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Consideration of the deterioration of stabilised subgrade soils in analytical road pavement design

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ABSTRACT

The stabilisation of road subgrade soil may improve its mechanical properties considerably, however under the combined effect of cumulative traffic load and weathering these materials deteriorate over time and lose performance. However, current road design procedures neglect such deterioration of stabilised soils and consequently their use may result in the under-design of road pavements and as a result unplanned maintenance and/or premature road failure. To address this, this research presents the results of a research programme marrying experimental, analytical and numerical work which was used to develop a methodology which can be used for the first time to design accurately road pavements incorporating stabilised subgrade soils. An extensive experimental programme was carried out consisting of laboratory durability tests to determine the mechanical behaviour of stabilised subgrade soils, in terms of resilient modulus and permanent deformation, under cycles of wetting and drying. Results of the durability tests were used to validate an analytical predictive equation which considers the changes that take place to the material after cycles of wetting and drying. The experimental results show a decrease in the resilient modulus after 25 cycles of wetting and drying cycles for three types of fine grained subgrade soils stabilised with varying amounts of lime-cement. In order to adequately replicate the stress dependency of the performance of the stabilised subgrades for analytical pavement design, two equations were developed that relate the resilient modulus of a stabilised soil with unconfined compressive strength (UCS). The developed equations were utilised with a numerical finite element model of a road pavement to determine the most appropriate road pavement designs, on an engineering basis, for a variety of stabilised soils.

Keywords: Deterioration, Stabilisation, Subgrade Soils, Analytical Pavement Design
1 INTRODUCTION

The road pavement is a structural system which is designed, for a predetermined period of time, to withstand the combined effects of traffic and the environment so that the subgrade is adequately protected and that vehicle operating costs and safety are maintained within acceptable limits (McElvaney and Snaith, 2002). When carrying out the structural design of road pavements using an analytical process a numerical model of the pavement structure is used to determine the stresses, strains and deformations at critical locations within the pavement structure. Such models require the characterisation of appropriate resilient modulus values for the materials comprising the road pavement. The critical stresses, strains and deformations so determined are compared with allowable values determined via repeated load laboratory experiments to formulate the design. The resilient modulus and resistance to permanent deformation of many fine-grained subgrade soils however is affected considerably by changes in moisture content. As a result these soils often require stabilisation by mechanical or chemical means (Little, 1987; Bell, 1996; Addison and Polma, 2007; Solanki et al., 2010; Rout et al., 2012; Jameson, 2013; Bowers et al. (2013); Rasul et al., 2015). Nevertheless, stabilised soils can still experience notable deterioration with load repetition and weathering (see for example Wu et al. 2011). Therefore when stabilised soils are to be used within a road pavement, it is important to properly characterise their performance so that the road pavement can be designed appropriately (Wu et al. (2011). Hicks (2002) identified three important considerations for the successful design of a stabilised subgrade layer; the structural design, the material mix design and the construction of the stabilised layer. Regarding the structural design, the performance criteria to be used depends on the type of the stabilisation used. These are in three categories in terms of their performance criteria: (i) unbound material; for which the thickness is governed by subgrade strain, this type has no significant tensile strength; (ii) modified material; the design criteria is subgrade strain and modification is carried out to increase the strength and to reduce the moisture and frost susceptibility of fine grained soils; (iii) bound material; the addition of a stabiliser of this type increases the tensile strength of the layer and the performance criteria are fatigue and erosion (Hicks, 2002). Appropriate stabilisation mix design requires the combination of the soils and the stabilisers in the correct proportions to achieve the required strength and durability (Paige-green, 2008). However, whilst the most widely used and recognised analytical road pavement design procedures, allow for the use of stabilised subgrade layers, they do not take into account the deterioration of the mechanical properties of these layers. Such design procedures include using: USA (ASHTO MEPDG, Texas DOT, Florida DOT and Illinois DOT); ii) UK design method; French design method and Australian design methods (Queensland DOT, Victoria design method and Roads and maritime services design methods). A useful summary of these design methods to the consideration of stabilised subgrade layers is given by Jameson (2013). A number of researchers have evaluated the performance of stabilised subgrade soils in terms of the resilient modulus and permanent deformation properties (see for example Chauhan et al., 2008; Abu-Farsakh et al., 2014). However, little research can be found in the literature considering the durability of stabilised subgrade soils subject to cycles of wetting and drying (i.e. weathering) for analytical pavement design. This includes the use of appropriate resilient modulus values to characterise the numerical model and the permanent deformation behaviour for the empirical laboratory based models of material performance. To address the above issues, this paper describes a novel rigorous approach to the design of road pavements using marginal materials. The approach utilizes (i) a suite of laboratory experiments to determine the durability of a number of stabilised soils as a function of cumulative traffic load and weathering, (ii) a method to determine appropriate resilient
modulus values for analytical pavement design and, (iii) a novel durability model, (iv) a numerical model of a road pavement. The usefulness and significance of the approach for road pavement design is demonstrated via an example.

2 EXPERIMENTAL PROGRAMME

Three fine grained subgrade soils were considered. Their classification as per the AASHTO classification system (AASHTO, M 145) and index properties and particle size distribution are presented in Table 1. The soils were stabilised with different stabiliser ratios, as follows: 2%CC, 4%CC, 2%CC+1.5%LC and 4%CC+1.5%LC respectively (CC: cement content and LC: lime content). All the stabilised soil samples were cured for 7 days in a moist cabinet at 100% humidity and a temperature of 21°± 2°.

Table 1 Properties of the three subgrade soils

<table>
<thead>
<tr>
<th>Property and test type</th>
<th>A-4</th>
<th>A-6</th>
<th>A-7-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sieve 5.00 mm</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Sieve 3.35 mm</td>
<td>100.00</td>
<td>91.41</td>
<td>98.97</td>
</tr>
<tr>
<td>Sieve 2.00 mm</td>
<td>100.00</td>
<td>82.00</td>
<td>98.00</td>
</tr>
<tr>
<td>Sieve 1.18 mm</td>
<td>99.95</td>
<td>76.45</td>
<td>97.49</td>
</tr>
<tr>
<td>Sieve 0.600 mm</td>
<td>89.66</td>
<td>71.56</td>
<td>96.79</td>
</tr>
<tr>
<td>Sieve 0.425 mm</td>
<td>85.45</td>
<td>69.81</td>
<td>96.74</td>
</tr>
<tr>
<td>Sieve 0.300 mm</td>
<td>81.59</td>
<td>68.20</td>
<td>96.53</td>
</tr>
<tr>
<td>Sieve 0.212 mm</td>
<td>79.30</td>
<td>67.23</td>
<td>96.35</td>
</tr>
<tr>
<td>Sieve 0.150 mm</td>
<td>77.07</td>
<td>66.18</td>
<td>96.01</td>
</tr>
<tr>
<td>Sieve 0.075 mm</td>
<td>69.27</td>
<td>61.64</td>
<td>93.79</td>
</tr>
<tr>
<td>Maximum dry density (gm/cm³)</td>
<td>1.913</td>
<td>1.889</td>
<td>1.485</td>
</tr>
<tr>
<td>Optimum moisture content (%)</td>
<td>10.3</td>
<td>11.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>21.0</td>
<td>35.0</td>
<td>51.0</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>6.0</td>
<td>14.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.72</td>
<td>2.71</td>
<td>2.64</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>16</td>
<td>26</td>
<td>52</td>
</tr>
<tr>
<td>Silt content (%)</td>
<td>50</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>Sand content (%)</td>
<td>34</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>Fine gravel content (%)</td>
<td>0</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

Experiments were carried out using the samples to: (i) derive a durability equation based on the resilient modulus and deterioration behaviour of the materials, (ii) develop two equations relating the resilient modulus and unconfined compressive strength (UCS) and, (iii) validate the equations derived in (i) and (ii).

The resilient modulus values of stabilised and unstabilised soils were determined using two procedures. The first method followed the AASHTO T307 procedure (AASHTO, 2006) in which, resilient modulus values of combinations of five deviatoric stress and three confining pressures were determined (i.e. 15 combinations). The five deviatoric stresses used were; 12.4, 24.8, 37.3, 49.7 and 62.0 kPa respectively and the three confining pressures were; 41.4,
27.6 and 13.8 kPa respectively. In the second procedure the resilient modulus values were determined from single and multi-stage permanent deformation tests in which the resilient and permanent strains were separated. The resilient and permanent strains were used to determine the resilient modulus and cumulative permanent deformation respectively. The multi-stage permanent deformation tests consisted of five stages of 10,000 cycles at five deviatoric stresses of 12.4, 24.8, 37.3, 49.7 and 62.0 kPa respectively. The same confining pressure of 27.6 kPa was used for all stages. In the single stage test the materials were subjected to 50,000 cycles, a deviatoric stress of 62.0 and 120.0 kPa and a confining pressure of 27.6 and 12.4 kPa, respectively. Resilient modulus values in the second procedure were determined from the average of the final five cycles of each stage; i.e. after 10,000 cycles for the multi-stage and 50,000 cycles for the single stage tests, these values were used for road pavement design purposes.

Samples of 100 mm by 200 mm were prepared for the resilient modulus and permanent deformation tests, whilst for the unconfined compressive strength test samples were prepared to dimensions of 50 mm by 100 mm. The maximum dry density and optimum moisture contents of the samples were determined using Proctor tests. For unstabilised and stabilised soils the procedures given in BS 1377-4: 1990 section 3, Methods of test for soils for civil engineering purposes part 4: Compaction-related tests and BS 1924-2: 1990 section 2, Stabilised materials for civil engineering purposes part 2: Methods of test for cement-stabilised and lime-stabilised materials, were followed. All samples were compacted at 95% of maximum dry density and at 100% optimum moisture content, see Table 2.

Table 2 Moisture-Density relation for the three soils

<table>
<thead>
<tr>
<th>Soil type</th>
<th>MDD (gm/cm³)</th>
<th>OMC (%)</th>
<th>Standard used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstabilised</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>1.913</td>
<td>10.3</td>
<td>BS1377-4:1990</td>
</tr>
<tr>
<td>A-6</td>
<td>1.889</td>
<td>11.0</td>
<td>Section 3</td>
</tr>
<tr>
<td>A-7-5</td>
<td>1.485</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td>Stabilised 2%CC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>1.853</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>A-6</td>
<td>1.862</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>A-7-5</td>
<td>1.48</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>Stabilised 4%CC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>1.847</td>
<td>13.2</td>
<td>BS1924-2:1990</td>
</tr>
<tr>
<td>A-6</td>
<td>1.845</td>
<td>13.5</td>
<td>Section 2</td>
</tr>
<tr>
<td>A-7-5</td>
<td>1.465</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>Stabilised 2%CC+1.5%LC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>1.845</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>A-6</td>
<td>1.847</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>A-7-5</td>
<td>1.472</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Stabilised 4%CC+1.5%LC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>1.838</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>A-6</td>
<td>1.842</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>A-7-5</td>
<td>1.463</td>
<td>24.5</td>
<td></td>
</tr>
</tbody>
</table>
In order to simulate the effect of weathering the materials were subjected to cycles of wetting and drying according to ASTM designation D559, Standard test methods for wetting and drying compacted soil-cement mixtures (ASTM, 2004). The procedure specified in D559 was modified with respect to the number of cycles of wetting and drying (25 cycle were used instead of 12) to represent 25 years of design life of the pavement. Following recommendations of Chittoori (2008), in order to replicate in-situ behaviour the samples were allowed to swell and shrink vertically and horizontally. The changes to the resilient modulus and permanent deformation were assessed instead of the soil-cement losses and moisture and volume changes.

3 DURABILITY EQUATION

The Mechanistic-Empirical Pavement Design Guide, MEPDG (2004) recommends a minimum unconfined compressive strength (UCS) of 1,724 kPa (250 psi) for stabilised sub-bases and subgrade soils for flexible pavements. However, it is preferable to use a mechanical property of the material such as resilient modulus instead.

The ratio of the resilient modulus of a particular soil stabilised with a given amount and type of stabiliser is subject to weathering, MrAWD, to the resilient modulus of the stabilised soil not subject to weathering, MrA, can be written as:

\[ F_A = \frac{M_{r, AWD}}{M_{r,A}} \]  \hspace{1cm} (1)

Where FA is the deterioration factors of the material A

Assuming that the ratios of the deterioration factors of the same soil, each with different amounts of the same stabiliser, is a function of the resilient modulus values of the two materials and can therefore be written as:

\[ \frac{F_A}{F_B} = \frac{M_{r, A}}{M_{r,B}} \]  \hspace{1cm} (2)

\[ F_B = \frac{M_{r, BWD}}{M_{r,B}} \]  \hspace{1cm} (3)

This (Equation 3) has the same meaning as equation (1) but for material B

Combining Equations 1, 2 and 3 and rearranging yields:

\[ M_{r, AWD} = M_{r, BWD} \times \left( \frac{M_{r,A}}{M_{r,B}} \right)^2 \]  \hspace{1cm} (4)

Accordingly using Equation 4, the resilient modulus of material A subject to weathering can be determined from the values of the resilient modulus of material A prior to weathering together with the resilient modulus of material B both before and after weathering.

The significance of equation 4 is that, by knowing the weathered resilient modulus of a soil with one stabiliser content and type, the weathered resilient modulus values for a range of stabiliser ratios and types can be predicted without carrying out the respective laboratory tests.

To validate the equation the results of resilient modulus and permanent deformation tests were used carried out on three soils at four different stabilisation ratios before and after
cycles of wetting and drying, see Tables 3, 4, 5 and 6. Figure 1 compares the measured values of resilient modulus versus those predicted using Equation 4. From Figure 1 it may be seen that there is a close agreement between the measured and predicted resilient modulus values with associated coefficient of significance ($R^2$) value of 0.77. Therefore, the equation can be used straightforwardly to determine the deteriorated resilient modulus value or any other properties of lightly stabilised subgrade soils, as demonstrated in the pavement design example shown below.

Table 3 Resilient modulus for stabilised soil and corresponding values after wetting and drying for soil A-4

<table>
<thead>
<tr>
<th>Stress (kPa)</th>
<th>2% CCT $Mr$ (Mpa)</th>
<th>2% CCWD $Mr$ (Mpa)</th>
<th>4% CCT $Mr$ (Mpa)</th>
<th>4% CCWD $Mr$ (Mpa)</th>
<th>2% CC+1.5% LC $Mr$ (Mpa)</th>
<th>2% CC+1.5% LCWD $Mr$ (Mpa)</th>
<th>4% CC+1.5% LC $Mr$ (Mpa)</th>
<th>4% CC+1.5% LCWD $Mr$ (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>131</td>
<td>70</td>
<td>168</td>
<td>128</td>
<td>105</td>
<td>73</td>
<td>129</td>
<td>117</td>
</tr>
<tr>
<td>24.8</td>
<td>160</td>
<td>80</td>
<td>194</td>
<td>143</td>
<td>129</td>
<td>89</td>
<td>165</td>
<td>137</td>
</tr>
<tr>
<td>37.3</td>
<td>185</td>
<td>90</td>
<td>214</td>
<td>159</td>
<td>152</td>
<td>103</td>
<td>195</td>
<td>151</td>
</tr>
<tr>
<td>49.7</td>
<td>206</td>
<td>101</td>
<td>235</td>
<td>180</td>
<td>176</td>
<td>117</td>
<td>223</td>
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<td>62</td>
<td>224</td>
<td>112</td>
<td>255</td>
<td>201</td>
<td>198</td>
<td>131</td>
<td>250</td>
<td>182</td>
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<tr>
<td>120</td>
<td>282</td>
<td>160</td>
<td>328</td>
<td>292</td>
<td>295</td>
<td>194</td>
<td>352</td>
<td>255</td>
</tr>
</tbody>
</table>

Table 4 Measured resilient modulus from tests to predicted from equation (4) resilient modulus values for soil A-4

<table>
<thead>
<tr>
<th>Stress (kPa)</th>
<th>2% CC Measured $Mr$ (Mpa)</th>
<th>2% CC Predicted $Mr$ (Mpa)</th>
<th>4% CC Measured $Mr$ (Mpa)</th>
<th>4% CC Predicted $Mr$ (Mpa)</th>
<th>Control Measured $Mr$ (Mpa)</th>
<th>Control Predicted $Mr$ (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>70</td>
<td>47</td>
<td>128</td>
<td>186</td>
<td>73</td>
<td>117</td>
</tr>
<tr>
<td>24.8</td>
<td>80</td>
<td>58</td>
<td>143</td>
<td>201</td>
<td>89</td>
<td>137</td>
</tr>
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<td>37.3</td>
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<td>159</td>
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<td>101</td>
<td>85</td>
<td>180</td>
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<td>218</td>
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<td>182</td>
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<td>120.0</td>
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<td>212</td>
<td>292</td>
<td>238</td>
<td>194</td>
<td>255</td>
</tr>
</tbody>
</table>

Table 5 Resilient modulus for stabilised soil and corresponding values after wetting and drying for soil A-6

<table>
<thead>
<tr>
<th>Stress (kPa)</th>
<th>2% CC $Mr$ (Mpa)</th>
<th>4% CC $Mr$ (Mpa)</th>
<th>4% CCWD $Mr$ (Mpa)</th>
<th>2% CC+1.5% LC $Mr$ (Mpa)</th>
<th>2% CC+1.5% LCWD $Mr$ (Mpa)</th>
<th>4% CC+1.5% LC $Mr$ (Mpa)</th>
<th>4% CC+1.5% LCWD $Mr$ (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>136</td>
<td>116</td>
<td>90</td>
<td>110</td>
<td>76</td>
<td>115</td>
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<td>24.8</td>
<td>156</td>
<td>146</td>
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<td>129</td>
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<td>37.3</td>
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<td>309</td>
<td>221</td>
<td>228</td>
<td>167</td>
<td>279</td>
<td>243</td>
</tr>
</tbody>
</table>
Table 6 Measured resilient modulus from tests to predicted from equation (4) resilient modulus values for soil A-6

<table>
<thead>
<tr>
<th>Deviatoric Stress (kPa)</th>
<th>Predicted</th>
<th>Measured</th>
<th>Predicted</th>
<th>Control</th>
<th>Measured</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>119</td>
<td>90</td>
<td>86</td>
<td>76</td>
<td>95</td>
<td>84</td>
</tr>
<tr>
<td>24.8</td>
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<td>103</td>
<td>109</td>
<td>86</td>
<td>112</td>
<td>113</td>
</tr>
<tr>
<td>37.3</td>
<td>133</td>
<td>117</td>
<td>134</td>
<td>95</td>
<td>128</td>
<td>132</td>
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<tr>
<td>49.7</td>
<td>142</td>
<td>117</td>
<td>134</td>
<td>95</td>
<td>128</td>
<td>132</td>
</tr>
<tr>
<td>62</td>
<td>153</td>
<td>149</td>
<td>183</td>
<td>115</td>
<td>164</td>
<td>170</td>
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<tr>
<td>120</td>
<td>198</td>
<td>221</td>
<td>307</td>
<td>167</td>
<td>243</td>
<td>249</td>
</tr>
</tbody>
</table>

Figure 1 Relationship between resilient modulus measured from tests and predicted from Equation 4

4 RESILIENT MODULUS NONLINEARITY

Generally the response of subgrade soils and granular materials to an applied load is dependent on the stress state to which the soil is subjected (Huang, 2004). This can be seen clearly from Figures 2 and 3 for soils A-4, A-6 and A-7-5 which show the resilient modulus values of stabilised and unstabilised subgrade soils as a function of the number of load cycles from multi-stage permanent deformation tests (the stress levels for each stage are presented...
on the figures). Figure 4 shows the permanent deformation test from which these resilient modulus values are determined.

These Figures also show that an increase in deviatoric stress results in an increase in the resilient modulus values of stabilised subgrade soils, and generally the stress decreases with depth of the pavement. Therefore, the resilient modulus of the stabilised subgrade layer can be considered to behave nonlinear especially, when the material has been lightly stabilised.

Figure 2 Resilient modulus values vs. number of load repetitions for different deviatoric stress levels for unstabilised soils
To account for this nonlinear behaviour a number of authors have suggested various models which relate the resilient modulus to the stress state, a useful summary of which is given by Puppala (2008). The so called k-θ model (Equation 7) is widely used to replicate the behaviour of granular materials and a bilinear equation (Equation 8) to replicate the behaviour of fine grained materials.

\[ Mr = K_1 \theta^{K_2} \]  \hspace{1cm} (7)
Where: $M_r$ is resilient modulus, $\theta$ is bulk stress or invariant stress; $\theta = \sigma_1 + \sigma_2 + \sigma_3$ or $\theta = \sigma_x + \sigma_y + \gamma z(1 + 2K_o)$ if the normal stresses and surcharge is considered in which $\gamma$ is average unit weight, $z$ is the depth and $K_o$ is the coefficient of earth pressure.

$$M_r = K_1 + K_3(K_2 - \sigma_d) \quad (8a)$$

$$M_r = K_1 - K_4(\sigma_d - K_2) \quad (8b)$$

Where $\sigma_d$ is the deviatoric stress $= \sigma_1 - \sigma_3$ and $K_1$, $K_2$, $K_3$ and $K_4$ are material constants.

The universal model proposed by Witczak and Uzan (1988) (Equation 9) for subgrade and unbound material includes the octahedral shear stress ($\tau_{oct}$) and bulk stress ($\theta$) to account for the influence of a combination of stresses.

$$M_r = k_1 \frac{\theta}{P_a} (\frac{\tau_{oct}}{P_a})^{k_2} \quad (9)$$

Where $M_r$ is resilient modulus, $P_a$ is the atmospheric pressure for the location of the project, $\theta$ is bulk stress $= \sigma_1 + \sigma_2 + \sigma_3$, $\tau_{oct}$ is octahedral shear stress $= \sqrt{\frac{2}{3}} (\sigma_1 - \sigma_3)$ for $\sigma_2 = \sigma_3$ and $K_1$, $K_2$, $K_3$ are regression parameters.

MEPDG (2004) proposes the use of the relationship given in equation 10 in which the parameters $K_1$, $K_2$ and $K_3$ are determined from regression analysis of resilient modulus tests carried out in the laboratory.

$$M_r = k_1 \frac{\theta}{P_a} (\frac{\tau_{oct}}{P_a} + 1)^{k_3} \quad (10)$$

Herein two relationships were derived (Equations 11 and 12) to take into account findings from the literature, i.e. that resilient modulus is a function of the deviatoric stress. The two developed equations are for stabilised (modified, lightly stabilised) subgrade soils. From the two correlation equations it is possible to find resilient modulus values for a range of stress levels from UCS test results without carrying out the resilient modulus test. The first equation is as follows:

$$M_r = UCS^{a + b\sigma_d} \quad (11)$$

Where $a$ and $b$ are regression parameters.

In the second equation the bulk stress and octahedral shear stress were also introduced as suggested by Witczak and Uzan (1988), as follows:

$$M_r = UCS^{[a(\frac{\theta}{\sigma_{atm}}) + b(\frac{\tau_{oct}}{\sigma_{atm}})]^c} \quad (12)$$

In which $\theta$ = bulk stress $= \sigma_1 + 2\sigma_3$, $\tau_{oct}$ = octahedral shear stress $= (\sqrt{2/3}) (\sigma_1 - \sigma_3)$, $\sigma_{atm}$ = atmospheric pressure $= 101$ kPa and $a$, $b$ and $c$ are regression parameters.

The resilient modulus and UCS values given in Tables 3-6 and 7, respectively were used to determine the parameters $a$, $b$ and $c$ and to validate the models given in equations 11 and 12. For this purpose soil samples stabilised with 2%CC+1.5%LC and 4%CC+1.5%LC were used to determine the regression parameters, and samples stabilised with 2%CC and 4%CC were used for validation. From the analysis values of $a$ and $b$ were found to be 0.737 and 0.001
with an $R^2 = 0.791$ for the model given in equation 11 and $a = 0.882$, $b = 0.017$ and $c = 0.066$ with an $R^2 = 0.833$ for equation 12. The resilient modulus values obtained from the tests for soils A-4 and A-6 with 2%CC and 4%CC were compared with those found from equations 11 and 12 and plotted in Figures 5 and 6. The corresponding $R^2$ are 0.733 and 0.821, respectively.

From the above, it may be seen that the relationships described by Equations 11 and 12 appear to predict the resilient modulus with satisfactory accuracy and they provide conservative values of resilient module for design purposes.

Little and Yusuf (2001) used an equation (13), first proposed by Thompson (1970), for lime stabilised soils in mechanistic empirical pavement design procedures.

$$E_R = 0.124\ (UCS) + 9.8$$

(13)

Where $E_R$ is resilient modulus in Ksi and UCS is unconfined compressive strength in Psi.

For soils, A-4, A-6 and A-7-5 a comparison was made between the resilient modulus predicated for each soil using Equations 11 and 13 together with those determined from the laboratory results described above. The results can be seen in Table A.1. A statistical measure of the similarity, the Mean Absolute Percentage Error, MAPE (Hyndman and Koehler, 2006) was used to compare the resilient modulus values obtained from the laboratory and from the two equations. The MAPE when using equation 11 is 19, while for equation 13 it is 25. This suggests that equation 11 predicts the value of resilient modulus more closely than equation 13.

### Table 7 Unconfined compressive strength results after 7 days curing

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Stabiliser content (%)</th>
<th>UCS* (kPa)</th>
<th>Soil Type</th>
<th>Stabiliser content (%)</th>
<th>UCS (kPa)</th>
<th>Soil Type</th>
<th>Stabiliser content (%)</th>
<th>UCS (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstabilised</td>
<td>197</td>
<td></td>
<td>Unstabilised</td>
<td>178</td>
<td></td>
<td>Unstabilised</td>
<td>171</td>
<td></td>
</tr>
<tr>
<td>2%CC</td>
<td>580</td>
<td>579</td>
<td>2%CC</td>
<td>275</td>
<td>2%CC</td>
<td>2%CC</td>
<td>956</td>
<td>956</td>
</tr>
<tr>
<td>4%CC</td>
<td>956</td>
<td>874</td>
<td>4%CC</td>
<td>357</td>
<td>4%CC</td>
<td>4%CC</td>
<td>618</td>
<td>618</td>
</tr>
<tr>
<td>A-4</td>
<td>4%CC+ 1.5%LC 618</td>
<td>557</td>
<td>A-6</td>
<td>2%CC+ 1.5%LC 557</td>
<td>4%CC+</td>
<td>A-7-5</td>
<td>4%CC+ 1.5%LC 501</td>
<td></td>
</tr>
<tr>
<td>4%CC+ 1.5%LC 955</td>
<td>774</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*the average of four replicate samples
Figure 5 Measured resilient modulus from tests versus predicted resilient modulus from Equation 11

Figure 6 Measured resilient modulus from tests versus predicted resilient modulus from Equation 12
5 PAVEMENT SECTION ANALYSIS

A hypothesised pavement section and a finite element model (FEM) developed by Rasul et al. (2015) were used to determine the compressive strain at the top of the subgrade in order to determine the best of the three soil types for use in an untreated form and when stabilised with 2%CC, 4%CC, 2%+1.5%LC and 4%CC+1.5%LC, respectively. The FEM was characterised according to Table 9 and a pressure of 550 kPa and a loading area of 152 mm was applied to simulate a wheel load. The example takes into account the deterioration of resilient modulus with time using a performance model developed by Rasul et al. (2015).

Following a process suggested by Huang (2004), among others, an iterative method was developed to determine appropriate modulus values to be used within the FEM. For each analysis, an initial seed value of the resilient modulus was obtained from the relationship between deviatoric stress and resilient modulus values obtained from multi-stage permanent deformation tests. The seed value was used within the FEM to determine the resulting deviatoric stresses at the critical locations of interest. An iterative process thereafter was followed by which the computed deviatoric stresses were used to determine a new resilient modulus value from the results of the laboratory tests. This process was repeated until the computed resilient modulus value and that determined from the laboratory between two iterations converged. Subsequently the resilient modulus values so computed were used for the 30 analysis scenarios described in Table 14 and the compressive strains were calculated at the top of the subgrade.

As mentioned previously, the performance criterion chosen in this research for the modified soils was the compressive strain at the top of the subgrade. Therefore the selection of the stabiliser type and design was taken on the basis of the compressive strain value. However, the variability of subgrade soil type and property encountered in a project makes it problematic to select different stabilisers for different soil types. For example soil A-4 in this research can be stabilised with 4% cement with a degree of certainty for long term performance where the change in compressive strain after 25 cycles of wetting and drying is from 326 micro-strains to 388 micro-strains. In contrast under similar conditions the compressive strain for soil A-7-5 varies between 541 micro-strains and 839 micro-strains. However, any increase in cement stabiliser content for improving soil A-7-5 for its long term performance may affect the performance of the soil A-4, as the increase in amount of stabiliser may introduce other issues such as reflective cracking that can occur with excessive stabiliser content (Paige-Green, 2008). Therefore the most appropriate choice from this range of stabiliser contents for the three soils could be considered to be stabilisation with 4% cement content plus 1.5% lime content.

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Thickness (mm)</th>
<th>Modulus of elasticity (MPa)</th>
<th>Poisson’s ratio</th>
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</thead>
<tbody>
<tr>
<td>Asphalt concrete</td>
<td>100</td>
<td>3000</td>
<td>0.3</td>
</tr>
<tr>
<td>Base course</td>
<td>200</td>
<td>300</td>
<td>0.35</td>
</tr>
<tr>
<td>Compacted subgrade</td>
<td>200</td>
<td>Variable</td>
<td>0.45</td>
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<tr>
<td>Natural subgrade</td>
<td></td>
<td>Variable</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Table 9 Determination of resilient modulus, compressive stress and compressive strain for the pavement section and stabiliser selection

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Stabiliser ratio</th>
<th>Start Mr (Mpa)</th>
<th>End compressive stress (kPa)</th>
<th>End Mr (Mpa)</th>
<th>Compressive strain (µ strain)</th>
<th>End compressive stress (kPa)</th>
<th>End Mr (Mpa)</th>
<th>Compressive strain (µ strain)</th>
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<td>39</td>
<td>110</td>
<td>346</td>
<td>78</td>
<td>130</td>
<td>579</td>
</tr>
<tr>
<td></td>
<td>Untreated (WD)</td>
<td>77</td>
<td>38</td>
<td>100</td>
<td>363</td>
<td>70</td>
<td>90</td>
<td>706</td>
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<tr>
<td></td>
<td>2%CC</td>
<td>282</td>
<td>43</td>
<td>150</td>
<td>277</td>
<td>97</td>
<td>260</td>
<td>365</td>
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<tr>
<td></td>
<td>2%CC (WD)</td>
<td>160</td>
<td>38</td>
<td>100</td>
<td>367</td>
<td>75</td>
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<td>4%CC</td>
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<td>4%CC (WD)</td>
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<td>99</td>
<td>349</td>
<td>88</td>
<td>240</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>2%CC+1.5%LC</td>
<td>295</td>
<td>43</td>
<td>150</td>
<td>276</td>
<td>96</td>
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<td>376</td>
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<td>352</td>
<td>42</td>
<td>150</td>
<td>270</td>
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<td>312</td>
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<td>669</td>
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<td>513</td>
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<tr>
<td></td>
<td>4%CC</td>
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<td>35</td>
<td>100</td>
<td>342</td>
<td>90</td>
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<td>365</td>
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<tr>
<td></td>
<td>4%CC (WD)</td>
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<td>50</td>
<td>499</td>
<td>72</td>
<td>180</td>
<td>485</td>
</tr>
<tr>
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<td>36</td>
<td>100</td>
<td>357</td>
<td>84</td>
<td>192</td>
<td>449</td>
</tr>
<tr>
<td></td>
<td>2%CC+1.5%LC (WD)</td>
<td>167</td>
<td>27</td>
<td>50</td>
<td>535</td>
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<td>110</td>
<td>647</td>
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<td>35</td>
<td>100</td>
<td>347</td>
<td>88</td>
<td>240</td>
<td>388</td>
</tr>
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<td>50</td>
<td>490</td>
<td>72</td>
<td>177</td>
<td>501</td>
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<td>541</td>
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<td>46</td>
<td>68</td>
<td>839</td>
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<td>2%CC+1.5%LC</td>
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<td>70</td>
<td>437</td>
<td>75</td>
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<td>516</td>
</tr>
<tr>
<td></td>
<td>2%CC+1.5%LC (WD)</td>
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<td>26</td>
<td>707</td>
<td>52</td>
<td>92</td>
<td>730</td>
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<td>70</td>
<td>430</td>
<td>77</td>
<td>180</td>
<td>478</td>
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<tr>
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<td>26</td>
<td>713</td>
<td>54</td>
<td>106</td>
<td>685</td>
</tr>
</tbody>
</table>

* denotes for Wetting/Drying
6 PROGRESSIVE DETERIORATION OF RESILIENT MODULUS

Conventional analytical pavement design procedures use the same resilient modulus value of stabilised layers throughout the design life, while the deterioration of the asphalt is accounted for in the design by selecting appropriate resilient modulus values from the laboratory (MEPDG, 2004). The cumulative traffic load to which the road pavement is to be subject (i.e. the design traffic load) is typically based on current traffic loads plus an increment to account for future traffic growth. However, the deterioration of resilient modulus of the stabilised layers and unbound materials are not usually considered.

This deterioration process is illustrated in Figure 7 in the pavement design example which shows how the resilient modulus value of soil changes with cycles of wetting and drying. To account for this behaviour Rasul et al. (2015) proposed a model given by equation 14 which can be used to determine incremental plastic strains as a function of the change in resilient modulus which may be expected seasonally and throughout the life of a road pavement.

\[
\sum_{t=1}^{m} \varepsilon_p = a \times \left( \frac{\sigma_{dt}}{M_{rt}} \right) \times N_t^b
\]

\[
\sum_t t = T
\]

Where: \( \varepsilon_p \) is accumulated permanent strain in micro strain
\( \sigma_{dt} \) is deviatoric stress in kPa during a period of time \( t \)
\( M_{rt} \) is resilient modulus in MPa for a period of time \( t \)
\( N_t \) is the number of load repetitions in the period of time \( t \),
\( a \) and \( b \) are material parameters
\( T \) is the design life of the road pavement

7 PAVEMENT DESIGN EXAMPLE

To illustrate the use of the relationships described above, a hypothetical road pavement section with the dimensions, properties and design parameters shown in Table 10 was used. The design process may be considered as a number of steps as follows:

Step 1:

Using equation 11, the resilient modulus values of the stabilised subgrade soil determined from known UCS values at a variety of deviatoric stresses (see Table 11).
Table 10 Pavement section dimensions and properties

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Stabilisation ratio and type</th>
<th>UCS* (kPa)</th>
<th>UCS** (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>A-7-5</td>
<td>2% CC</td>
<td>275.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4% CC</td>
<td>357.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2% CC + 1.5% LC</td>
<td>427.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4% CC + 1.5% LC</td>
<td>501.0</td>
</tr>
</tbody>
</table>

Pavement section

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Thickness (mm)</th>
<th>Resilient modulus (MPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt concrete</td>
<td>100</td>
<td>2500</td>
<td>0.3</td>
</tr>
<tr>
<td>Base course</td>
<td>150</td>
<td>300</td>
<td>0.35</td>
</tr>
<tr>
<td>Compacted subgrade</td>
<td>150</td>
<td>Variable</td>
<td>0.35</td>
</tr>
<tr>
<td>Natural subgrade</td>
<td>-</td>
<td>47</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Traffic Data

| Traffic load for the base year | 300000 Heavy Trucks |
| Tyre pressure                  | 860 kPa             |
| Loading radius area            | 152 mm              |
| Truck growth factor            | 4%                  |

* Stabilised soil before the durability test
** Stabilised soils after the durability test

Table 11 Resilient modulus values for a range of deviatoric stresses from UCS test results

<table>
<thead>
<tr>
<th>Deviatoric Stress (kPa)</th>
<th>4%CC+1.5%LC</th>
<th>4%CC+1.5%LC (WD)</th>
<th>2%CC+1.5%LC</th>
<th>4%CC</th>
<th>2%CC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UCS (kPa)</td>
<td>Mr (Mpa)</td>
<td>UCS (kPa)</td>
<td>Mr (Mpa)</td>
<td>UCS (kPa)</td>
</tr>
<tr>
<td>12.4</td>
<td>106</td>
<td>81</td>
<td>94</td>
<td>82</td>
<td>67</td>
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<tr>
<td>24.8</td>
<td>114</td>
<td>87</td>
<td>101</td>
<td>88</td>
<td>72</td>
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<td>37.3</td>
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<td>109</td>
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<td>49.7</td>
<td>501</td>
<td>133</td>
<td>100</td>
<td>117</td>
<td>102</td>
</tr>
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<td>126</td>
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<td>120.0</td>
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<td>339</td>
<td>242</td>
<td>292</td>
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<td>193</td>
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</table>

Step 2:

From equation 4 the deteriorated (WD) resilient modulus values for soil A-7-5 stabilised with 2%CC+1.5%LC, 4%CC and 2%CC are determined from the known deteriorated resilient modulus value of stabilised soil with 4%CC+1.5%LC. To account for the deterioration in resilient modulus over the life of the pavement, the analysis is divided into a number of stages (increments). For the purposes of this example five stages have used, each of which represents five years of analysis (i.e. 1/5th of the design life). Thereafter the deteriorated...
resilient modulus for each year is calculated using an Annual Deterioration Factor (ADF) which was determined as follows:

$$ADF = \frac{Mr \text{ before durability test} - Mr \text{ after durability test}}{NDC}$$  \hspace{1cm} (15)$$

Using equation 15 the resilient modulus of the specified stage was determined as function of deviatoric stress. Table 12 gives the results obtained for soil A-7-5 at 2%CC. Figure 7 plots resilient modulus values, for each of these stages.

Table 12 Deteriorated resilient modulus for five stages for soil A-7-5 stabilised with 2%CC

<table>
<thead>
<tr>
<th>Deviatoric Stress (kPa)</th>
<th>Mr Before W&amp;D (MPa)</th>
<th>Mr After WD (MPa)</th>
<th>ADF after 5 year (MPa)</th>
<th>Mr after 10 year (MPa)</th>
<th>Mr after 15 year (MPa)</th>
<th>Mr after 20 year (MPa)</th>
<th>Mr after 25 year (MPa)</th>
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<tr>
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<td>4.58</td>
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<td>102</td>
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Figure 7 Iteration analysis of resilient modulus and deviatoric stress convergence for soil A-7-5 stabilised with 2%CC and for five stages of 5 years each
Step 3:

Step 3 incorporates the iterative procedure described above in which a seed resilient modulus value is chosen and used within the FEM to determine a corresponding computed deviatoric stress at the top of the subgrade. The laboratory determined resilient modulus value corresponding to the computed deviatoric stress is then used again within the FEM to obtain a new deviatoric stress. This process is iterated until the difference between resilient modulus values between successive iterations is within an acceptable limit. This process is shown graphically in Figure 7 for soil A-7-5. So obtained values of resilient modulus and deviatoric stress are later used in the performance model (Equation 14) to determine the incremental accumulation of permanent deformation.

Step 4:

Step 4 involves the determination of the model parameters. For soil A-7-5 the parameters $a$ and $b$ of the performance model (Equation 14) were found from regression analysis to be $a = 2205.015$ and $b = 0.038$

**Results**

Table 13 shows the results of the pavement section analysis presented above for subgrade soil A-7-5 stabilised with four different stabiliser ratios.

Typically in analytical design procedures it is usual to specify the amount of permanent deformation which occurs in all layers of the pavement structure (including the subgrade). The procedure described here, since it enables the amount of deformation within a stabilised layer to be predicted as a function of stabiliser content, allows the designer to specify the contribution to total deformation to be made by the stabilised subgrade layer (see Table 13) This can enable the designer to trade off lower material performance in the upper layers of the road pavement against the amount of stabilisation required in the subgrade. With reference to the results given in Table 13, should it be decided that the subgrade is to contribute 2mm of deformation throughout the design life, then subgrades of material of type A-7-5 should be lightly stabilised using 2%CC+1.5%LC. On the other hand if it was felt that the subgrade should contribute more to the overall deformation (perhaps because of a lack of more durable materials for the upper layers) then A-7-5 stabilised using 2%CC could be used.
Table 13 Pavement section analysis for stabilised subgrade soil with 2%CC, 4%CC, 2%CC+1.5%LC and 4%CC+1.5%LC, respectively

<table>
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<tr>
<th>Parameter</th>
<th>A-7-5_2%CC</th>
<th>A-7-5_4%CC</th>
<th>A-7-5_2%CC+1.5%LC</th>
<th>A-7-5_4%CC+1.5%LC</th>
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<td>Increment 3</td>
<td>Increment 4</td>
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<td>-461</td>
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<td>-474</td>
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<td>81</td>
<td>80</td>
<td>79</td>
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<td>60</td>
<td>60</td>
<td>60</td>
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<td>1237</td>
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<td>Growth rate (%)</td>
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<td>4</td>
<td>4</td>
<td>4</td>
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<td>Years of the stage (years)</td>
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<td>10</td>
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<td>20</td>
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<tr>
<td>Number of heavy trucks in the base year</td>
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<td>300000</td>
<td>300000</td>
<td>300000</td>
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<tr>
<td>Growth factor</td>
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<td>12.006</td>
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<td>1,976,935</td>
<td>2,405,244</td>
<td>2,926,347</td>
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<tr>
<td>Accumulated number of heavy trucks for the stage parameter (b)</td>
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<td>2205.015</td>
<td>2205.015</td>
<td>2205.015</td>
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<tr>
<td>Permanent strain MDL3 (mm)</td>
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<td>0.516</td>
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<td>0.687</td>
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<td>Total permanent deformation (mm)</td>
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<td>Resilient modulus MDL3 (Mpa)</td>
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<td>92</td>
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<td>-454</td>
<td>-460</td>
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<td>Vertical stress MDL3 (kPa)</td>
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<td>59</td>
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<td>150</td>
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<tr>
<td>Total permanent deformation (mm)</td>
<td>1.63</td>
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</table>
8 CONCLUDING DISCUSSION

Stabilisation can improve the performance of the subgrade layers of road pavements. However, in order to account for such improvements in performance within analytical pavement design procedure there is a need for appropriate durability tests and the development of associated relationships to quantify likely in situ soil performance. This approach is lacking in current analytical design procedures and the research paper demonstrated for the first time a rigorous methodology which can be used to take into account the performance of stabilised subgrade layers. To effect this, a research programme marrying experimental, analytical and numerical work was undertaken to develop:

1. A novel relationship which can predict the deteriorated resilient modulus values for different stabiliser contents and types from a deteriorated resilient modulus value of one specified stabiliser content tested for durability.

2. Two correlation equations derived from permanent deformation and unconfined compressive strength tests. The equations predict with an adequate accuracy the resilient modulus from the unconfined compressive strength and the stress state, for three soil types at four different stabiliser contents. The correlation equations can be used to determine a set of resilient modulus values for a series of different stress states.

3. A procedure to take into account the nonlinearity of the stress dependency of the resilient modulus values of stabilised and unstabilised subgrade soils.

4. A performance model for stabilised subgrade soils which can predict with a satisfactory degree of accuracy the incremental accumulation of permanent deformation.

The above procedure was demonstrated within an analytical design procedure which incorporated a FEM. It was also shown how the amount of stabiliser could be varied to facilitate different design options. The results produced are transformative and demonstrate to the highway engineer for the first time the importance in analytical road pavement design of including suitably characterised values of resilient modulus which consider stress dependency and the effects of environmental deterioration.

9 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Kurdistan Regional Government (KRG) for generously funding this work and the Department of Civil Engineering at the University of Birmingham for the provision of laboratory facilities to enable the research.
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Appendix

A. 1 Comparison between the prediction capability of equation 11 & 13

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Stabilisation Ratio</th>
<th>Average UCS (kPa)</th>
<th>Deviatoric Stress (kPa)</th>
<th>Measured Mr (Mpa)</th>
<th>Predicted Mr (Mpa) eq.12</th>
<th>Predicted Mr (Mpa) eq.13</th>
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