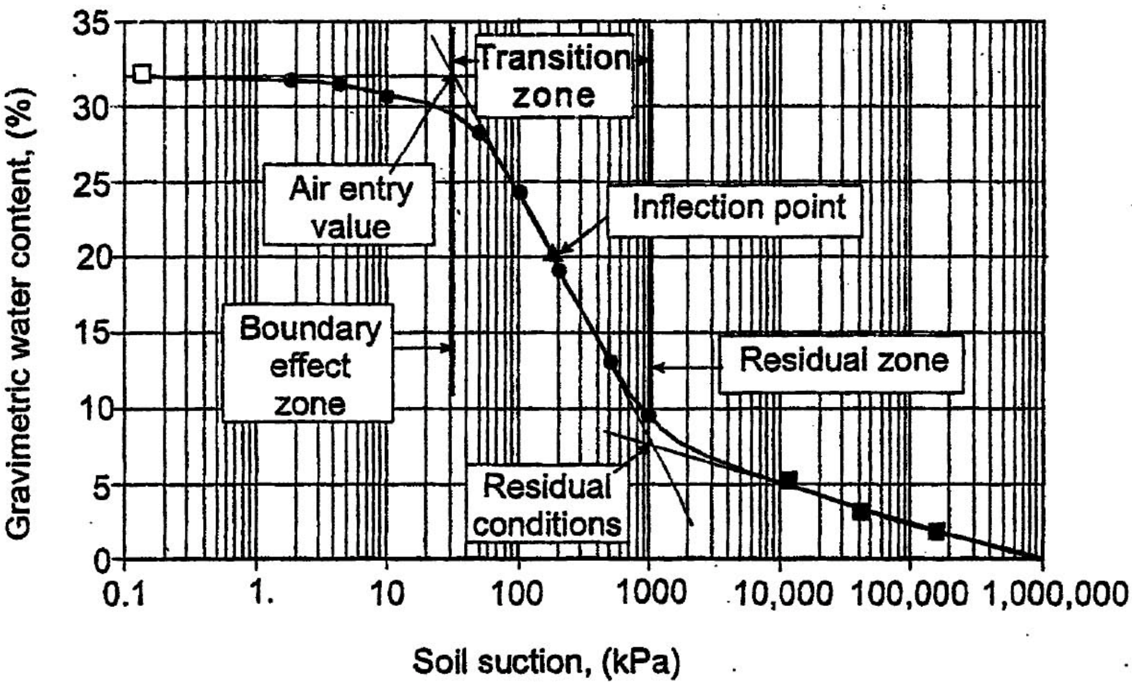


Picture:4.1 Phase diagram for unsaturated soil

An unsaturated soil is commonly referred to as a three-phase mixture (i.e., solids, air, and water) but there is strong recommendation for including a fourth independent phase - the contractile skin or the air–water interface.

The contractile skin acts like a thin membrane interwoven throughout the voids of the soil, acting as a partition between the air and water phases. It is the interaction of the contractile skin with the soil structure that causes an unsaturated soil to change in volume and shear strength. The unsaturated soil properties change in response to the position of the contractile skin (i.e., water degree of saturation). It is important to view an unsaturated soil as a four-phase mixture for purposes of stress analysis, within the context of multiphase continuum mechanics. Consequently, an unsaturated soil has two phases that flow under the influence of a stress gradient (i.e., air and water) and two phases that come to equilibrium under the influence of a stress gradient (i.e., soil particles forming a structural arrangement and the contractile skin forming a partition between the fluid phases) (Fredlund and Rahardjo 1993).

The pore–water pressures in the unsaturated soil zone can range from zero at the water table to a maximum tension of approximately 1,000,000 kPa (i.e., soil suction of 1,000,000 kPa) under dry soil conditions (Croney et al. 1958). The water degree of saturation of the soil can range from 100% to zero. The changes in soil suction result in distinct zones of saturation. The zones of saturation have been defined in situ as well as in the laboratory with the soil–water characteristic curve (Fig.4.2).



4.2 Soil water characteristic curve

The contractile skin has physical properties differing from the contiguous air and water phases and interacts with the soil structure to influence soil behavior. Numerous research studies on the nature of the contractile skin point toward its important, independent role in unsaturated soil mechanics. Terzaghi (1943) suggested that the contractile skin might be in the order of 10^{-6} mm in thickness. More recent studies suggest that the thickness of the contractile skin is in the order of 1.5-2 water molecular diameters (i.e., 5 A).

4.1.1 Stiffness of partly saturated soils

Knowing the effect of water presence in soil is important in the process of understanding the impact of a degree of saturation upon the mechanical properties of soil. One of the most important mechanical properties of soil in case of dynamic loading is low amplitude shear modulus or initial shear modulus (stiffness) of soil. Usually, when defined by laboratory tests, it is measured under different effective confining stresses σ'0. As we know from the capillarity effect, the impact of capillary pressure (Table 4.1) might be significant. It has to be taken into account as an important impact upon the stress state of a soil.

What happens if the risen water menisci are destroyed due to some big voids in soil? Does the whole effect of capillary pressure disappear? Fig. 4.3 shows the impact of degree of saturation upon the initial stiffness properties. Bender element tests were performed on the same reconstituted sample during its saturation (Lenart, 2006). The effective confining stress (σ'0), meaning the difference between confining and pore pressure, was more or less constant during the test. Parallel, some resonant column tests were performed on samples reconstituted at the same density conditions, but at different effective confining stress and degree of saturation. It can be seen from the results that the initial shear modulus normalized by void ratio function and effective confining stress decreases as the degree of saturation increases.

Table 4.1: Approximate theoretical capillary pressure that can be expected in different soils (based on data from Hansbo, 1975)

	Loose	Dense
Coarse sand	0,3-1,2 kPa	0,4-1,5 kPa
Medium sand	1,2-5 kPa	3,5-11 kPa
Fine sand	3-20 kPa	4-35 kPa
Silt	15-100 kPa	25-120 kPa
Clay	> 100 kPa	

That can be explained by understanding of soil-water characteristic curve (Fig. 4.4). The attraction that exists in partly saturated soil between soil grains and the water is termed soil suction and manifests itself as a kind of tensile hydraulic stress. The magnitude of the attractive force is governed by the size of the pores in soil.

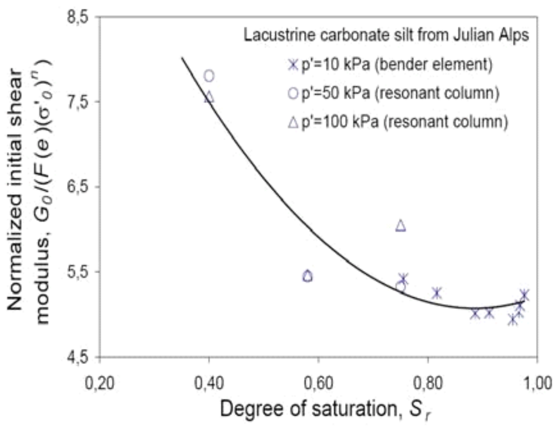


Fig. 4.3: The effect of degree of saturation upon the normalized initial shear modulus (Lenart, 2006)

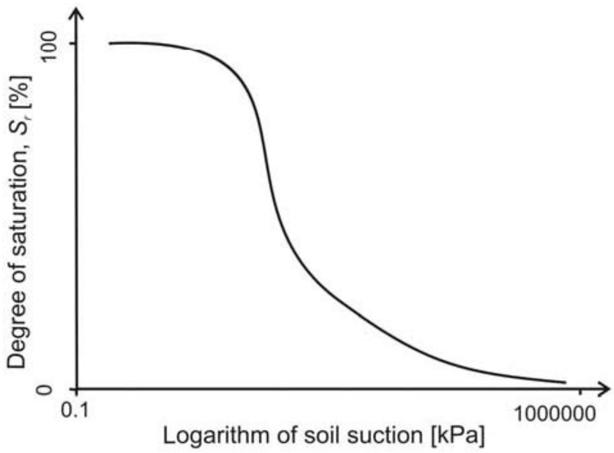


Fig. 4.4: Shape of a typical soil-water characteristic curve, SWCC (Fredlund, 2006)

From the results shown above one can find out that water in pores of partly saturated soil effect an increase of soil strength as well as soil stiffness. The increases are caused by the increase of effective confining stress due to the attractive forces between soil grains and water. This attraction exists even in the case of destroyed menisci in soil and does not depend only on capillarity. The attraction decreases as the degree of saturation increases. In case of tested material, a normalized initial shear modulus value becomes constant at degree of saturation Sr~0.75. It seems that the soil suction disappears at degrees of saturation above this value.

4.2 SWCC

The curve showing the relationship between water content for a soil and the soil suction is called soil-water characteristic curve or retention curve (SWCC).

As the soil is finer the soil-water interaction forces are greater. This means that in the same conditions of humidity clays have considerably higher values of soil suction in comparison with the sands. Moreover, suction is also dependent on plasticity the montmorillonite suction is greater than the kaolinite suction, for the same water content. Typical soil-water characteristic curves for different classes of soils are represented in Figure 4.5.

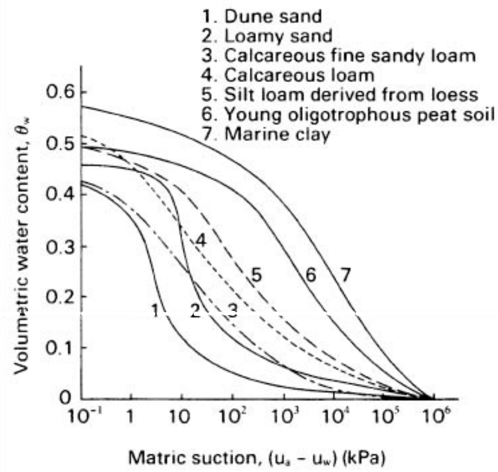


Figure 4.5. Typical soil-water characteristic curves for some Dutch soils (Koorevaar et. Al, 1983)

Another interesting aspect regards the phenomen on of air entry in the pores of a saturated soil, which suddenly becomes unsaturated during a drying process. The vertical branch of the soil-water characteristic curve indicates the saturation state (Figure 4.6), while its upper part corresponds to the air-entry suction which may be thus easily determined.

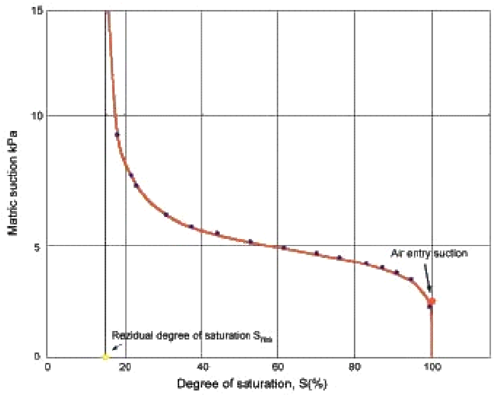


Figure 4.6. SWCC putting into evidence the air-entry suction value and residual degree of saturation.

Another parameter that can be obtained from the soil-water characteristic curve is the residual degree of saturation that is defined as the degree of saturation which does not change significantly at the increase of matric suction. Practically, the degree of saturation under which the branch of the soil-water characteristic curve becomes almost vertical is the residual degree of saturation.

The soil undergoes processes of drying and wetting as a result of climatic changes. It is important to know the nature of the soil-water characteristic curve of an unsaturated soil in order to predict the water content changes when the soil is subjected to drying or wetting. An unsaturated soil in the field is often subjected to more significant and frequent changes in matric suction, than in total stress.

Croney and Coleman (1954) have summarized soil-water characteristic curves which illustrate the different behaviour observed for incompressible and compressible soils. Figure 4.7 compares the soil-water characteristic curves of soft and hard chalks, which are considered relatively incompressible. The drying curves of these incompressible soils exhibit essentially constant water contents at low matric suctions and rapidly decreasing water contents at higher suctions. The point where the water content starts to decrease significantly indicates the air entry value of the soil. The data show that the hard chalk has a higher air entry value than the soft chalk. The high preconsolidation pressure during the formation of the hard chalk results in a smaller average pore size than for the soft chalk.

Another noticeable characteristic is that the drying curves for both hard and soft chalks become identical at high matric suctions. This indicates that at high suctions, both soils have similar pore size distributions. There is a marked hysteresis between the drying and wetting curves for both soils.

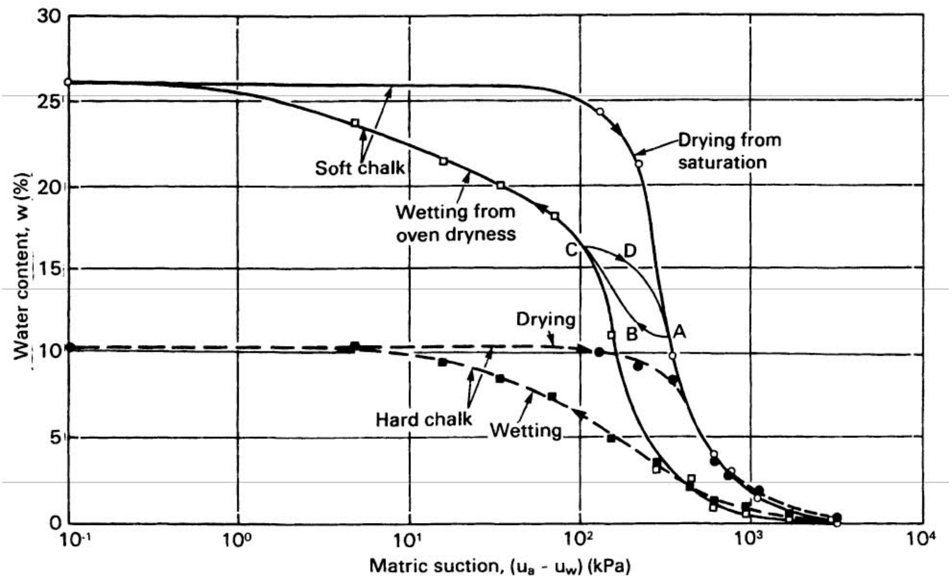


Figure 4.7 Soil-water characteristic curves for soft and hard chalks with incompressible soil structures (from Croney and Coleman, 1954).

An increase in the initial water content of the soil results in a decrease in the air entry value (Fig. 4.8). This can be attributed to the larger pore sizes in the high initial water content mixtures. These soils drain quickly at relatively low matric suctions. As a result, the water content in the soil with the large pores is less than the water content in the soil with small pores at matric suctions beyond the air entry value. In other words, soils with a low initial water content (which means, higher compaction and thus small pore sizes) require a larger matric suction value in order to commence desaturation. There is then a slower rate of water drainage from the pores.

The initial dry density of incompressible soils has a similar effect on the soil-water characteristic curve, as was illustrated by the initial water contents. As the initial dry density of an incompressible soil increases, the pore sizes are small and the air entry value of the soil is higher, as illustrated in Fig. 4.9. The high-density specimens desaturate at a slower rate than the low-density specimens. As a result, the high-density specimens have higher water contents than the low-density specimens at matric suctions beyond their air entry values. In addition, the hysteresis associated with the high-density specimens is less than the hysteresis exhibited by the low-density specimens.

The soil –water characteristic curves for cohesionless soils are usually investigated by means of column test. It is evident the influence of different coarse materials on the value of suction in shape of wetting – drying curve (Fig. 4.10).

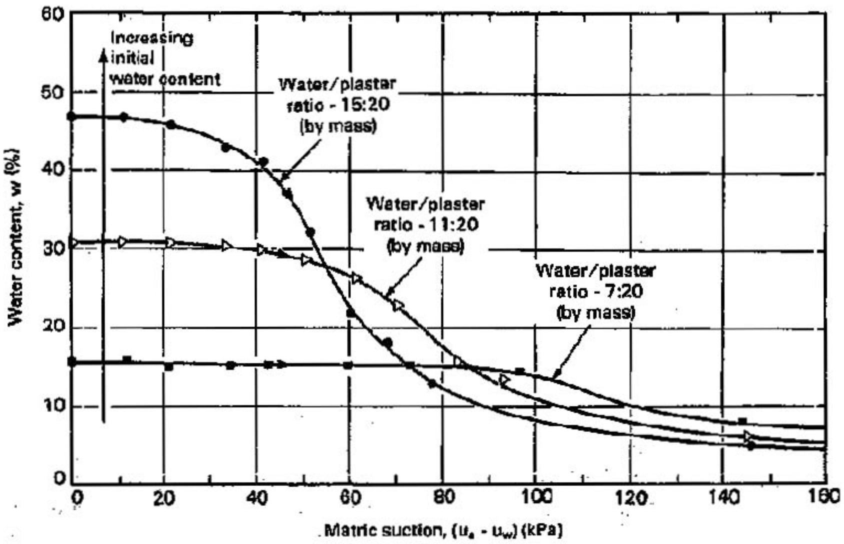


Figure 4.8 Effects of initial water content on the drying curves of incompressible mixtures (from Croney and Coleman, 1954).

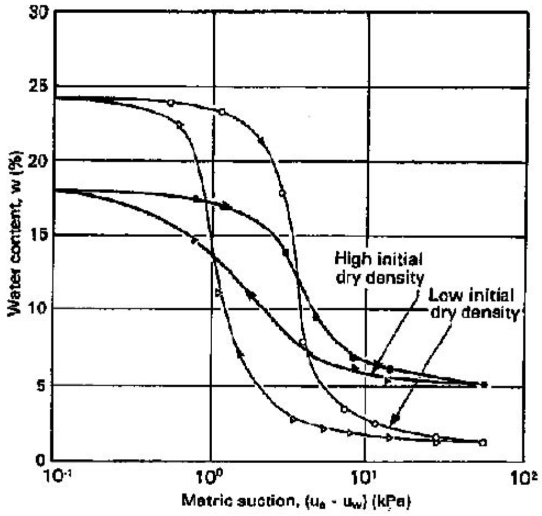


Figure 4.9 Effect of initial dry density on the soil-water characteristic curves of a compacted silty sand (from Croney and Coleman, 1954).

4.3 Problematic soil types

For natural subgrade soils two special conditions have to be checked; the potential for swelling clays and the potential for collapsible silts. Those two types of soils are particularly sensitive to drying - wetting processes in the ground.

4.3.1 Swelling soil

The use of swelling subgrade soils in pavements can have a seriously detrimental effect on pavement performance. Swelling soils must be identified so that they can be either removed, stabilized, or accounted for in the pavement design.

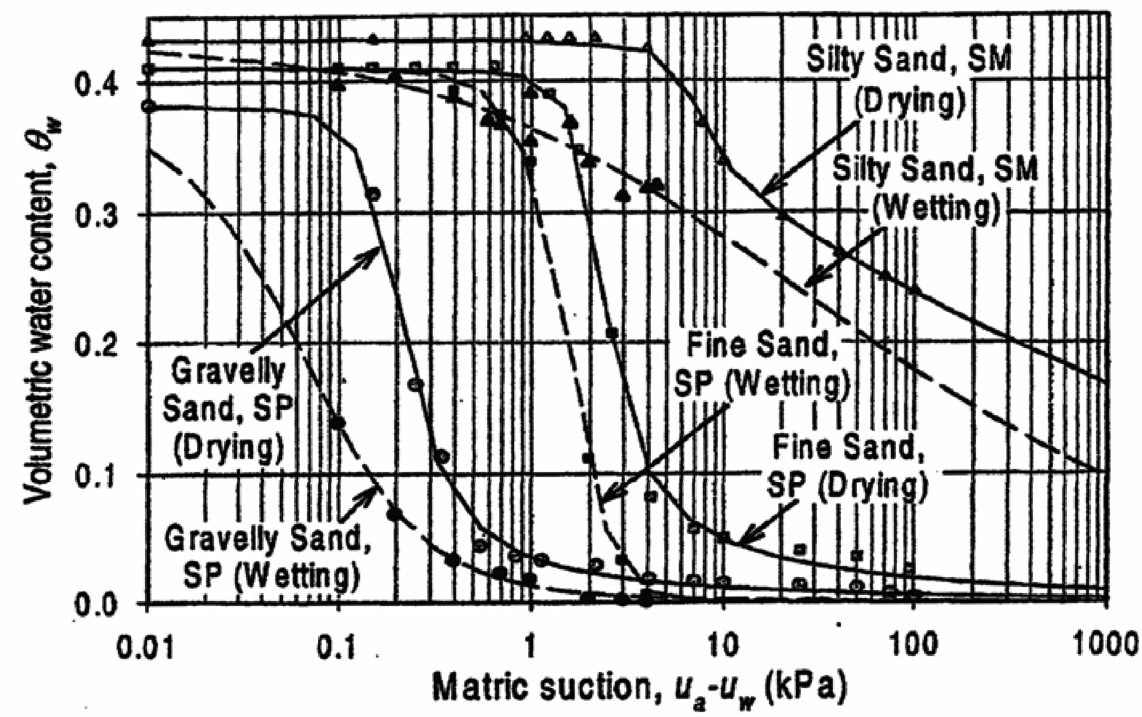


Fig. 4.10 In situ measurements of matric suction below a thin asphalt pavement over an extended period of time using heat dissipation sensors

Swelling or expansive soils are susceptible to volume change (shrink and swell) with seasonal fluctuations in moisture content. An increase in moisture will cause it to expand or swell, a loss of moisture will cause the soil to shrink. The volume change of clay soils can result in longitudinal cracks near the pavement's edge and roughness along the pavement's length.

Expansive soils are especially a problem when deep cuts are made in a dense (over-consolidated) clay soil.

Clay mineralogy and the availability of water are the key factors in determining swelling potential. Different clay minerals exhibit greater or lesser degrees of swell potential based on their specific chemistry. Montmorillonitic clays tend to exhibit very high swell potentials due to the particle chemistry, whereas illitic clays tend to exhibit very low swell potentials. The soil fabric will also influence the swell potential. The finer-grained and more plastic the soil, the higher the swell potential the soil will exhibit.

The identification of swelling soils in the subgrade is a key component of the geotechnical investigation for the roadway. Soils at shallow depths beneath the proposed pavement elevation are generally sampled as part of the investigation, and their swell potential may be identified in a number of ways. Index testing is a common method for identifying swell potential. Laboratory testing to obtain the plastic and liquid limits and/or the shrinkage limit will usually be conducted. The soil activity, defined as the ratio of the plasticity index to the percentage of the soil by weight finer than 0.002 mm is also used as an index property for swell potential, since clay minerals of higher activity exhibit higher swell. Activity calculation requires measurement of gradation using hydrometer methods. In addition to index testing, agency practice in regions where swelling soils are a common problem may include swell testing, for natural or compacted soil samples. Such testing generally includes measurement of the change in height (or volume) of a sample exposed to light loading similar to that expected in the field and then allowed free access to water. Typical values of swell potential can be estimated in terms of soil physical properties; see Table 4.2.

Table 4.2 Typical Values of Swell potential

<0.001 mm	**PI**	**SI**	**Probable expansion**	**Potentional for expansion**
%	%	%	% total volume change	
>28	35	< 11	> 30	Very high
20-31	25-41	7-12	20-30	high
13-23	15-28	10-16	10-30	Medium
< 15	< 18	>15	< 10	Low

Based on a loading of 6.9 kPa (1 psi).

The swelling properties of expansive, unsaturated soils are most often performed with one-dimensional oedometer tests. The assumption is made that it is possible to eliminate the matric suction from the soil and obtain the necessary soil properties and stress state values from the net normal stress plane. The "free-swell" and "constant volume" tests (Fig. 4.11) are two commonly used procedures which first eliminate the soil matric suction.

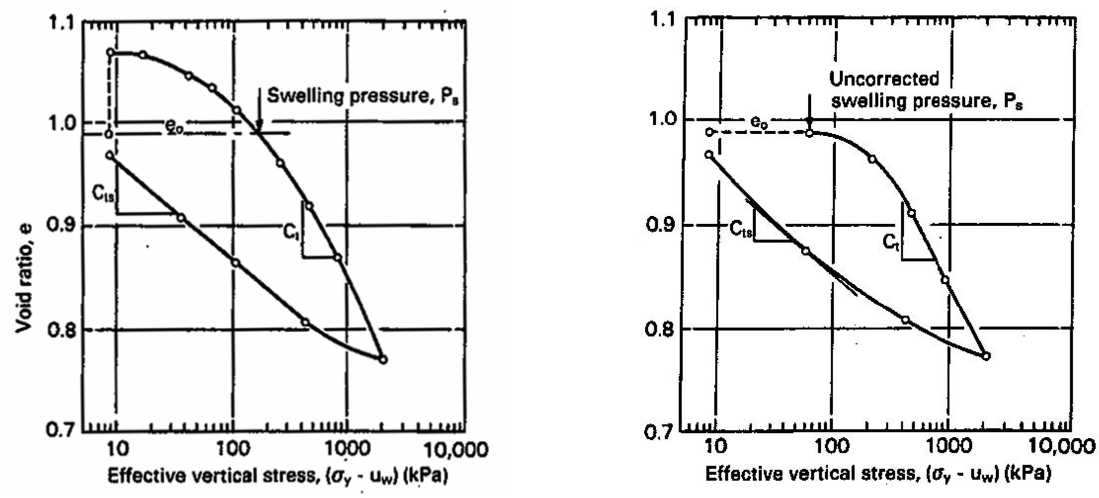


Figure 4.11 Typical "free-swell" and "constant volume" one-dimensional oedometer test results. (a) "Free-swell" test procedure; (b) "constant volume" test procedure.

Many empirical methods have been proposed to correlate the swelling potential of a soil to properties such as are shown Fig. 4.12. These relationships are useful for identifying the swelling potential of a soil.

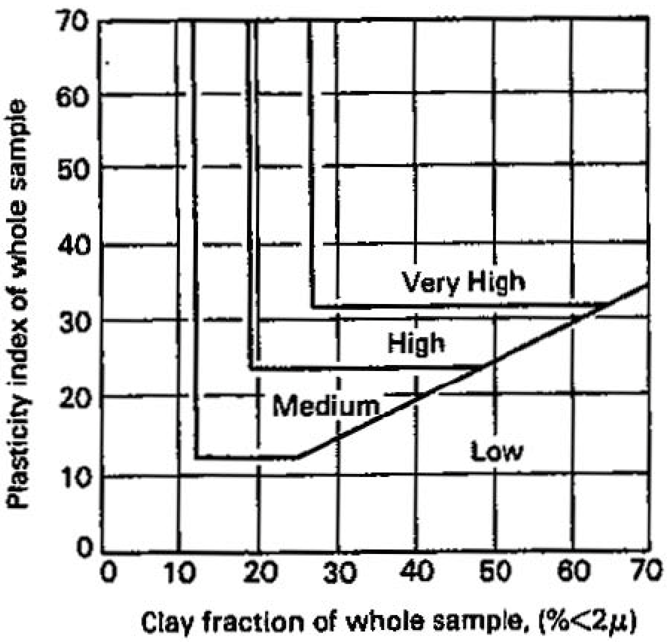


Fig. 4.12 Correlation between soil properties and sweeling potential (Merwe, 1964).

4.3.2 Collapsible soil

Changes in surface and groundwater regimes, resulting from urbanization and associated transportation infrastructure development, often bring significant increases in soil moisture contents. While collapsible soils commonly exhibit high shear strength and stiffness in their naturally dry state, they are subject to large volume reduction upon wetting.

The climates of arid regions and the typical soil types found in these areas give rise to soil collapse problems. In arid climates, evaporation greatly exceeds rainfall. Only the relatively near-surface soils become wetted from normal rainfall. It is the combination of depositional processes and climatic conditions that lead to the formation of collapsible soils. The primary depositional processes, which account for almost all naturally occurring collapsible soils, are debris flows, alluvial and colluvial deposition, and wind-blown (aeolian) deposition.

Collapsible soils exhibit abrupt changes in strength at moisture contents approaching saturation. When dry or at low moisture content, collapsible soils give the appearance of a stable deposit. At high moisture contents, these soils collapse and undergo sudden decreases in volume. Collapsible soils are found most commonly in loess deposits, which are composed of windblown silts. Other collapsible deposits include residual soils formed as a result of the removal of organics by decomposition or the leaching of certain minerals (calcium carbonate). In both cases, disturbed samples obtained from these deposits will be classified as silt. Loess, unlike other non-cohesive soils, will stand on almost a vertical slope until saturated. It has a low relative density, a low unit weight, and a high void ratio.

Differential collapse settlement across roadway sections can result from either a nonhomogeneous subgrade deposit in which differing degrees of collapse potential exist or from nonuniform wetting of subgrade materials. By far the most serious problems with collapsible soils result from differential wetting, particularly when an accidental water ponding situation occurs, for example from poor drainage control. Differential collapse settlements result in a rough, wavy surface, and, potentially, many miles of highway distress.

Uses in Pavements Collapsible subgrade soils can have a seriously detrimental effect on pavement performance. Collapsible soils must be identified so that they can be either removed, stabilized, or accounted for in the pavement design.

Native subgrades of collapsible soils should be soaked with water prior to construction and rolled with heavy compaction equipment.

Tadepalli (1990) conducted collapse tests in a specially designed oedometer with matric suction measurements. Soil specimens were statically compacted in the oedometer ring. Small tip tensiometers were installed along the side of the specimen for the measurement of matric suction during the test. The specimen was then subjected to an applied total stress under constant water content conditions. At equilibrium, the soil specimen was inundated, with the result that the soil gradually decreased in volume as the suction went to zero. During inundation, the matric suction and volume decrease were measured simultaneously at various elapsed times.

Volume change and matric suction measurements taken during the inundation of compacted Indian Head silty sand are shown in Figs. 4.13. The results indicate that there is a unique relationship between the change in matric suction and the total volume change during collapse. Similar types of observations were made on undisturbed specimens of Mississippi Delta silt, as shown in Fig. 4.14.

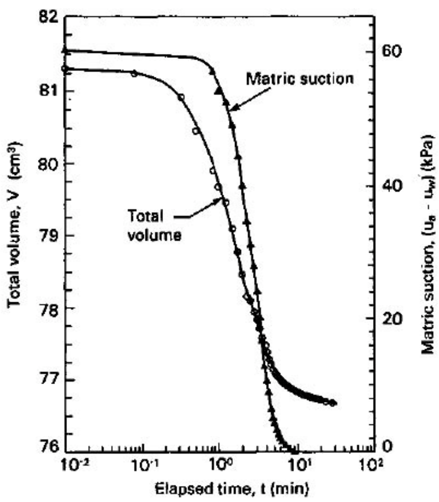


Figure 4.13 Matric suction and total volume change versus time after inundation of a compacted specimen of Indian head silty sand (Tadepallo, 1992)

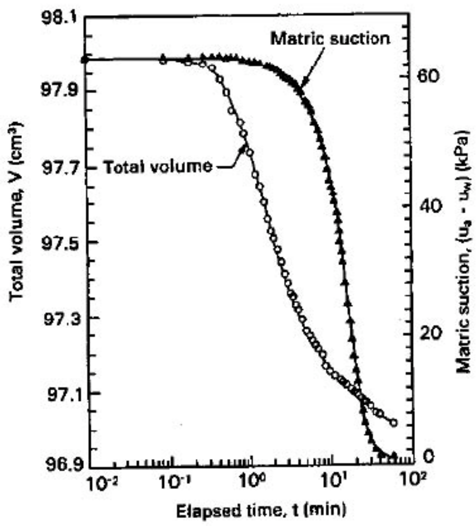


Figure 4.14 Matric suction and total volume change versus time after inundation of an undisturbed specimen of Mississippi Delta silt (Tadepallo, 1992)

The most common collapse test is the 1D response-to-wetting test performed in an oedometer. This test has been standardized in the ASTM collapse test (ASTM 1993). An undisturbed soil specimen is placed in an oedometer ring, loaded dry to the anticipated stress level, and then given free access to water. The collapse strain in situ should be estimated as the dry strain plus the strain due to wetting under load.

With respect to the zone of influence for collapsible soils, it is actually the depth of wetting that is of primary concern. If the soil does not get wetted, then collapse will not occur. The other relevant factor is the depth of the collapsible soil deposit. Collapsible soil deposits can be quite deep, exceeding 20 m or more.

To estimate the depth of wetting, it is necessary to first postulate the source of wetting. The depth of wetting and the degree of saturation achieved are largely controlled by the source conditions. For example, if hydrogeologic conditions allow for rising groundwater table and a large amount of water is added to the region, then bottom-up wetting from groundwater will result in essentially full saturation and full collapse. The height of the groundwater rise or mound would need to be evaluated to compute the wetting-induced settlement.

4.4 Volume Change Predictions

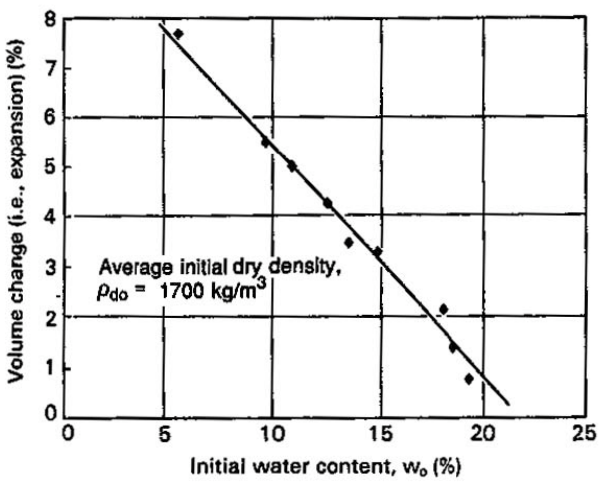
Under a constant total stress, an unsaturated soil will experience swelling and shrinking as a result of matric suction variations associated with environmental changes or from man-made causes.

Non uniform changes in water content will result in differential heaves which can cause severe damage to the structure. In fact, the differential heave experienced by a light structure is often of similar magnitude to the total heave.

The heave potential of a soil depends on the properties of the soil, such as clay content, plasticity index, and shrinkage limit. In addition, the heave potential depends upon the initial dryness or matric suction of the soil.

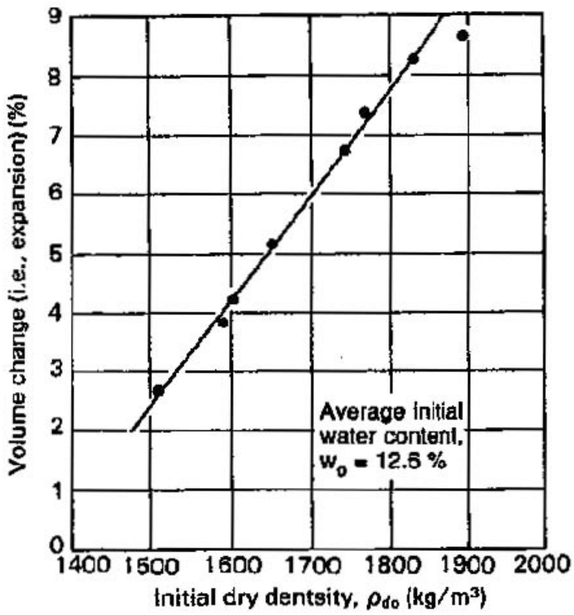
There are several heave formulations related to the volume change indices which have been proposed by various researchers. The prediction of heave on the basis of matric suction measurements has not been extensively used due to difficulties associated with accurate measurements of matric suction and appropriate soil properties. More common are the methods for heave prediction based on one-dimensional oedometer test results.

Chen (1988) studied the effect of initial water content and dry density of compacted soils on the amount of total heave. The study was conducted using "free-swell" oedometer tests on expansive shahs from Denver, CO. The shale had 63% silt and 37% clay, with a liquid limit and plasticity index of 44.4 and 24.4%, respectively. The results indicate that total heave increases with a decrease in the initial water content of specimens compacted at a constant initial dry density (Fig. 4.15).



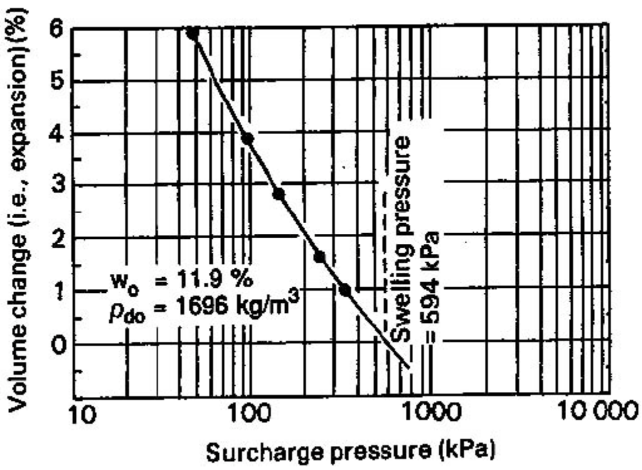
4.15 Effect on total heave of varying the initial water content for specimens of constant initial dry density (from Chen, 1988).

On the other hand, total heave increases with increasing initial dry density for specimens compacted at a constant initial water content (Fig. 4.16).



4.16 Effect on total heave of the initial dry density for specimens, of constant initial water content (from Chen, 1988).

In addition to soil properties such as dry density and water content, the amount of total heave is also a function of the total stress applied to the soil specimen. Figure 4.17 demonstrates the influence of the surcharge pressure during an oedometer test on the amount of swelling. The results show that the total heave decreases with an increasing surcharge pressure. In other words, it is possible to reduce the amount of swelling by applying a high total stress to the soil.



4.17 Effect on total heave of the surcharge pressure for a specimen at a specified density and water content (from Chen, 1988).

4.5 Examples of test fields

Expansive soils undergo large volumetric changes due to seasonal moisture fluctuations. These volumetric changes cause swelling or shrinkage of the soils, which in turn inflict severe damage to structures built on them.

Volume change in expansive soils due to changes in the matric suction is generally caused by moisture variations. Vegetation transpiration may significantly decrease the moisture content of active soils and cause shrinking and deformation.

4.5.1 Fort Worth in Texas

Basic Soil Properties and classification are described for Fort Worth in Texas (Thammanoon, 2009). Based on the Atterberg limit and other physical soil tests, the soil is characterized as highly expansive (table 4.3).

Table 4.3 Characteristis of soil in Fort Worth test field

Passing #40 (%)	Passing #200 (%)	Specific Gravity	Liquid Limit (LL,%)	Plastic Limit (PL,%)	Placticity Index (PI,%)	Volumetric Swell Strain	USCS
100	85	2,70	61	24	37	17	CH

Texas was selected for field instrumentation and monitoring because its subgrade are known to cause pavement distresses in the form of cracks in both longitudinal and transverse directions.

The field instrumentations consisting of moisture sensors and suction probes were installed at three points (Fig 4.18).

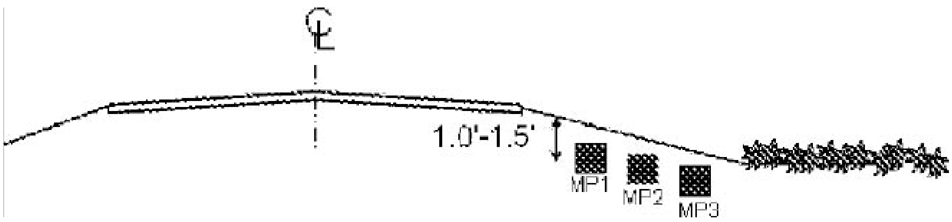


Fig. 4.18 Location of instruments

For the pavements at the Fort Worth site, the instruments were located next to irrigated farmland with normal side slopes. Numerous transverse and longitudinal cracks were observed at the site. From observation, several old cracks were noticeably amplified and a few new cracks appeared on late September 2007.

The moisture variation is defined as the difference between maximum and minimum moisture content values in a particular month. Between August and October 2007, the percent soil moisture variation values from all three sensors were more than 20% (Fig. 4.19) which is considered to be high. Such moisture content changes could result in considerable swell and shrink related volume changes in the subgrade in a short period of time. Also several cracks were observed during September 2007, and these cracks became wider with time. In addition, the mean moisture contents during this time period were 15% or lower, while rainfall levels during these months were moderate.

Generally, pavement cracks usually appear when the soils shrink in dry weather conditions. However, at this site, the observed cracks were exhibited while the pavement elevation data recorded directly on the test section were raising (as seen in Figure 4.19), which means the soil under the pavement was swelling. This might be the contribution of the existing cracks since those cracks might have allowed moisture content ingress in the subgrade faster than the areas where no cracking was noted. Differential moisture contents and swell/shrink movements of the soil occurred, and these were attributed to the development of cracks.

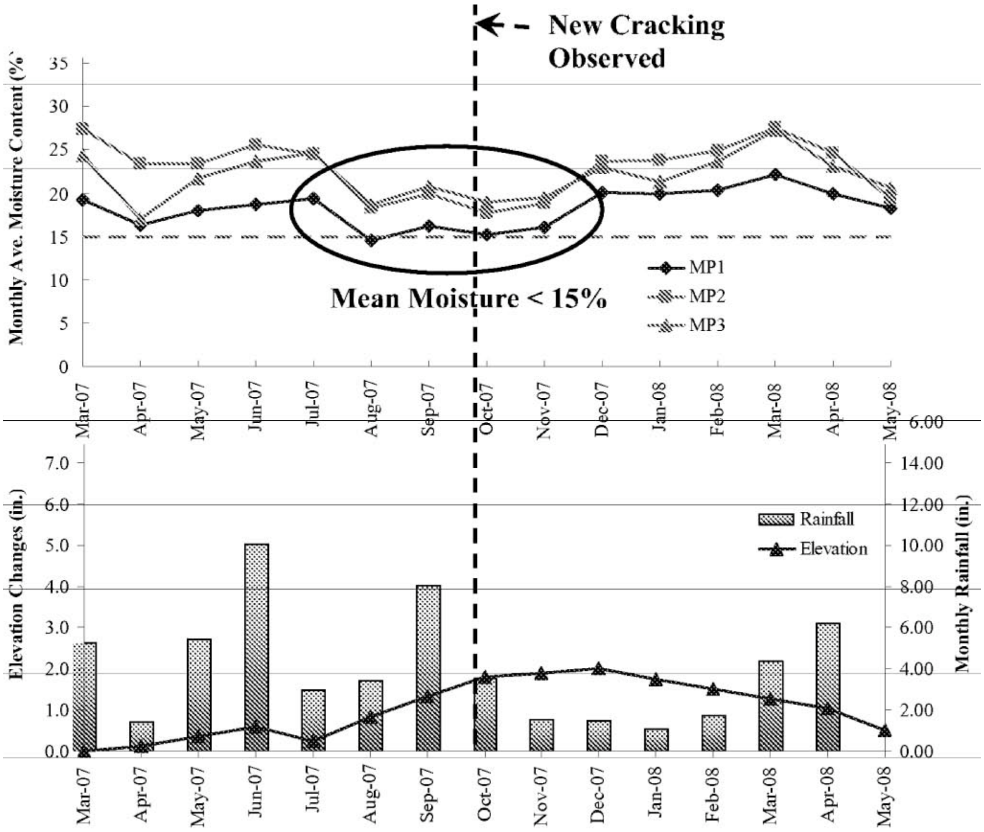


Fig. 4.19 Monthly average of moisture contents and (a) Elevation changes with rainfall data (b) for Fort Worth

From the field measured matric suction results presented in Fig. 4.20, it can be noted that the matric suction readings in August and September 07 were high indicating high shrinkage behavior. The maximum values were measured at the site visits during a summer period of high temperature.

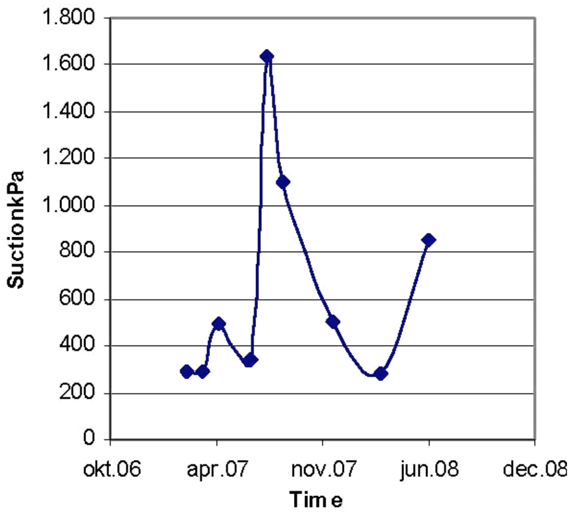


Fig.4.20 Field matric suction reading at Fort Worth site

4.5.2 Paris in Texas

Next location was Paris in Texas (Thammanoon, 2009). The site was located in the vicinity of large trees, the position of sensors was the same as the previous sample. During the initial site visits, large cracks on travel lanes were noted. The soil slope next to the pavement shoulder also exhibited severe cracking, and numerous cracks were about 1 to 2-inch wide and from 1 to 3-feet deep along the test section length. Consequent laboratory testing on the subsoil confirmed highly expansive behavior of this subgrade (Table 4.4). This site can be considered as a highly problematic soil conditions site, since the site soil is highly expansive and several large trees exist along the road. Roots of Hackberry type trees could deplete the moisture from surroundings which may result in shrinkage conditions in soils.

Table 4.4 Characteristics of soil in Paris test field

Passing #40 (%)	Passing #200 (%)	Specific Gravity	Liquid Limit (LL,%)	Plastic Limit (PL,%)	Placticity Index (PI,%)	Volumetric Swell Strain	USCS
100	81	2,70	60	23	37	15,3	CH

This road had been rehabilitated in April 07 and then in July 07; minor cracks still appeared in the pavement shortly after the rehabilitation. These cracks were widened, and this observation was made during the site visit on September 07. At this time condition, soil moisture content readings from MP 1 and MP 2 sensors were close to 15% (dry side), and the overall moisture content variations of all three moisture sensors was exceeding 20%.

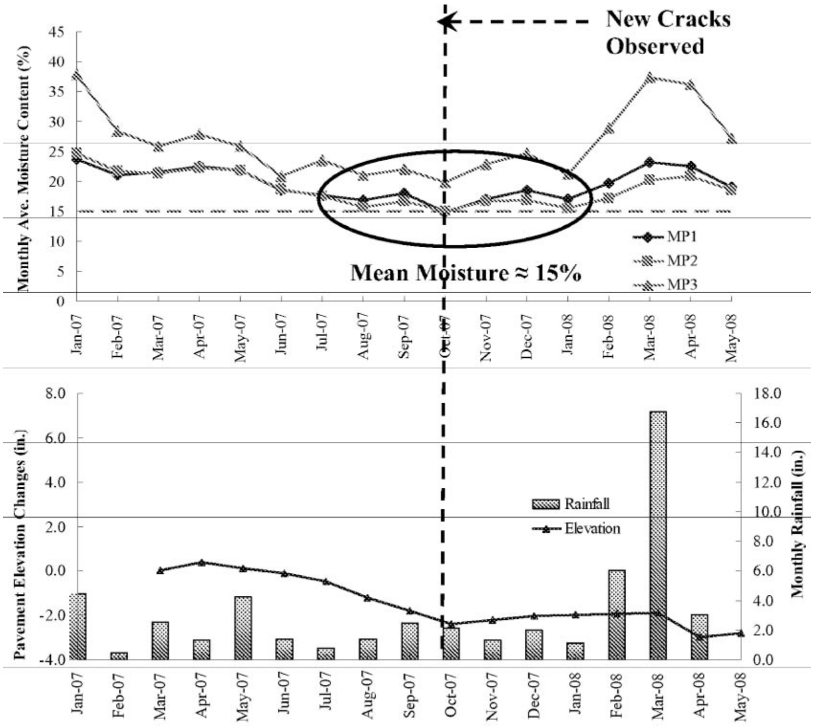


Fig. 4.21 Monthly average of moisture contents and (a) Elevation changes with rainfall data (b) for Paris

Elevation survey data presented in Figure 4.21 noted a decrease in the elevations indicating significant shrinkage behavior in the underlying and adjacent soil. Consequently, new cracks were also detected. Measurements show that soil moisture content readings from MP3 was always highest since MP3 is near the edge of soil side slope and also close to the large trees. It is interesting to note that soil moisture content of MP3 had not only exhibited highest moisture contents, but also the highest rate of moisture changes as well. This can be seen in Figure 4.21, which is presenting the differences in moisture readings of MP3 and MP1 over the time period.

From Figure 4.22, the slopes of the graph are mostly negative which indicates that MP 3 readings were decreasing faster than MP 1 readings. This is possible because MP 3 is situated near the large trees and the tree roots can absorb the moisture content in a soil in relatively faster period. It has been reported by many researchers that the location of large trees is critical to the stability of the pavement structures situated on expansive soils, since their roots can absorb water or moisture thereby resulting in moisture depletion and settlement of soil underneath the structures.

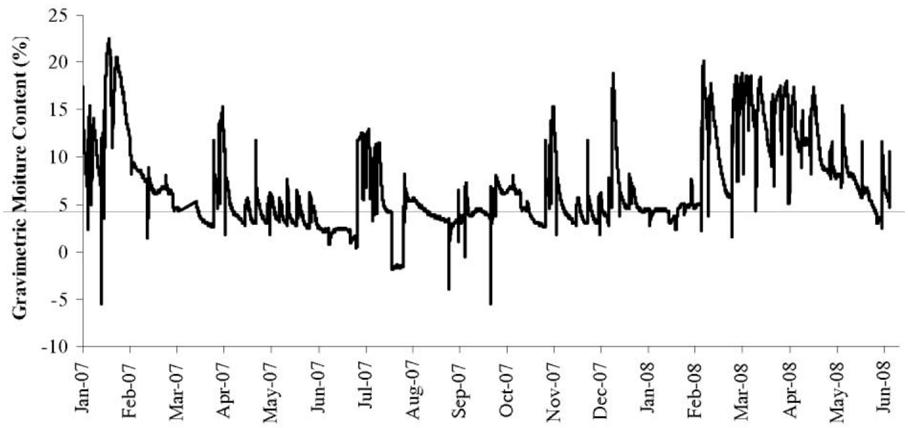


Figure 4.22 Plot of differences in moisture contents of MP3 and MP1 (MP3 - MP1) with time period

Ward (1953) recommended safe planting distance of trees to avoid soil shrinkage induced settlement and damage to buildings. He prescribed the first "proximity rule" of D:H where D is referred as the distance of the structure from the tree and H is referred to as the height of tree. When this ratio is close to one, shrinkage induced settlements might be a problem.

The averaged heights of Hackberry trees at the Paris site and the distance from the trees to the existing cracks are about 42 ft. and 38 ft. As a result, the D/H reading of the Paris site is around 0.9 which is closed to problematic level of 1.0 as noted by Ward. Hence, remedial measures are suggested to prevent moisture depletion caused by large trees.

The matric suction readings at this site (Fig. 4.23) were also high on September and December 2007 (2,137 and 1,932 kPa, respectively). No data are available on May and June 2007 because the cable of sensor was damaged. It should be noted that by the time of site visit on August 2007 and March 2008, rainfall was intense and soil slope was almost saturated and hence zero suction readings were measured.

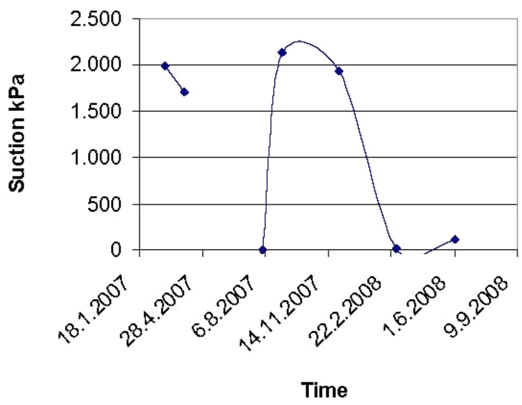


Fig.4.23 Field matric suction reading at Paris site

Based on the results it was concluded that new cracks will appear or old cracks will widen if any one of the following three conditions occur:

1. Moisture content variations are more than 20% and monthly mean moisture contents are less than 15% for more than a month. The observation was based on the field monitored data from Fort Worth and Paris sites.

2. Monthly mean moisture contents are less than 15% for more than 2 months. This observation was based on field monitored data from San Antonio site.

3. Matric suctions monitored during dry seasons exceeded 1,500 kPa and hence such high suction values could indicate potential problem levels for soil shrinking.

4.5.3 Benson, Arizona

In situ tests and laboratory collapse tests were performed at the collapsible soil site in Benson, Ariz (Houston, 2002). The wetted curve collapse data from this test series is shown in Fig. 4.24. Stress-strain data such as that shown in Fig. 4.24 can be used in estimating the amount of potential collapse settlement. Adjustments for partial wetting should be applied to laboratory test results. The degree of wetting achieved in the in situ test is comparable to that achieved in field conditions for downward infiltration from a near surface source of water, and an adjustment for partial wetting is not normally needed.

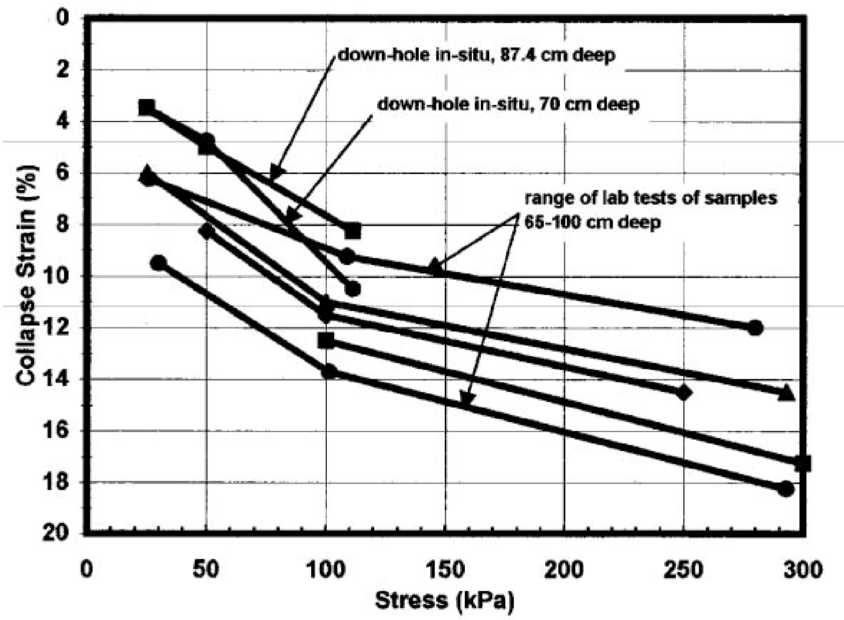


Fig. 4.24. Laboratory and in situ test results from collapsible soil site in Benson, Ariz.

5 Conclusion

The level of moisture in a subgrade soil results from the interaction of numerous factors.

These data suggest that water moves readily through the asphaltic base and into the stone base of the pavement subgrade. It seems likely that repeated increases in stone base water content will eventually result in increased soil subgrade water content.

Some observations with respect to factors affecting subgrade moisture content follow:

1. The correlation between precipitation and subgrade moisture content is usually positive; however, the extent to which precipitation affects subgrade moisture varies from one site to another, and depends on a variety of factors, such as internal drainage, water table location, and pavement/shoulder condition.
2. Soil type is perhaps the most important factor that affects long-term subgrade moisture content. The type of soil affects drainage characteristics and the water capacity of the soil.
3. Results of water content measurements and precipitation measurements were collected from literature from 19 test fields. Data were analysed for 5 types of soil. Natural moisture content can be, even for the same type of soil, very different. For the interpretation we calculate the percentage of change of moisture content in comparison with the natural one. For every type of soil, the minimum and maximum trend line was defined.
4. Changes in water content occur very slowly if the material that constitutes the subgrade is impermeable and exhibits a high soil-water tension. Changes will most likely either be seasonal or vary with unusually wet or dry years.

   Coarser-textured subgrades, with higher permeability and lower water retention forces, may eventually show some seasonal water content changes.

   Although there was a variation in the amount of precipitation during one year period, it was found that the subgrade soil moisture contents did not change as significantly as precipitation (Kansas, Pennsylvania). Again, when there was some change in the soil moisture content over one year period, it was not proportionate to the amount of rainfall. Delays from precipitation to water content increase could be 1 or 2 months (Arkansas, Rogla).
5. The lower equilibrium values for the subgrade moisture contents at the deeper depths are typically higher, and, on average, more than 3 percent higher than the corresponding values at the shallow depths (Arkansas).
6. Type of road construction

   In addition, subgrade moisture variations are reduced when pavements are constructed using well-draining materials for the base and subbase. A major pavement factor related to subgrade moisture is the type and condition of the pavement shoulders and edges.

   The change in subgrade moisture under base and rock cap is noticed only at shallow depths just below the base or rock cap layer.
7. Problematic soils can be treated using a variety of methods or combination techniques that can be used to improve the strength and reduce the climatic variation of the foundation on pavement performance include:

   - Improvement of subsurface drainage

- Removal and replacement of original material with better materials (e.g., thick granular layers).

- Mechanical stabilization using thick granular layers.

A thick granular layer is an important feature in pavement design and performance. Thick granular layers increase load-bearing capacity, frost protection, and improved drainage. The main aim is to achieve desired pavement performance through improved foundation characteristics.

- Mechanical stabilization of weak soils with geosynthetics (geotextiles and geogrids) in conjunction with granular layers can be another option. Geotextiles or geogrids in conjunction with an appropriately designed thickness of subbase aggregate provide stabilization for soft, wet subgrades with a CBR of less than 3 (a resilient modulus less than 30 MPa (4500 psi)).

- Lightweight fill
  The compacted unit density of most soil deposits consisting of sands, silts, or clays ranges from about 1,800 - 2,200 kg/m^3. Lightweight fill materials are available from the lower end of this range down to 12 kg/m^3. In many cases, the use of lighter weight materials on soft soils will likely result in both reduced settlement and increased stability. Many types of lightweight fill materials have been used for roadway construction as foamed concrete, wood fiber, flyash, slag, etc.

- Stabilization of weak soils with admixtures (highly plastic or compressible soils).
  Lime may also be used to treat expansive soils. Lime will reduce swell in an expansive soil to greater or lesser degrees, depending on the activity of the clay minerals present.

If collapsible soils are detected prior to pavement construction, then the possible mitigation alternatives include prewetting, removal, and dynamic compaction. When problems arise after the pavement is in place, then mitigation methods are more limited, but chemical stabilization or grouting and controlled wetting can be considered to remedy problems in localized regions.

The challenge to the pavement engineer is to asses the moisture sensitivity of a very large volume of subgrade. Cost control on maintenance and initial construction and attention to public safety and comfort will dictate the appropriate blend of investigative tools for identification and solution development for swelling and collapsible soils.

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