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THE EFFECT OF WETTING AND DRYING ON RESILIENT MODULUS BEHAVIOUR AND PAVEMENT RESPONSES OF LIME-CEMENT STABILISED SUBGRADE SOILS

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ABSTRACT

Stabilization of road pavement subgrade soils, by significantly improving their strength and mechanical properties may consequently reduce the required thickness and engineering properties of the engineered layers of the road pavements. However, moisture changes associated with environmental conditions cause deterioration to the stabilized subgrade soils by continuous cycles of wetting and drying. This paper demonstrates and quantifies the changes to the resilient modulus of the stabilized subgrade soils after cycles of wetting and drying, as it is a key mechanical property and element in analytical pavement design procedures. A series of tests were conducted on three types of subgrade soils that were stabilized to varying degrees with combinations of lime and cement. The results showed a decrease in resilient modulus values with increase in moisture content for untreated soils. Although the stabilization of the soils increased the resilient modulus value to twice of the untreated one, however the increase of mixing water had a different effect on each of the soil types. Moreover the resilient modulus after cycles of wetting and drying for two types of the tested soils decreased, while for the other one no significant change was observed. Furthermore pavement responses to the applied loads changed with moisture content for untreated soils.

1 INTRODUCTION

When road pavements are built on soft fine-grained subgrade soils, the soils are often compacted and in addition to this, soils may be protected by an extra compacted fine-grained subgrade soil layer. Ingress of water to these layers affects their strength and other mechanical properties and reduces their performance; consequently affecting the life of the road pavement as a whole. Stabilization of subgrade soils can be used to improve both the strength and mechanical properties. However, as there are many techniques and agents of stabilization, all stabilized soils should be assessed for sensitivity to changes in moisture to evaluate their durability and the effectiveness of the stabilization on their performance.

To this end, the paper describes an investigation of the conditions of the subgrade soils under the changes of moisture in terms of the changes to the resilient modulus and unconfined compressive strength for treated and untreated soils.

2 LITERATURE REVIEW

Analytical methods of pavement design use the mechanical properties of the materials as inputs to the response and distress models. An important part of such a process is to determine a suitable resilient modulus which is used in response models to characterise material performance under cyclic loads. Therefore, it is important to measure and evaluate the resilient modulus under various conditions within road pavement subgrade. Besides it is affected by many factors such as stress level, soil type, moisture changes (Lekarp et al., 2000).

The moisture within a road pavement fluctuates according to the environment of a particular geographical area and its influence on resilient modulus is most apparent during spring thawing followed by drying during the summer months. Consequently the repetition of this wetting and drying cycle will affect the performance of the road pavement structure. To simulate the moisture condition Kim and Siddiki (2006) suggest the use of the wet side of the optimum moisture content for subgrade resilient modulus determination, because the use of optimum moisture content may lead to an un-conservative design (AASHTO M-E design guide, 2004).

To improve the behaviour of road pavement subgrades a large amount of research has focused on the use of stabilization methods. Two of the most popular methods are stabilization by lime and cement (see for example Little, 1987; Mohammad and Saadeh, 2008; Milburn and Parsons, 2004; Wu et al., 2011). Adding lime to the soil improves its plasticity, workability and strength properties, via the reaction of lime with fines in the soil (Mallela et al., 2004). Lime as modifier for wet subgrades is also common (Gautreau et al., 2009).On the other hand cement has the ability of providing strength properties to the soils. Research by Wu et al. (2011) for example, showed that cement stabilized soils prevented excessive rutting from occurring for 6.5 times longer than lime stabilized ones. In general, however, cement is used for stabilizing of coarser grained soils and adding a high portion of cement for fine-grained soil stabilization is not economically cost-effective. For these reasons lime and cement are often used in combination (Rout et al., 2012).

Little research however, has been carried out to quantify resilient modulus behaviour of lime-cement stabilized subgrade soils after cycles of wetting and drying. To address this, this paper describes research to assess the behaviour of untreated and treated subgrade soils in terms of strength and mechanical properties and demonstrates the effect of wetting and drying on resilient modulus values and overall road pavement responses through the incorporation of the resultant resilient modulus values in a pavement design procedure

3 LABORATORY TESTING PROGRAM

Three different types of soil samples were prepared for analysis to simulate conditions found in Kurdistan. The index properties and moisture-density relationships of the soils were determined using standard laboratory tests and are shown in table 1. Two of the soils; A-4 and A-6 were stabilized with a combination of 4% cement and 1.5% lime and the other one, A-7-5, was stabilized with 8% cement and 1.5% lime content by weight of the sample.

A number of laboratory tests were performed on the samples as follows:

1) Unconfined compressive strength tests: Unconfined compressive strength tests are conducted; to compare the strength of the untreated and treated soils, to find a correlation between this test results and resilient modulus, to find

the modulus of elasticity of treated soils for strength determination and correlation with resilient modulus and to compare the strength difference between 7 days and 28 days curing.

2) Resilient modulus tests: For the resilient modulus test the procedure of AASHTO T307 was followed. The test starts with preconditioning of 500-1000 cycles to simulate pre-compaction at 41.4 kPa confining pressure and 27.6 kPa deviatoric stresses. The test continues for different combinations of confining pressure and deviatoric stresses 100 cycles each for 15 sequences, the results from the last five cycles are averaged to obtain resilient modulus of a specified stress combination.

3) Wetting and drying tests: Wetting and drying consists of cycles of wetting the soil samples by submerging them in water at room temperature for 5 hours followed by drying in an oven of 71°±3° for 42 hours. The ASTM procedure uses 12 cycles for soil-cement losses and volume and moisture changes, however the test used by researchers to compare strength properties after cycles of wetting and drying. Chittoori et al. (2012) used 21 cycles of wetting and drying to compare strength of the stabilized soils in terms of UCS test at 3, 7, 14 and 21 cycles. This research uses 20 cycles of wetting and drying to obtain resilient modulus values that will be compared to resilient modulus after 7 days of curing.

Table 1. Index and moisture-density relationships of soil samples

Soil(AASHTO Classification)	Liquid limit LL (%)	Plastic limit PL (%)	Plasticity Index PI (%)	MDD (untreated) (gm/cm^3)	OMC (untreated) (%)	MDD (treated) (gm/cm^3)	OMC (treated) (%)
A-4	21	14	6	1.938	11.0	1.93	12.5
A-6	35	21	14	1.925	12.0	1.91	12.5
A-7-5 (4%cc)	51	31	20	1.480	20.0	1.46	24.0
A-7-5 (8%cc)	51	31	20	1.480	20.0	1.433	22.0
Standard used	BS 1377-2: 1990 sections 4 and 5			BS 1377-4: 1990 section 3		BS 1924-2:1990 section 2	

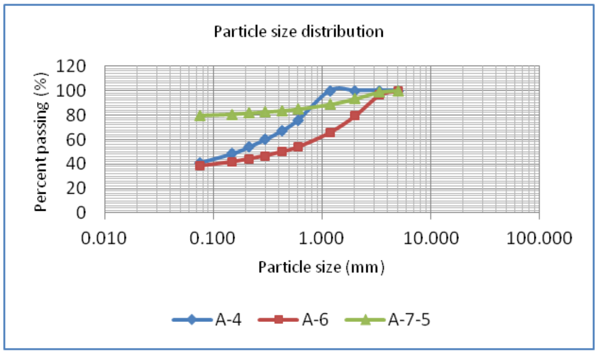

Figure 1. Particle size distribution curves of soils

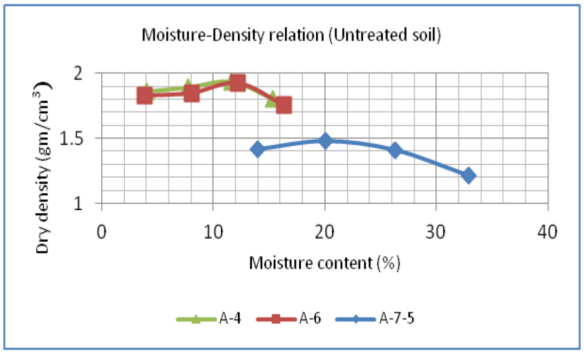

Figure 2. Moisture-density relations of untreated soil

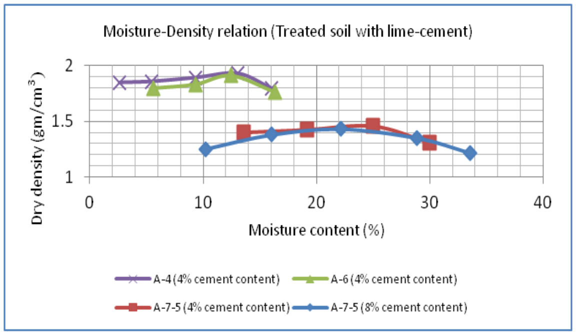

Figure 3. Moisture-density relations of treated soil

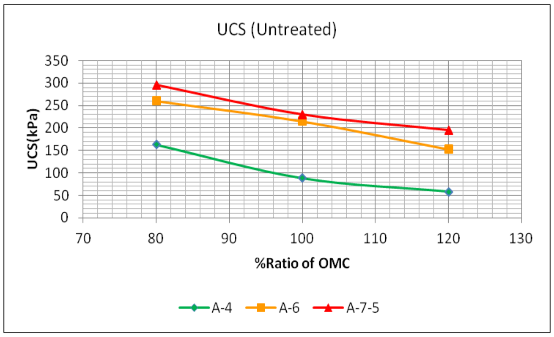

Figure 4. Unconfined compressive strengths of untreated soils

4 RESULTS

4.1 Unconfined compressive strength

Tables 2 and 3, show the results of the unconfined compressive strength (UCS) for treated and untreated soils. The results show a decrease in unconfined compressive strength with increase of moisture content for the three soil types, (figure 4). Of these, the soil A-7-5 has a higher UCS compared to the other two soil types; this indicates that silty sandy soils are weaker and more affected by moisture change than cohesive soils. On the other hand treated soils show a different trend for the three soil types, where the silty sandy soils have obtained more strength than cohesive soils with stabilization, see table 3. Soil A-6 which has a higher proportion of sand obtained a higher strength than the other two soils. This tendency of the sandy silty clays confirms the need of stabilization of subgrade soils consisting of these types of soils.

The effect of moisture change on silty sandy clays is more sensible from the ratio of the strength loss of these soils, for example this ratio for A-4 is about 3, while it is 1.5 for soil A-7-5 which is a cohesive soil.

Figures 5 and 6 show the stress-strain relation for soil A-6 at a range of moisture contents of dry, OMC and wet of optimum moisture content. From these figures it is clear that permanent deformation of the material has increased with increase of water content for untreated soils. At the time that this property for treated soils has improved and almost is the same for all moisture contents. This, demonstrate the improvement of soil properties and resistance to permanent deformation by stabilization.

4.2 Resilient modulus

Tables 4 and 5 show the resilient modulus values for 15 different stress combinations and 3 moisture contents for 3 soil types, the relative decrease of resilient modulus for each stress combination is presented and averaged. These tables show a decrease in resilient modulus value by a relative decrease of about 1.8 for untreated soils with increase in mixing water content from 80%OMC to 120%OMC, this ratio for treated soils is 1.1 to 1.4. However, the increase of mixing water slightly increased the resilient modulus values for soil A-6. Moreover the tables show the increase in resilient modulus of about 2 times when stabilized for all cases.

In general the increase of deviatoric stress causes a decrease in the resilient modulus for untreated soils. However, there are occasions that the resilient modulus increases with increase of deviatoric stress and then decreases or continues on increasing. On the other hand for treated soils the increase of deviatoric stress results in an increase of resilient modulus for different moisture contents in all cases.

4.3 Wetting and drying

Wetting and drying tests are shown in table 6; samples of A-7-5 at 80% and 100% moisture content are not included in the table as they failed at the first cycle of wetting and drying. The table shows that for soils A-7-5 and A-4, the resilient modulus at OMC decreased by 35% and 20% respectively, where soil A-6 which contains a high portion of sand shows no significant change.

5 PAVEMENT DESIGN

A hypothetical road pavement section was used to examine the performance of three soil types (table 6) under a load of 80 KN. In order to quantify the effect of changes in moisture on pavement performance an analysis was carried out using Kenlayer programme (Huang, 2004) to model the hypothetical road pavement. The analysis performed consisted of determining, using Kenlayer, the critical strains which would accrue for the 9 scenarios investigated and the consequential changes in design life for the 80 KN design load. For this process it was necessary to choose a representative value of the resilient modulus for each of the 9 scenarios. The procedure to achieve this was as follows: Firstly the average of 15 stress combinations in the resilient modulus test used for stresses, strains and displacements determination, from these results the vertical stress at the top of the subgrade was found to be between 25-33 kPa (the confining stress in all cases was 2 kPa), therefore a stress combination of 37.3 kPa and 13.8 kPa was used for next step of analysis.

Table 2. Unconfined compressive strength test result for untreated soils

	%OMC		Untreated UCS (kPa)	Average (kPa)	Relative decrease in strength
A-4	80	1	159	163	1.0
		2	165		
		3	164		
	100	1	114	88	1.8
		2	81		
		3	70		
	120	1	41	58	2.8
		2	50		
		3	84		
A-6	80	1	264	260	1.0
		2	257		
		3	260		
	100	1	223	215	1.2
		2	216		
		3	205		
	120	1	136	153	1.7
		2	155		
		3	167		
A-7-5	80	1	298	296	1.0
		2	337		
		3	252		
	100	1	237	230	1.3
		2	233		
		3	219		
	120	1	193	195	1.5
		2	200		
		3	191		

Table 3. Unconfined compressive strength test result for treated soils

	%OMC		Treated UCS (kPa)	Average (kPa)
A-4	80	1	778	714
		2	724	
		3	640	
	100	1	741	797
		2	831	
		3	818	
	120	1	1086	1016
		2	985	
		3	978	
A-6	80	1	638	658
		2	678	
		3	_	
	100	1	894	958
		2	965	
		3	1016	
	120	1	909	1047
		2	1111	
		3	1122	
A-7-5	80	1	515	553
		2	510	
		3	634	
	100	1	435	452
		2	465	
		3	455	
	120	1	246	341
		2	441	
		3	337	

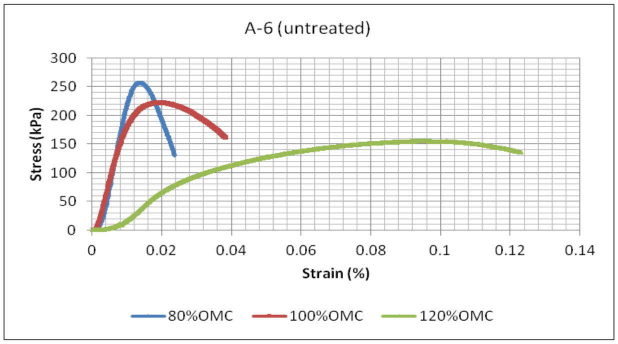

Figure 5. Stress-strain relations for soil A-6 at three different moisture contents (Untreated)

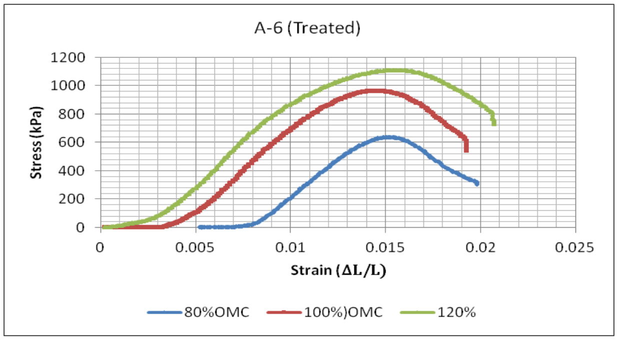

Figure 6. Stress-strain relation for soil A-6 at three different moisture contents (Treated)

Table 4. Resilient modulus test results (Untreated)

		A-4 (Untreated)				A-6 (Untreated)				A-7-5 (Untreated)			
σ₃ (kPa)	σd(kPa)	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Ratio 80%/120%	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Ratio 80%/120%	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Ratio 80%/120%
41.4	12.4	70.1	56.9	27.6	2.54	77.3	72.0	55.0	1.40	74.0	66.5	52.5	1.41
	24.8	74.6	57.6	36.2	2.06	83.4	67.1	49.8	1.68	79.1	69.7	47.4	1.67
	37.3	74.7	57.0	42.5	1.76	84.4	62.1	45.9	1.84	79.0	68.6	42.4	1.86
	49.7	76.5	58.3	44.5	1.72	85.5	60.3	44.6	1.92	77.5	66.9	39.0	1.99
	62	80.1	57.8	_	_	87.5	60.3	43.4	2.01	77.0	65.1	36.7	2.10
27.6	12.4	66.4	54.2	28.2	2.36	79.2	71.4	56.0	1.41	74.8	70.0	59.0	1.27
	24.8	72.0	53.9	40.2	1.79	87.3	64.6	46.0	1.90	77.7	71.1	51.8	1.50
	37.3	74.4	56.2	45.5	1.64	89.1	58.7	42.6	2.09	78.7	70.0	44.4	1.77
	49.7	77.0	57.8	46.7	1.65	89.9	57.1	43.4	2.07	78.9	68.1	39.3	2.01
	62	81.0	56.4	_	_	90.5	57.1	_	_	77.9	66.0	36.7	2.12
13.8	12.4	56.5	51.1	42.0	1.35	72.1	66.3	_	_	73.2	67.3	59.5	1.23
	24.8	69.7	51.3	45.4	1.54	90.8	60.0	_	_	78.0	70.6	52.7	1.48
	37.3	72.4	54.1	49.1	1.47	92.3	54.5	_	_	78.2	69.1	44.8	1.75
	49.7	75.8	55.9	50.4	1.51	93.2	53.7	_	_	78.0	67.4	39.4	1.98
	62	80.1	53.9	_	_	93.7	54.6	_	_	78.0	65.9	36.9	2.12
Average		73.4	55.5	41.5	1.8	86.4	61.3	47.4	1.8	77.3	68.1	45.5	1.7

Table 5. Resilient modulus test results (Treated)

		A-4 (Treated)				A-6 (Treated)				A-7-5 (Treated)			
σ₃ (kPa)	σd(kPa)	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Ratio 80%/120	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Ratio 80%/120	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Ratio 80%/120
41.4	12.4	117.9	129.3	80.4	1.47	101.0	112.5	113.3	0.89	108.4	94.7	92.4	1.17
	24.8	138.5	152.5	97.1	1.43	127.9	137.7	141.2	0.91	123.8	112.2	106.4	1.16
	37.3	150.8	167.3	107.4	1.40	144.1	150.6	154.9	0.93	133.8	125.9	116.4	1.15
	49.7	163.0	182.9	118.1	1.38	161.7	165.2	170.1	0.95	145.1	139.5	126.8	1.14
	62	175.9	200.7	129.1	1.36	176.8	180.2	186.7	0.95	158.1	153.9	137.0	1.15
27.6	12.4	108.6	117.3	73.9	1.47	95.3	106.1	107.5	0.89	97.3	90.4	88.3	1.10
	24.8	127.0	138.3	89.5	1.42	118.2	129.1	132.4	0.89	112.3	105.2	101.8	1.10
	37.3	142.9	160.0	102.7	1.39	138.0	145.6	151.9	0.91	126.0	121.4	114.7	1.10
	49.7	159.0	179.9	115.7	1.37	157.8	163.3	169.2	0.93	141.0	136.9	127.1	1.11
	62	174.8	200.7	128.0	1.37	175.8	179.4	186.4	0.94	155.1	152.9	137.9	1.13
13.8	12.4	97.3	107.6	72.7	1.34	90.7	97.8	101.2	0.90	92.2	89.5	87.3	1.06
	24.8	122.9	129.1	87.5	1.40	115.1	122.7	128.6	0.90	107.6	103.6	100.6	1.07
	37.3	140.1	149.8	100.6	1.39	135.1	141.3	149.2	0.91	123.0	120.3	114.1	1.08
	49.7	156.8	171.2	114.0	1.38	154.8	159.4	167.4	0.92	137.7	135.8	126.6	1.09
	62	173.0	190.6	126.6	1.37	173.2	177.1	184.4	0.94	152.7	151.4	137.4	1.11
Average		143.2	158.5	102.9	1.4	137.7	144.5	149.6	0.9	127.6	122.3	114.3	1.1

Table 6. Resilient modulus values after 20 cycles of wetting and drying

		A-4 (Mr after W/D cycles)			A-6 (Mr after W/D cycles)			A-7-5 (Mr after W/D cycles)		
σ₃ (kPa)	σd(kPa)	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC	Mr (MPa) 80%OMC	Mr (MPa) 100%OMC	Mr (MPa) 120%OMC
41.4	12.4	123.7	111.4	84.8	109.1	113.2	130.8			61.25
	24.8	148.0	133.0	100.4	126.6	144.6	145.9			72.31
	37.3	165.6	148.0	112.9	135.8	161.8	152.4			77.40
	49.7	183.0	163.0	128.3	144.1	182.0	164.2			85.97
	62	204.3	175.1	142.6	155.0	201.1	177.8			95.37
27.6	12.4	113.5	86.3	79.6	98.7	107.4	114.0			56.81
	24.8	136.8	113.5	93.8	112.0	128.1	127.8			62.58
	37.3	156.8	134.2	108.1	123.2	150.9	141.0			72.78
	49.7	177.9	151.8	124.1	136.5	173.3	157.5			83.97
	62	199.6	166.9	140.6	150.5	194.6	172.0			94.78
13.8	12.4	95.6	78.0	77.7	92.5	87.1	106.4			55.40
	24.8	131.3	105.9	91.0	107.6	120.6	121.6			61.24
	37.3	151.3	126.4	105.5	118.9	142.0	136.0			70.23
	49.7	173.5	144.0	121.2	131.7	165.3	152.6			82.08
	62	195.5	161.5	137.6	145.8	187.0	168.6			93.08

From the results of the resilient modulus tests the resilient modulus values corresponding to this stress combination was selected and assigned as the design resilient modulus for any specified condition. This gives the highest level (level 1 in AASHTO design guide) of input data. Table 7 shows the results of stresses, strains and displacements after using the design resilient modulus in the response models. In table 7, the strains at the top of the subgrade layer are highlighted; here an increase of moisture resulted in an increase of compressive strain. This will lead to the decrease of the number of load repetitions to failure and pavement life. One model that has been used in Kenlayer program can more clearly show the effect of the increase of moisture on the life of the pavement structure and is shown in Equation 1 below. Equation 1 is an expression of rutting failure criteria whose parameters are determined by road tests or field performance (Huang, 2004). The Asphalt institute and Shell suggested different values for the equation constants; here the values of Asphalt Institute are used as they have been utilized in the Kenlayer programme (Huang, 2004).

$$N_d = 1.365 * 10^{-9}(\in_c)^{-4.477} \qquad (1)$$

Using Equation 1within Kenlayer, together with resilient modulus values described above the number of load repetitions to failure for each condition of the three materials was obtained and is given in Table 8. From the results it can be concluded that the dry condition for the three soil types result in a higher number of repetitions to failure, at the same time the ratio of the number of load repetitions of 80%OMC to 120%OMC shows the effect of moisture on the performance.

Table 6. Hypothetical pavement section properties *

Layer	Thickness (mm)	Resilient Modulus (Mpa)	Poisson's ratio
Surface course (Asphalt concrete)	100	4000	0.3
Base course (Unbound granular material)	200	200	0.3
Subgrade (compacted fine-grained soil)	200	40-90	0.45
Subgrade (Natural)	_	40-90	0.45

*Typical values from literature are used except for resilient modulus of subgrade which is used from tests.

6 CONCLUDING DISCUSSION

This paper has described a series of tests which were carried out to quantify the changes to the resilient modulus of the stabilized subgrade soils after cycles of wetting and drying. A series of tests were conducted on three types of subgrade soils that were stabilized to varying degrees with combination of lime and cement. The results showed a decrease in resilient modulus values with increase in moisture content for untreated soils. To demonstrate the influence of the soil types on road pavement performance laboratory measures of performance were utilized within a numerical model known as Kenlayer. The main findings of this research can be summarized as follows:

1. The properties of silty sandy soils drops significantly by increase in moisture content, it is therefore important to stabilize these types of soils that gain high durability properties to resist moisture fluctuations with stabilization.
2. Fine-grained soils with higher portion of clay content need a higher stabilizer agent ratio than soils with higher portion of sand and silt, as the later behaves similar to coarse granular material rather than fine-grained soil.
3. It is important to assess the conditions of stabilized subgrade soils after wetting and drying in terms of the resilient modulus as it is an important property to characterize the soils and its use in pavement design procedure.
4. The decision on a single value of resilient modulus is important in analytical pavement design, a procedure proposed here for each of the 3 scenarios of each soil type. The resilient modulus at worst condition can be used to represent the resilient modulus value for design purposes.

Table 7. Stresses, strains and displacements for design resilient modulus at various moisture contents

	point	vertical coordinate (Z) in cm	Vertical dispt. (ΔZ) in cm	Vertical stress (kPa)	**Vertical Strain ε_z(μstrain)**	Major P. stress, σ_1 (kPa)	Major P. strain,ε_1 (μstrain)	Minor P. stress, σ_3 (kPa)	Minor P. strain,ε_3 (μstrain)
A-4 80%OMC	1	10.0000	0.054	95	106	95	106	-928	-227
	1	30.0001	0.045	50	500	50	500	4	-312
	1	50.0001	0.036	31	401	31	401	2	-192
A-4 100%OMC	1	10.0000	0.065	91	113	91	113	-983	-236
	1	30.0001	0.057	44	711	44	711	4	-364
	1	50.0001	0.045	28	477	28	477	2	-227
A-4 120%OMC	1	10.0000	0.069	90	115	90	115	-1002	-240
	1	30.0001	0.061	42	749	42	749	4	-382
	1	50.0001	0.048	27	504	27	504	2	-239
A-6 80%OMC	1	10.0000	0.046	99	101	99	101	-884	-219
	1	30.0001	0.038	55	519	55	519	5	-270
	1	50.0001	0.029	34	344	34	344	2	-166
A-6 100%OMC	1	10.0000	0.065	91	113	91	113	-981	-236
	1	30.0001	0.056	44	709	44	709	4	-363
	1	50.0001	0.045	28	475	28	475	2	-226
A-6 120%OMC	1	10.0000	0.076	88	119	88	119	-1030	-245
	1	30.0001	0.068	39	806	39	806	4	-409
	1	50.0001	0.054	25	546	25	546	2	-258
A-7-5 80%OMC	1	10.0000	0.051	97	104	97	104	-914	-224
	1	30.0001	0.043	52	575	52	575	5	-298
	1	50.0001	0.033	32	382	32	382	2	-183
A-7-5 100%OMC	1	10.0000	0.055	95	107	95	107	-936	-228
	1	30.0001	0.047	49	619	49	619	4	-320
	1	50.0001	0.037	31	419	31	419	2	-197
A-7-5 120%OMC	1	10.0000	0.074	89	118	89	118	-1020	-243
	1	30.0001	0.065	40	786	40	786	4	-400
	1	50.0001	0.052	26	531	26	531	2	-251

Table 8. Number of load repetitions for each condition

Soil type	%OMC	Vertical Strain εz(μstrain)	N	Ratio N80%/N120%
A-4	80	401	2.20E+06	
	100	477	1.01E+06	
	120	504	7.91E+05	2.8
A-6	80	344	4.37E+06	
	100	475	1.03E+06	
	120	546	5.53E+05	7.9
A-7-5	80	382	2.74E+06	
	100	419	1.81E+06	
	120	531	6.26E+05	4.4

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