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Speed and reloading effects on pavement rutting

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This paper concentrates on two factors that affect the permanent deformation (rutting) of unbound pavement layers. These factors are the loading speed and stress history. The loading speed has a simultaneous two-way effect: the permanent response of the unbound material itself, and the change in the stress state depending on the resilient properties of the upper-bound layers. The modelled examples show that the dominating factor in the speed effect is the change in stress state due to the change in the resilient properties of the bound layers, whereas the speed effects on the unbound material itself have a smaller role. In addition, the effect of loading speed depends greatly on the temperature, varying from 10–15% at 10°C to 20–25% at 25°C. The measured effects can be estimated reasonably well with modelling. Unloading–reloading cycles at various load levels have little effect on the permanent deformation. The effect is usually so small that it can be neglected in calculations, but the preloading history itself has a clear effect on the permanent deformation.

1. INTRODUCTION

The rutting of a pavement is a complex phenomenon, with many factors affecting the deformation response of the pavement. This study concentrates on two different factors: the effects of loading speed, and unloading–reloading. The general hypothesis of the loading speed effect is that loading speed does affect the response of bituminous layers, but not so much the responses of unbound layers. Yet there are only few studies that have dealt with this particular problem.

Bituminous materials are thermo-viscoplastic materials. So the loading speed and temperature have an effect on the stress and strain responses of the material. The effect can be taken into account in many material models. However, the effect of loading speed on unbound frictional materials is not a well-known phenomenon. There have been studies of speed effects on fine-graded granular materials under shear loading,[1] but only a few studies have dealt with the effect of loading speed during cyclic loading. Because the behaviour of granular materials is based mainly on their frictional properties, it is obvious that the time effect is smaller in frictional materials than in cohesive materials. The first objective of this study was to estimate the effect of loading speed on the permanent deformation, and to determine which factor (the viscoplastic behaviour of bituminous or unbound materials) dominates.

The second objective of the study was to determine whether the rutting calculations could be done by using one rutting model for all loading levels in spite of the real scatter in load levels. In other words, the objective was to see whether the responses of varied load types and load levels could be summed together using superposition.

2. LITERATURE REVIEW

The time effect depends greatly on the pavement structure (material, thickness, density etc.) and on the depth. The question of the time effect is important in cases where responses from accelerated pavement tests with slower testing speed are compared with those of the in situ pavements. Lekarp and Dawson[2] have collected some test results that show that loading duration and frequency have little or no significance for the resilient behaviour of granular materials. There are only a few studies or laboratory tests concerning the effect of loading duration and frequency on permanent deformation response. Cheung[3] has studied the effect of the loading waveform and frequency on permanent deformation in a couple of repeated loading tests. He found that, on average, a square waveform resulted in 10% greater permanent strains than sinusoidal or ramp waves. He also observed that a lower frequency (0·05 Hz) and thus a lower loading speed produced larger permanent deformations than higher frequencies (1 Hz). He asserted that the permanent deformation of granular materials was slightly dependent on the loading speed.

Lourens[4] has collected test data on the time effect from different accelerated pavement tests. He detected that with a loading speed of 12 km/h the deformation responses were about 27% greater than with a loading speed of 80 km/h. The results were based mainly on data from accelerated loading tests on bituminous materials with various loading speeds.

According to Chenevière *et al.*[5] the frequency of the loading pulse can be calculated from the loading speed using

$$f = 0{\cdot}46v \tag{1}$$

where f is the frequency in Hz, and v is the loading speed in km/h. So, if the loading speed is about 10 km/h the corresponding frequency is 4·6 Hz, and if the loading speed is

80 km/h the frequency is 36·8 Hz. The frequency normally used in resilient and permanent deformation tests varies from 1 to 10 Hz. Thus a frequency of 5 Hz compares to a loading speed of about 11 km/h.

3. METHODS AND LABORATORY TESTS

3.1. Accelerated loading tests at the Danish Road Institute

The Danish Road Institute has measured the dynamic responses of the subgrade at four loading speeds in its accelerated pavement tests.[6] The test construction and its results are described in a Danish Road Institute report.[7] Before the accelerated loading test itself, a couple of test measurements with varied loading speeds were made. The test speeds were 8, 10, 16 and 20 km/h, and the temperature of the tested structure was +25°C. In the tests the vertical stresses and strains were measured at three subgrade depths. Fig. 1 illustrates the tested structure and the locations of the deformation transducers. The earth pressure cells were situated at the same depths as the transducers.

3.2. Triaxial tests at VTT

The traditional way to run cyclic loading tests is to increase the loading after a specified number of loading cycles. In real pavement design the magnitude of the loading changes constantly, and is statistically distributed. There have been occasional instances where unloading–reloading in cyclic tests has been studied. In the 'Deformation' project, VTT (the Technical Research Centre of Finland) performed one repeated loading test on a crushed rock sample to study the effect of unloading–reloading behaviour. The test was performed according to the Strategic Highway Research Programme (SHRP) protocol,[8] and was a stepwise loading test. The tested material was crushed rock from the Helsinki region, with a maximum grain size of 32 mm.

In the first loading phase crushed rock was tested stepwise by increasing the load in 40 kPa steps (from 200 through 240 and 280 to 320 kPa). In the second loading phase (Fig. 2) the load was dropped back to 200 kPa and again increased in 40 kPa steps (240, 280 and 320 kPa). Every loading step consisted of 100 000 loading cycles. The confining cell pressure was 20 kPa during the test.

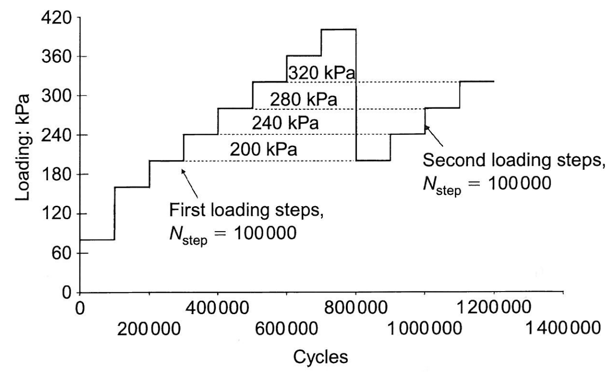

Fig. 2. Loading steps of σ_1 in VTT repeated loading test of crushed rock

3.3. Modelling calculations

The time effect was also studied through response calculations for the Danish accelerated loading test structure RTM2 and for the Finnish accelerated loading test structure of a low-volume road (HVS-SO). The objective was also to study the sensitivity of speed effect modelling for different structures and loading temperatures. The Finnish HVS test structure was chosen as a reference structure, because the test was conducted at a colder temperature of +10°C, and it had a thicker pavement. The Finnish accelerated loading test structure and its instrumentation are reported in a Finnish Road Administration report.[9] The resilient modulus of asphalt concrete in HVS tests has been measured in an HVS test series for a reinforced pavement structure.[10]

The calculations were conducted using two design programs: APAS and Plaxis. APAS is a multilayer program with a time-dependent material model for asphalt. APAS is used to define the changes in the resilient modulus of asphalt for temperatures of 10°C and 25°C and diverse loading speeds. Plaxis is a finite element code for soil and rock analyses. The Plaxis calculations were done with an elastic material model for asphalt, but its modulus was defined by APAS. The material behaviour of unbound materials was modelled by using the elasto-plastic material model of Mohr–Coulomb. Fig. 3 illustrates the changes in the resilient modulus of asphalt concrete at different temperatures and loading speeds according to the APAS material models and laboratory test results.

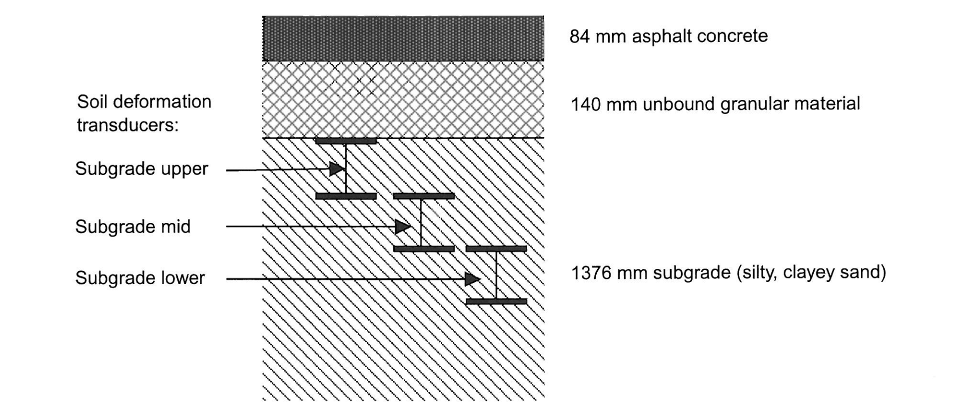

Fig. 1. RTM2 test construction and deformation transducers

4. RESULTS

4.1. Accelerated loading tests at the Danish Road Institute

The strain and stress measurements from RTM2 at the Danish Road Institute[11] are presented in Table 1 and Fig. 4. They show that the effect of speed decreases with depth. The change in strain response is slightly larger than the stress response (Fig. 5), yet is within the limit of measuring accuracy. The

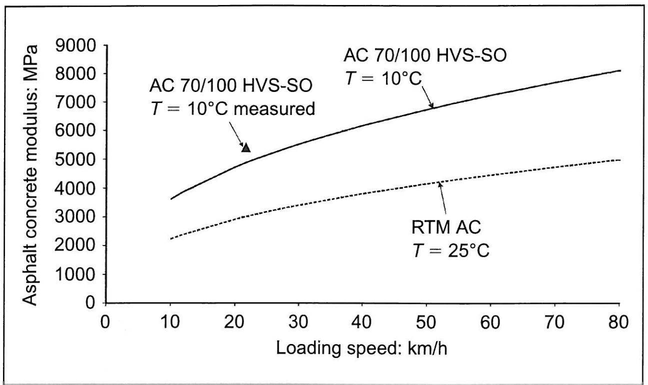

Fig. 3. Modulus of asphalt concrete in RTM2 and HVS-SO tests against loading speed according to material models in APAS compared with a laboratory test

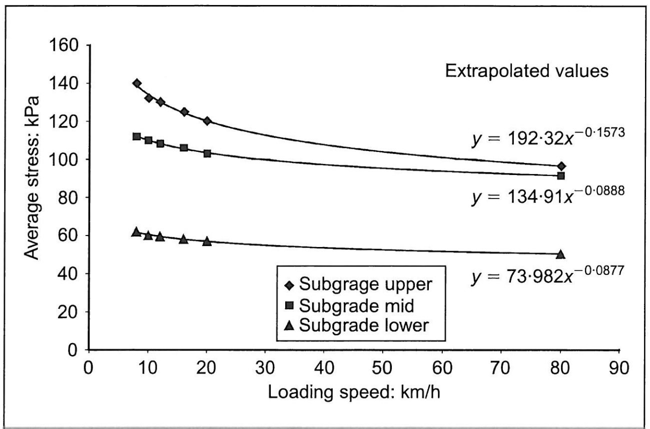

Fig. 4. Average vertical stresses and extrapolation at three subgrade levels[11]

loading speed results were extrapolated with a power function to estimate the effect at a loading speed of 80 km/h. Table 1 and Fig. 4 also include extrapolated values for a loading speed of 80 km/h and the average reduction ratio for permanent deformation, if the loading speed increased from 10 km/h to 80 km/h. The extrapolation was quite bold. However, the results are near the values that Lourens[4] has presented.

4.2. Triaxial test results from VTT

Figure 6 presents the vertical strains of the combined first and second loading phases. At each loading level a simple power function was fitted to the results of the first loading step. These fitted curves are also presented in Fig. 6. At the beginning of the second loading phase the measured strains were bigger than the fitted strains. However, the strains quickly reduced to a slightly lower level than the fitted curve would predict.

5. DISCUSSION

5.1. Speed effects on the permanent deformation

The speed of loading can affect the unbound layers in two ways:

(*a*) the changes in stress, which stem from changes in the bituminous overlay's modulus (thermo-viscoplastic material)

(*b*) the effects of loading speed itself on the plastic response of unbound material.

The basic hypothesis in pavement design is that the first factor has a bigger effect on response than the second one. The changes in the bituminous layer's modulus were evaluated by using the thermo-viscoplastic material models in APAS (Fig. 3).

The hydrostatic stress p' for both the RTM2 and HVS-SO structures was modelled with Plaxis with a varying asphalt concrete modulus to simulate different temperatures and loading speeds. The calculated results were changed to show how much larger (in percentage terms) the stress p' is if the loading speed is reduced from 80 km/h to 10 km/h. The calculated results, together with the extrapolated stresses and strains (Table 1), are displayed in Fig. 5. This figure demonstrates that the effect of loading speed is very sensitive to changes in temperature and also to the structure. If the asphalt is warmer and has a lower stiffness, as in RTM2, the reducing effect is much greater than in the colder structure of HVS-SO. While the increase of loading speed from 10 km/h to 80 km/h reduces the stress level by 5–25%, the permanent strains will probably decrease by at least the same amount because of a non-linear relationship between stress and permanent strain. The comparison between calculated and extrapolated reductions is reasonably close in the RTM2 tests for the upper layers, but diverges for the lower subgrade level.

5.2. Effect of unloading–reloading cycles and stress history

The VTT triaxial test results (Fig. 6) indicate that the permanent deformation of granular materials is dependent on the stress history. In other words, the response depends on the loading history and on the loading path. It is also important to notice that the strains normalise to the level of the first loading phase in the long term. Now it can be assumed that the same loading curve shape can be applied to the calculation of strains at one load level, even if the magnitude of loading in real structures changes all the time. Superposition will probably underestimate permanent deformation when the number of loading cycles is low, and overestimate it

Loading speed: km/h	Vertical stress/vertical strain: kPa/$\mu\varepsilon$		
	Subgrade upper 0–128 mm	Subgrade mid 128–280 mm	Subgrade lower 280–420 mm
8	140/2512	112/1762	62/1429
10	132/2418	110/1712	60/1393
16	125/2286	106/1634	58/1296
20	120/2165	103/1587	57/1245
80 (extrapolation)	97/1765	91/1363	50/1055
Reduction ratio 10–80 km/h	27%/25%	17%/19%	16%/20%

Table 1. Average stresses and resilient vertical strains in three subgrade parts[6,11]

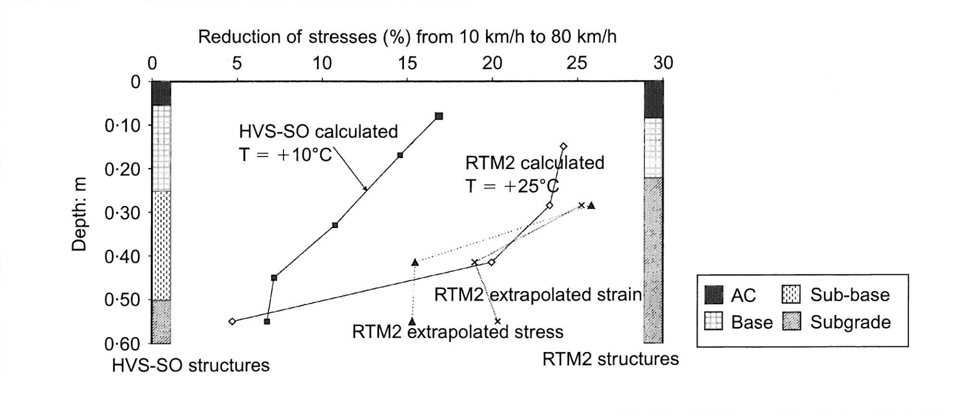

Fig. 5. Calculated theoretical reduction in stresses according to Plaxis when loading speed changes from 10 km/h to 80 km/h in HVS-SO and RTM2 tests, compared with extrapolated stress and vertical resilient strain reductions from RTM2 test

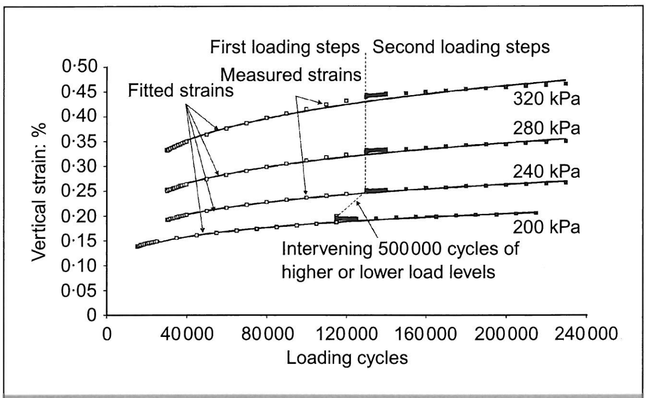

Fig. 6. VTT's repeated loading triaxial tests on crushed rock (measured and fitted strains in varied σ_1 levels)

when the number of cycles is high. This finding is very important for the development of calculation methods for rutting. It supports the assumption that rut depth calculations for different loads can be performed separately and then summed for each loading condition or loading period. Gidel *et al.*[12] and El Abd *et al.*[13] have also demonstrated that the superposition principle is valid and can be used in permanent deformation calculations.

6. CONCLUSIONS AND RECOMMENDATIONS

The effect of loading speed depends greatly on the structure and its temperature. According to the modelling and loading test results, decreasing the loading speed from 80 km/h to 12 km/h will increase the rutting of unbound layers in warm conditions (25°C) by about 20–25% and in colder conditions (10°C) by about 10–15%. According to the modelling calculations, the effect is stronger nearer to the road surface. Yet the measured effect is not so clearly dependent on depth. The speed effect also depends on the structure. The study demonstrates that the viscoplastic behaviour of bituminous materials is much more important for this loading speed effect than the viscoplastic behaviour of the unbound material itself.

The VTT triaxial test results prove that the permanent deformation of granular materials is dependent on the stress history. Yet the test results show that the superposition of individually calculated permanent deformations at separate loading levels can be used in calculation procedures relatively reliably. The calculation will probably underestimate the permanent deformation when the number of loading cycles is low, and overestimate it when the number of cycles is large.

The loading speed effect of viscoplastic bituminous materials is sufficiently marked that it should be taken into account when, for example, the results of slower accelerated loading tests are adjusted to a higher loading speed. One simple way to do this is by calculating the stress state at both loading speeds and estimating the effect on rutting and fatigue through the changes of the stress levels.

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