Permanent Deformation Behaviour of Low Volume Roads in the Northern Periphery Areas

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ABSTRACT: Roadex II has been an EU financed research project concentrating on the maintenance of the low volume road network in the Northern parts of Finland, Sweden, Norway and Scotland. One of the aims in the Roadex II project has been to assess the permanent deformation behaviour of the low volume roads in these Northern periphery areas especially for the purposes of finding efficient and cost-effective means of maintaining the structural condition of the road network with as little disruption as possible to the vital heavy transports of the forest and fishing industries and agriculture. This paper presents a tentative approach for estimating the risk of permanent deformations in a low volume road and the need for weight restrictions especially during the thawing period of seasonal frost. The assessment is based on a monotonic and repeated load triaxial test series performed at the Tampere University of Technology in Finland and at the University of Nottingham in the UK. The results of these tests have been interpreted using a non-linear finite element analysis to compute the likely plastic strain in the pavement and, hence, the risk of rut development, and a simplified approach proposed for routine use.

KEY WORDS: Permanent deformation, rutting, low volume road, Northern Periphery, seasonal variation.

1 INTRODUCTION

In the Northern parts of the three Nordic countries of Finland, Sweden and Norway, the low volume road network plays a vital role in keeping these scarcely populated periphery areas inhabited. In addition to fulfilling the needs of the local permanent population a functional road network has a very important role in attracting tourists to these areas and in guaranteeing the possibilities for timely and all-year round transportation operations of the forest and fishing industries and agriculture. One initiative to meet the challenge of maintaining the condition of the low volume road network at an acceptable level, in spite of the reducing trend in funding, has been Roadex II, an EU financed research project concentrating on the maintenance of the low volume road network in the Northern periphery areas.

In addition to partners from the three Nordic countries the Roadex II project, has involved the Highlands and Western Isles regions of Scotland in the UK, all under the leadership of the

Highlands Council. Even though located in an area with milder climate, the problems and challenges in maintaining their low volume road network are, due to heavy rainfalls, analogous to ones prevailing in the Nordic countries.

2 CURRENT WEIGHT RESTRICTION POLICIES

One straightforward means of protecting low volume roads from excessive damage caused by permanent deformations is to set weight restrictions for a long enough time during the seasonal frost thawing period in the spring. On the other hand, minimization of the harmful effects of weight restrictions to the local heavy transport industry requires that the weight restrictions were set as late as possible and removed as early as possible. In practice, different policies to find the optimal balance between these two contradictory aims have been developed in different countries.

Among the countries regularly using temporary spring time weight restrictions are Finland, Sweden, Canada and a number of the Northern states of the USA. In Finland, for instance, the decisions on when and at which level the weight restrictions are set have, until now, been mostly based on local experience and judgement, which has resulted in fairly non-uniform policies between different road districts. Quite recently, however, the Finnish Road Administration has launched new guidelines on the use the weight restrictions (Saarenketo & Perälä, 2003). These new guidelines aim at more uniform rules on both setting and removing the weight restrictions. During the last five years the amount of weight restricted roads in Finland has been on an average 3000 to 4000 km per year, which corresponds to about 5 % of the length of the public road network.

In Sweden the weight restriction policy has been somewhat similar to Finland even though the share of the weight restricted roads in the Central and Northern parts of Sweden has normally been higher that in the respective road districts on the Finnish side. Both in Sweden and in Finland it is also possible to apply special traffic permits for especially important transports even during the restricted time. A clear exception among the Nordic countries is Norway in which spring time weight restrictions have been applied since 1995 only in some special cases. If that happens, information about the restricted area is efficiently transmitted via newspapers, television, radio and internet.

Both in the USA and Canada the weight restriction policies are non-uniform among the states and provinces (Kestler at al., 2000). In comparison to the Nordic countries a special feature in the Northern states of the USA is that most of the weight restricted roads are paved. The explanation for this is, however, that most of the gravel roads are owned by the cities, municipalities and private organisations that are thus also responsible for the weight restriction policy. In Canada a special feature concerning weight restrictions is that the allowable axle loads can not only be lower than the normal ones during thaw, but also higher during the winter time when the road is frozen.

All in all it can be concluded that management of the risk of permanent deformations due to the heavy traffic loads especially during the thawing period and also during rainy seasons is of vital importance. A better understanding on the mechanisms and factors influencing the development of permanent deformations in these extreme conditions is therefore required.

3 TEST MATERIALS AND METHODS

In connection with this research project, permanent deformation behaviour of a number of different types of unbound low volume road pavement materials were tested using a simple-to-perform Tube Suction test (Scullion & Saarenketo, 1997) and repeated load triaxial tests performed using equipments available at the Tampere University of Technology (TUT) in

Finland (Kolisoja, 1997) and at the University of Nottingham (UoN) in the UK (Brown et al., 1989). Together, the data covers a wide range of geological origins, grain size, stone quality, shape, etc. The majority of materials from which the conclusions of this paper derive have a crushed rock origin, but some sand and gravel type aggregate has also been studied. Table 1 summarizes the main properties of the aggregate types mostly used in the subsequent interpretation and analysis. One of these aggregates was moderate quality metamorphic aggregate from Scotland - known as "Quarriebraes" aggregate, after its source. The other two aggregates were taken from the site of the environmental pavement condition station ('Percostation') at Koskenkyla near to the town of Rovaniemi in Northern Finland. From that site the base course material was crushed rock while the subbase material was gravel.

Table 1: Aggregate results used in the following interpretation and analysis.

Material Description	**Code**	**Moisture Content** (%)	**Fines Content** (%)
Quarriebraes Dry	Qa	3.5	5.12
Quarriebraes Wet	Qb	7.8	3.53
Quarriebraes Saturated, High Fines	Qc	11.0	8.24
Koskenkyla Base, Dry	Ka	1.6	13.3
Koskenkyla Base, Wet	Kb	5.2	13.3
Koskenkyla Base, After Thaw	Kc	8.8	13.3
Koskenkyla Subbase, Dry	Kd	2.0	19.1
Koskenkyla Subbase, Wet	Ke	5.1	19.1
Koskenkyla Subbase, After Thaw	Kf	9.7	19.1

Most of the repeated load triaxial tests at TUT were performed according to a test procedure specifically developed to simulate the effects of seasonal variations including drying and wetting of the test specimen and a freeze-thaw cycle (Kolisoja at al., 2002). In addition, a number of both multi-stage monotonic and repeated load triaxial tests were performed. The applied permanent deformation tests procedures consisted of 5 000 to 10 000 load cycles at a number of different combinations of cyclic deviator stress. An example of the test results obtained in at UoN using cyclic deviator stress and a confining pressure decremented every 5 000 cycles is given in Figure 1 (Dawson & Kolisoja, 2004). Figure 2 shows the stress paths typically applied in terms of q and p which are, respectively, the 'deviatoric' (i.e. shear) stress and the average stress (=1/3rd of $\theta = \sigma_1+2\sigma_3$)..

4 INTERPRETATION

Plastic axial strain development such as those shown in Figure 3 (in which the strain under each successive stress path, SP, is shown relative to the strain state of the specimen at the beginning of the application of that stress path) was interpreted as a strain rate (i.e. incremental plastic strain per cycle of loading). As Figure 3 shows, once the initial settling of the specimen has been achieved (SP1 and SP2), those stress paths which get closest to failure – Numbers 3, 6 and 9 (Figure 2) – give rise to the highest amount of plastic strain, followed by Paths 5, 8 and 15, followed by 12. This sequence confirms that proximity to static failure is a key feature in the development of plastic strain and, thus, to the occurrence of rutting. Thus results, such as that given in Figure 4, are obtained showing that the plastic strain rate can, to some degree, be viewed as a function of proximity to static failure.

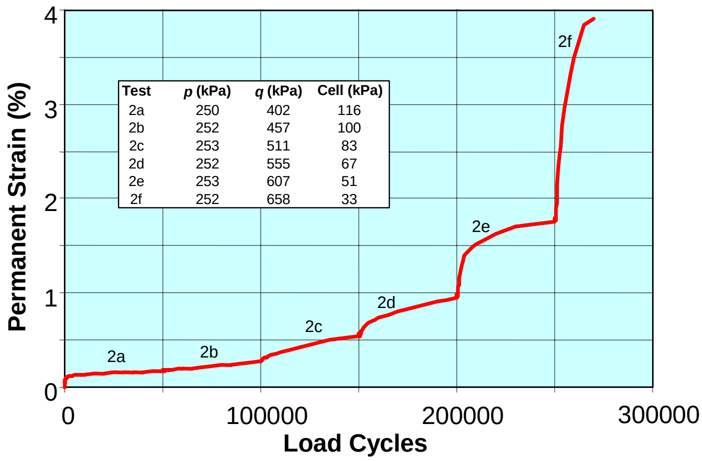

Figure 1: Cumulative plastic deformation (strain) under a series of increasing axial load pulses and decreasing confining pressures, 5000 load cycles applied at each stress state.

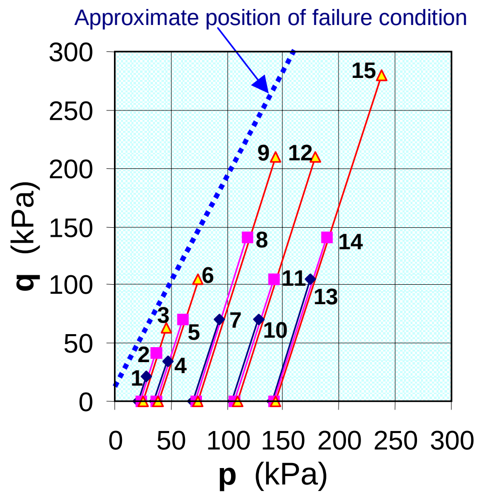

Figure 2: Stress paths used for data presented in Figure 3.

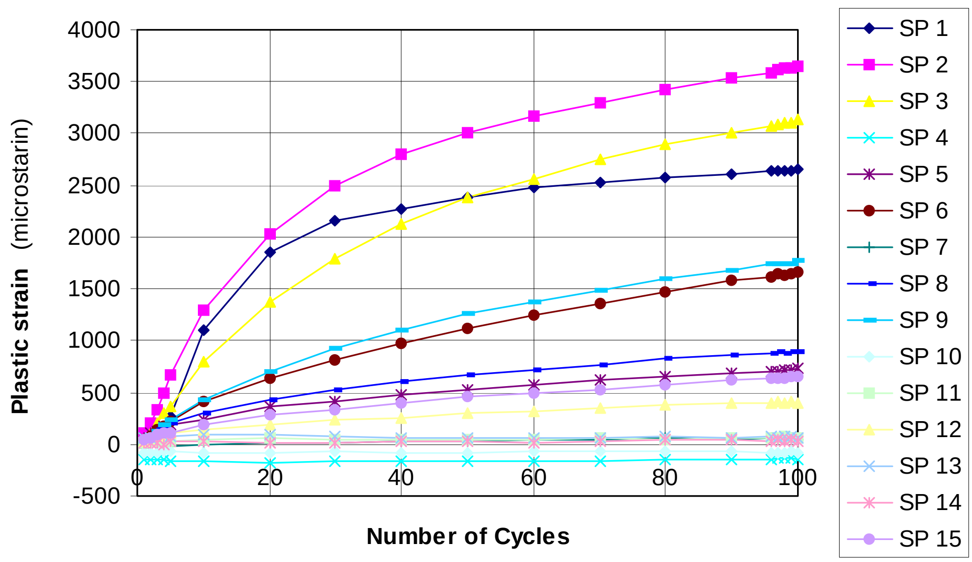

Figure 3: Development of Plastic Strain in a specimen of the Koskenkylä base aggregate after thawing (Material Kc). 15 stress paths (SPs) have been applied, each of 100 pulses.

It is also evident (although space does not permit all results to be illustrated) that the amount of plastic strain (and the rate of plastic strain development) in an aggregate increases

- When the aggregate gets wetter.
- When the aggregate has been frozen and then is thawed.
- When the stress applied gets closer to the static failure stress condition.

Further details of test results are available in Kolisoja et al. (2002) and Dawson and Kolisoja (2004).

The loss of quality upon freezing appears to be mostly due to increased water content caused by suctions developed during freezing and only a little by de-densification due to ice formation. Thus, if both the freezing layer is non frost-susceptible, and the layer beneath is also non frost-susceptible, then little reduction in performance should be expected in the pavement.

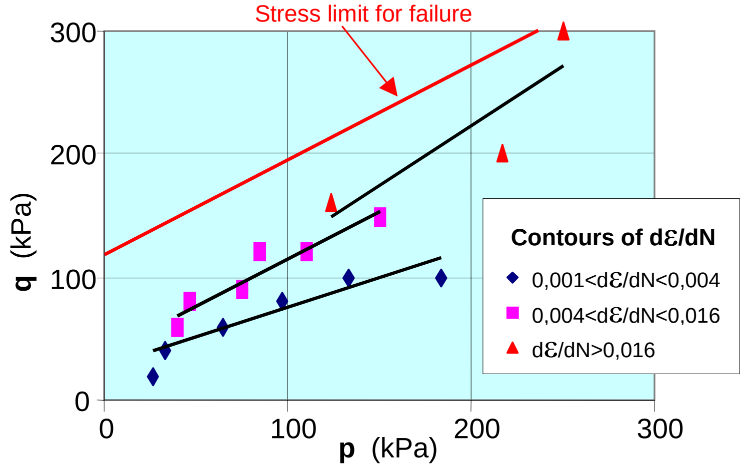

Figure 4: Plastic strain rate information obtained from test on Quarriebraes Qc material (saturated, high fines).

It is not clear from the testing whether the fines always have a direct effect on increasing plastic strain (though sometimes they do), but they certainly have a secondary effect, allowing the aggregate to hold more water. This ability to hold water, due to capillary suction, is undesirably exploited on freezing because cryo-suction effects, which act at the freezing front, are able to pull in more and more water, if it is available at the edge or bottom of an aggregate layer.

Therefore, for design purposes, taking into account the various findings given above, it would be sensible to ensure that the stress experienced by the pavement doesn't exceed a certain fraction of the failure stress. Previous researchers (Brown & Dawson, 1992) have suggested a ratio of q/qf =0.7 – i.e. the deviatoric (or shear) stress applied, q, is limited to 70% of that needed to induce static failure, qf, under, in other respects, the same conditions. The data obtained here suggests that this may, indeed, be a sensible determination. However, the materials tested in this project suggest that this limit should be set at 50-55% of the failure condition (for the same aggregate tested without freeze-thaw) when the aggregate is very wet and fines prevent rapid drainage, or during spring thaw conditions, if the amount of rutting is to be kept small.

5 ANALYSIS

A finite element analysis of typical northern pavement constructions was then performed using a non-linear axi-symmetric finite element routine known as FENLAP (d'Almeida, 1996). For computational reasons the programme requires an asphalt surface, so the analyses were performed with asphalt thicknesses varying from 1mm to 200mm. Only the results from the thinner asphalt pavements, typical of low-volume roads, are discussed in the subsequent text. A typical mesh used for the analysis is shown in Figure 5.

The asphalt and subgrade materials were allotted typical, constant, stiffness properties. In the case of the asphalt this was a stiffness modulus of 1.5 GPa and a Poisson's ratio of 0.45. For the subgrade the values were 40MPa and 0.45 respectively. In the aggregate layer, the stress-dependent modulus model developed specifically at the Technical University of Dresden for modelling unbound granular materials (Gleitz & Wellner, 1998), was implemented. The loading used was a circular plate of diameter 33.4cm with a tyre pressure of 650kPa.

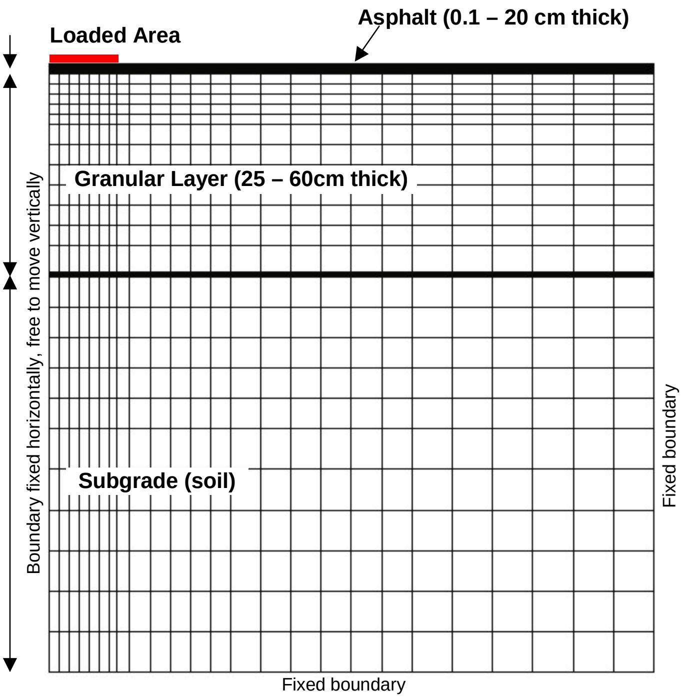

Figure 5: Typical finite element mesh used for the pavement analyses.

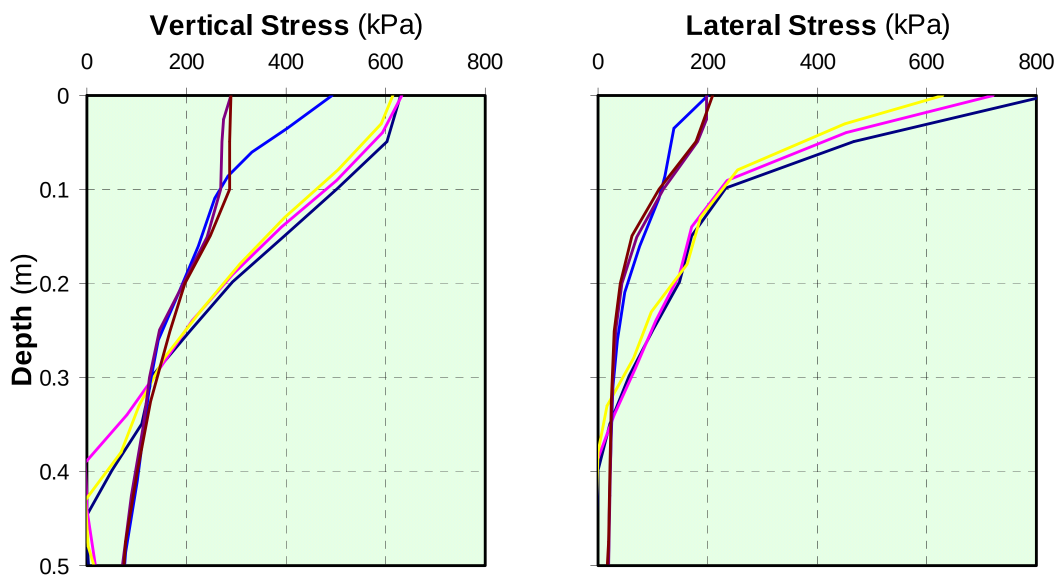

Figure 6: Variation of vertical and horizontal stress in the granular layer of pavements with various thicknesses of asphalt. Aggregate is Scottish Quarriebraes material in ‘saturated’, high fines condition (Qc).

Figure 6 shows the vertical and horizontal stresses in pavements containing the ‘saturated’ (moisture content is 11%) high fines Quarriebraes aggregate base in their granular layers. The rapid diminution of vertical stress [that reduces from the tyre pressure valve of 650 kPa and that leads to a consequential reduction in the horizontal stress] is evident. Note also how the increase of the asphalt above 4 cm thickness significantly reduces the vertical stress – because it is then that the asphalt begins to act as a beam in bending taking a far greater role in load spreading than it did when thinner. Thus this analysis shows that there is a threshold thickness (between 2 and 4 cm in this case) required if the asphalt is to achieve effective load spreading and significantly reduce stress on the lower aggregate base layers.

The computed mean normal stresses, p, in the aggregate layer can be quite a lot higher than those obtained from the laboratory testing (compare Figure 7 with Figure 4). Only in the thinnest pavements are the highest values of p and, hence of modulus, Mr, discovered. From such analyses stress loci can be plotted for the aggregate finite elements directly under the wheel load (e.g. Figure 7). N.B. Static failure as defined from laboratory testing (see Fig 4) is also plotted. The stresses get closest to the static failure line at a depth of 10cm or 15cm into the pavement (around 9 and 14cm respectively into the aggregate). It is this stress condition that the designer needs to keep away from the failure line in order to reduce the onset of rutting within the aggregate layer. This might be achieved by moving the failure line (e.g. by improving the granular material by, for example, drainage) or by placing more asphalt to move the aggregate stress condition lower.

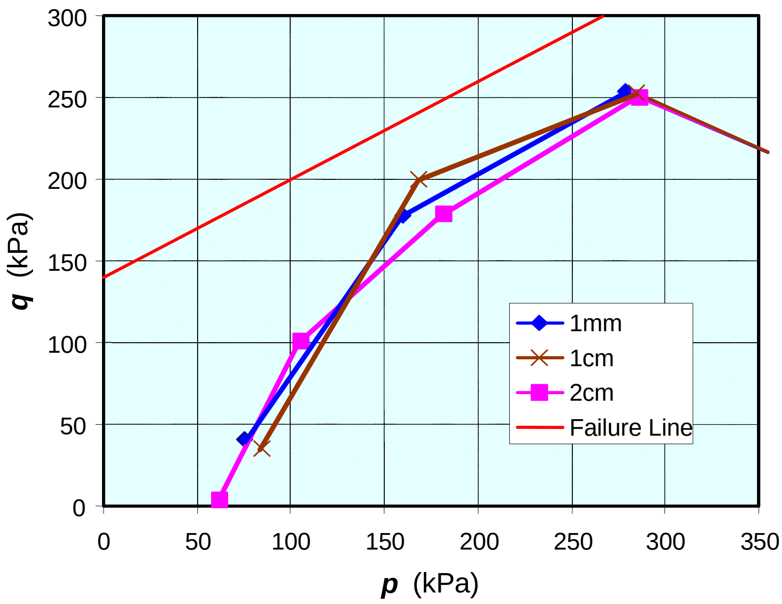

Figure 7: Stress condition at depths of 10, 12.5, 15, 20 and 25cm beneath the top of the asphalt. [Asphalt is 1mm, 1cm or 2cm thick as shown, so depth into aggregate varies with asphalt thickness. Stress at shallowest point on right, deepest point to left]. Data is for the Quarriebraes saturated high fines mix. (Compare with Figure 4).

Such a figure may now be related to the permanent deformation contour plot presented earlier as Fig 4. This provides a means of predicting whether an element of the aggregate will undergo rutting and, if so, the rate of straining which could be expected. This doesn't provide a direct estimation of rutting, but does provide a qualitative comparison of high and low rutting rates.

Previous researchers (Dawson & Brown, 1992) and observations made at a site comprising the Quarriebraes material (Killer et al., 2004) suggest that at a well-drained site q/qfailure should be limited to 70-80% of the static failure value of the same material to prevent rutting. From the test work summarised here, this is coincident with a strain rate contour of approximately 100 µ(/cycle. This contour is at about 50-55% of the well-drained static failure envelope when the aggregate is very wet due to rain, or when it is suffering the consequences of spring thaw.

Thus the basis of an analytical design procedure to prevent rutting in the aggregate layers of unsealed or chip-sealed low volume roads in cold and/or wet climates has been established as follows:

a) Define static failure strength of an aggregate in a well-drained condition
b) Relate permanent deformation rate as a function of stress state to this static, well drained condition for the moisture condition of interest
c) Select a deformation rate which is qualitatively appropriate given the trafficking expected (higher trafficking, lower strain rate)
d) Hence obtain an allowable stress state
e) Perform a finite element analysis for different pavement designs, finding one in which the aggregate under consideration is never stressed beyond the allowable level.

6 APPLICATION

In practice, for low-volume pavements, triaxial testing (especially to determine permanent deformation characteristics) and finite element analyses are not viable. The complexity, expense and technical competency levels available in conventional low-volume road teams, prevent its application and implementation.

Accordingly the authors propose a much simplified approach which builds on the above concepts but which is more practical for real use:-

i) Define static strength, probably using a simple in-situ device such as the Dynamic Core Penetrometer.
ii) Assume the allowable stress states to prevent significant rutting for all low-volume pavements is 70% of the failure strength when the material is well drained or 55% when it is wet or recently thawed.
iii) Estimate peak stress states in a pavement using Boussinesq's stress analysis.
iv) Check that the computed stress does not exceed the allowable one.
v) If it does, replace, improve, or lower the point of application, of the aggregate.

This simplified approach, at step iii, ignores multi-layer pavements (a semi-infinite, unsealed, aggregate is assumed) and ignores stiffness stress-dependency, so is quite a coarse approximation. However, it does allow a simplified approach, as the Boussinesq equation may be solved and presented graphically.

Rutting in the subgrade must also be considered. For unsealed roads, rutting in the aggregate is much more easy to address (by regrading or regravelling), and therefore to be preferred, than subgrade rutting. For chip-sealed pavements aggregate rutting is still to be preferred to subgrade rutting on the basis of easier maintenance, even if the differential is not as great as for unsealed surfaces.

Accordingly, to preclude subgrade rutting, the authors have adopted the approach of Brown and Dawson (1992) and require that the maximum vertical stress permitted on the surface of the subgrade is twice the undrained soil strength. To achieve this, subgrade strength may, again, be assessed by in-situ testing. Then the imposed stress will need computing. No simple means of doing this has been identified so resort is made to linear elastic theory as contained in many available computer programmes. In the absence of any better information the stiffness ratio between aggregate and subgrade can be assumed to be the same as the strength ratio (absolute stiffness values not being necessary to compute stresses). Thus the stress pattern at the top of the subgrade may be computed and compared with the allowable values.

If this subgrade stress computation method is adopted, a slightly more sophisticated means of calculating stresses in the aggregate is then available than as mentioned at (iii) above.

7 REFERENCES

Almeida, J.R. de, "Development and validation of a finite element code for pavement analysis", in *Flexible Pavements*, ed. A Gomes Correia, Balkema, 1996.

Brown, S.F. & Dawson A.R., "*Two-stage approach to asphalt pavement design*", Proc. 7th Int. Conf. on Asphalt Pavements, Nottingham, June 1992, Vol 1 pp 16-34

Brown, S.F., O'Reilly M.P. & Pappin J.W., "Repeated load triaxial apparatus for granular materials", in *Unbound Aggregates in Roads*, ed. Jones R H & Dawson A R, Butterworths, London, 1989, pp 143-158.

Dawson, A. & Kolisoja, P. 2004. *ROADEX II Final report, Part 2.1, "Permanent deformation"*. To be published in April 2005.

Gleitz, T. & Wellner, F., "*Investigations of the elastic and plastic deformation behaviour of unbound road construction material*", Straße + Autobahn, May, 1998, pp245-253. (In German).

Kestler, M.A., Knight, T. & Krat, A.S., "*Thaw weakening and load restriction practices on low volume roads*". Cold Regions Reserach and Engineering Laboratory. Technical Report ERDC/CRREL TR-00-6, 2000.

Killer, D., Paxton, S. & Dawson A., "*Engineering and legislative options for improved timber haulage in Scottish forests - an inclusive stakeholder approach*", Jnl. Transportation Research Board, No. 1819, 2003, Vol. 1, pp109-117

Kolisoja, P., "*Resilient deformation characteristics of granular materials*". PhD thesis, Tampere University of Technology, publication number 223, 1997, 216 p.

Kolisoja, P., Saarenketo, T. Peltoniemi, H. & Vuorimies, N., 2002. "*Laboratory testing of suction and deformation properties of base course aggregates*". Transportation Research Record, Vol. 1787, pp. 83 – 89.

Saarenketo, T. & Perälä. M., "*Harmonization of load restrictions for frost-thaw damage*". Report of the Finnish Road Administartion 56/2003, Helsinki, 2003, 60 p. (In Finnish)

Scullion, T. & Saarenketo, T., "*Using suction and dielectric measurements as performance indicators for aggregate base materials*". Transportation Research Record 1577, TRB, National Research Council, Washigton, D.C., 1997, pp. 37- 44.