Laboratory testing of pavement structure by traffic load simulation

Essais en laboratoire de la structure de la chaussée par simulation de la charge de circulation

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ABSTRACT: The results of tests performed in the laboratory on a flexible pavement structure subjected to simulated traffic loadings are presented. The aim of these tests was to help in practical applications in road design, so that the actual in-situ stress conditions and road traffic loads had to be adequately simulated. A new testing device known as a Traffic Load Simulator (TLS) has been constructed at the Slovenian National Building and Civil Engineering Institute (ZAG) for this purpose. In contrast to other similar experimental research methods, the TLS introduces synchronized vertical and horizontal cyclic loads which take into the account the specific characteristics of traffic loading, resulting in vertical and horizontal normal stresses as well as non-zero shear stress values. The latter cause rotation of the principal stress axis, which typically occurs during traffic loadings. The impact of traffic loading upon the development of rutting in the pavement structure is also presented.

RÉSUMÉ : Les résultats d 'essais en laboratoire d' une structure de chaussée souple soumise au trafic sont présentés. Des essais ont été effectués en tenant compte des résultats pour des applications pratiques dans la conception de routes. Ainsi, les essais où les conditions de stress in situ et les charges de circulation routière sont simulées de manière adéquate étaient nécessaires. Un nouveau dispositif d'essai appelé Traffic Load Simulator (TLS) a été construit à cet effet à Slovenian National Building and Civil Engineering Institute (ZAG). Contrairement à d'autres recherches expérimentales similaires, TLS introduit une charge cyclique verticale et horizontale synchronisée pour prendre en compte les spécificités de la charge du trafic, ce qui entraîne des contraintes normales verticales et horizontales ainsi que des valeurs de contrainte de cisaillement non nulles. Ce dernier provoque la rotation de l'axe de contrainte principal, qui se produit typiquement pendant le chargement du trafic. L'impact de la charge du trafic sur le développement de l'orniérage est présenté dans cet article.

KEYWORDS: traffic loading, traffic load simulator, principal stress rotation, rutting

1 INTRODUCTION

One of the major characteristics of cyclic loadings such as traffic loadings is rotation of the principal stress axis. The direction of the principal stresses acting on a soil element rotates as the wheel load passes. It can be observed by changes in the sign and magnitude of the shear stress.

Loadings involving principal stress axis rotation include non-coaxial behaviour which affects the stress-strain response of soil. A significant deviation between the principal stress direction and the principal plastic strain rate direction has been observed during rotation of the principal stress axis (Airey and Wood 1987). As shown in Figure 1, this principal stress rotation causes additional compression - tension cycles, which result in an increase in the cumulative residual strain in the pavement's subgrade. This has been shown by laboratory element tests (Ishihara and Towhata 1983, Gräbe and Clayton 2009), model tests (Hirakawa et al. 2002, Momoya et al. 2005), and field tests (Yang et al. 2009). There have been also a few attempts to model this phenomenon (Gutierrez et al. 1993, Gutierrez et al. 2009), particularly with regard to the effect of principal stress rotation in the case of sands.

In general, experiments performed on clay (Zdravković and Jardine 2001, Albert et al. 2003, Lin and Penumadu 2005, Qinghui et al. 2016) and sand (Ishihara and Towhata 1983, Gutierrez et al. 1993) have shown the effect of principal stress rotation on material response. Soil subjected to cyclic loading under drained conditions exhibits an increase in the cumulative residual strain, whereasin the presence of pore water and under undrained conditions cyclic loading results in an excess pore water pressures. Such behaviour can be reproduced in laboratory soil tests, where the axes of the principal stress are varied, and the plastic strain is measured. Simple shear tests (Airey and Wood 1987, Gutierrez et al. 2009) and torsional hollow cylinder tests (Ishihara and Towhata 1983, Zdravković and Jardine 2001, Gräbe and Clayton 2009) permit a certain level of control of the rotation of the principal stress axes rotation, so that laboratory tests of this kind can be used for the fine-grained materials.

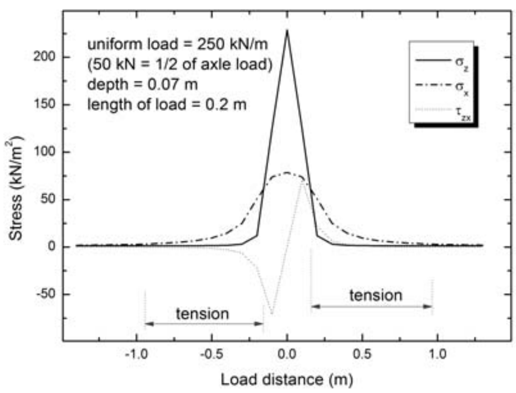

Figure 1. Typical stress distribution calculated in a pavement under a traffic load. The stress conditions were calculated using the theory of elasticity (Poulos and Davis 1974).

However, fewer attempts have been made to study the behaviour of coarse-grained granular materials exposed to principal stress rotation. The latter was also not attempted in the presented research, but it was the authors' goal to properly simulate the traffic loading as observed on a pavement structure where rotation of the principal stress axis is one of the major characteristics, as described above.

Some studies have indicated that design without considering the effect of principal stress rotation could be unsafe (Yang and Yu 2006, Qinghui et al. 2016). On the other hand, model tests with a moving wheel load (Momoya et al. 2005) are affected strongly by the scaling effect, whereas full-scale load tests (Tušar et al. 2011) are extremely expensive and time consuming.

Thus it was the aim of the presented work to develop a low-cost testing procedure for pavement structures to be tested in full-scale. The basic requirement of the testing procedure was to enable loading of the pavement structure similar to a real traffic loading, but without a moving wheel. The sample, i.e. pavement structure, to be tested is assumed to be up to 60 cm high, whereas subgrade conditions should be represented by adjustable boundary conditions (adjustable stiffness) at the bottom of the sample.

2 EXPERIMENTAL

2.1 *Experimental setup*

The basic idea of the device was to use the capability of a simple shear apparatus to apply the loading with controlled principal stress axes rotation. The simple shear apparatus is a conventional laboratory soil testing device. Lateral confinement of test specimen makes it possible to keep the cross-sectional area of the specimen constant, thus representing a K_0 stress state during the axial loading.

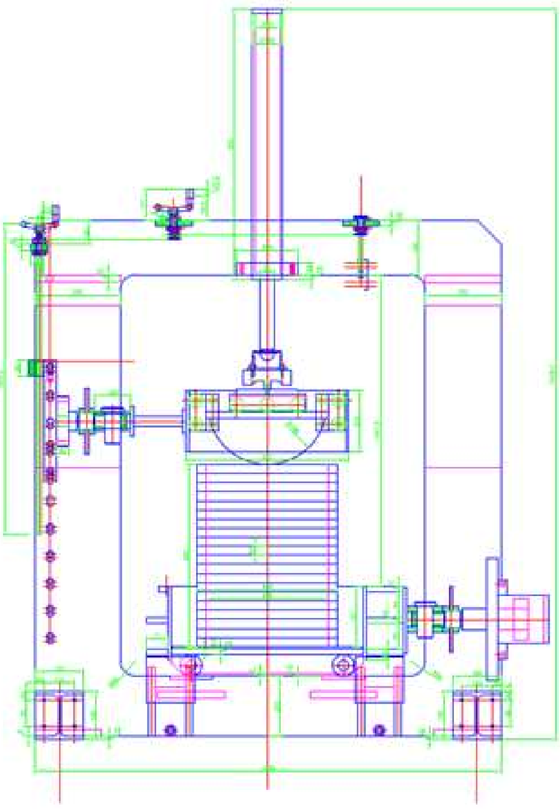

Figure 2. General arrangement of the testing device.

The lateral confinement device consists of 17 rigid aluminium frames each with a height of 3 cm, and internal plan dimensions of 40 cm x 40 cm (Figure 2). Test specimen is installed inside the confining frames with all layers of the structure, i.e. the unbound granular material and the asphalt layer. K_0 stress state should also correspond to the field conditions of the investigated road pavement.

A 5 cm thick layer of elastic foam was installed at the bottom of the specimen in order to simulate soft ground conditions. Elastic foam of different stiffnesses is commercially available, and can be used to simulate various ground conditions. This elastic bottom layer ensures equal and constant bottom boundary conditions, which are very important for replicability of the tests. Figure 3 shows the results of a plate loading test performed on the layer of elastic foam, which was used in the presented test. As can be seen, no permanent deformation developed during the cyclic loading of this material.

Free non-frictional movement of all the lateral confining frames was permitted in the horizontal direction, except the bottom frame which was loaded in the horizontal direction by the first of the hydraulic pistons. Axial load is applied to the specimen by means of a tyre which is fixed to the vertical hydraulic piston. The horizontal force is measured at the level of the upper aluminium frame, which is supported in the horizontal direction by the axially loaded tyre.

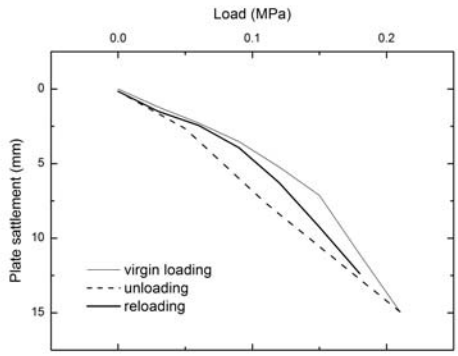

Figure 3. Plate loading tests of elastic foam installed as the bottom layer of the specimen.

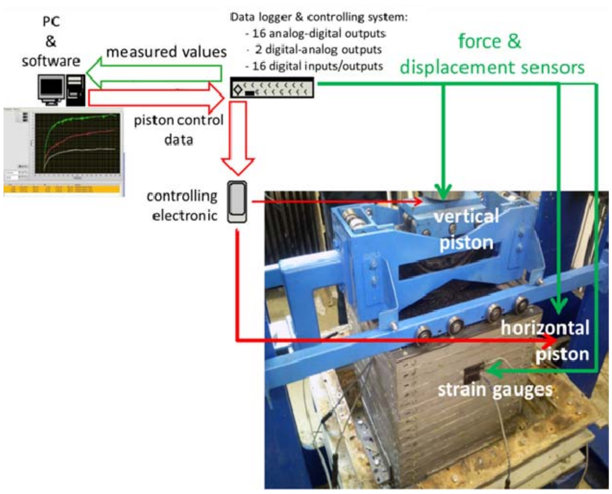

Figure 4. The computer-controlled experimental set-up.

The testing device, which is referred to as a "Traffic Load Simulator" (TLS) was built at the Slovenian National Building and Civil Engineering Institute (ZAG). The synchronized vertical and horizontal cyclic loadings which were applied by the two computer-controlled hydraulic pistons (Figure 4) simulate traffic load cycles following the stress path presented in Figure 1.

A disadvantage of this kind of loading is that the whole test specimen, i.e. the pavement structure, is loaded with the same stress, which is not actually the case in the field. In order to avoid underestimating the stress amplitudes, the shear stress τ_{zx} has been calculated from the proposed vertical load using the theory of elasticity (Poulos and Davis 1974) for the depth of the asphalt / unbound granular layer contact. Due to the fact that the pavement structure was horizontally supported by the tyre at the top of the specimen, the experimental set-up simulates the event of a vehicle braking rather than a vehicle passing. This means that the friction load at the surface layer is heavier, whereas the stress distribution inside the specimen is fairly constant.

The shear stress which has to be calculated for each selected depth (7 cm in the case of the presented experiment) was applied to the specimen via a horizontal piston which acted on the bottom frame. A uniform load and a uniform length of loading were selected taking into account the assumed tyre and axle load of the vehicle. A vertical load of 50 kN and a loading length 20 cm, which corresponds to a tyre with an outer diameter of 390 mm, were assumed. The normal stresses, σ_z and σ_x were applied directly by axial loading and the corresponding lateral confinement.

2 .2 *Materials*

The investigated pavement structure test specimen had a height of 51 cm, and consisted of 48 cm of an unbound bearing layer and a 3 cm thick surface asphalt layer. A 5 cm thick layer of elastic foam was installed at the bottom of the specimen (Figure 5). The granular gravel material for the unbound layer was manually compacted at a moisture content of 5.51% to a density of 2160 kg/m^3 (which is equal to 97% of the modified optimum Proctor test density). The asphalt layer consisted of an AC8 surf B50/70 A3 asphalt mix, was also manually compacted to a density of 2401 kg/m^3. A plate loading test which was performed on top of the unbound layer resulted in a deformation modulus E_{v2} equal to 172 MPa.

Table 1. Overview of the loading parameters for each test stage.

Stage	Number of load cycles	Loading amplitude [kPa] σ_z	Loading amplitude [kPa] τ_{zx}
1	1000	31.2	9.7
2	1000	62.5	19.5
3	4000	93.7	29.3
4	4000	125	39.0
5	1000	156	48.8
6	1000	187	58.6
7	1000	218.7	68.4

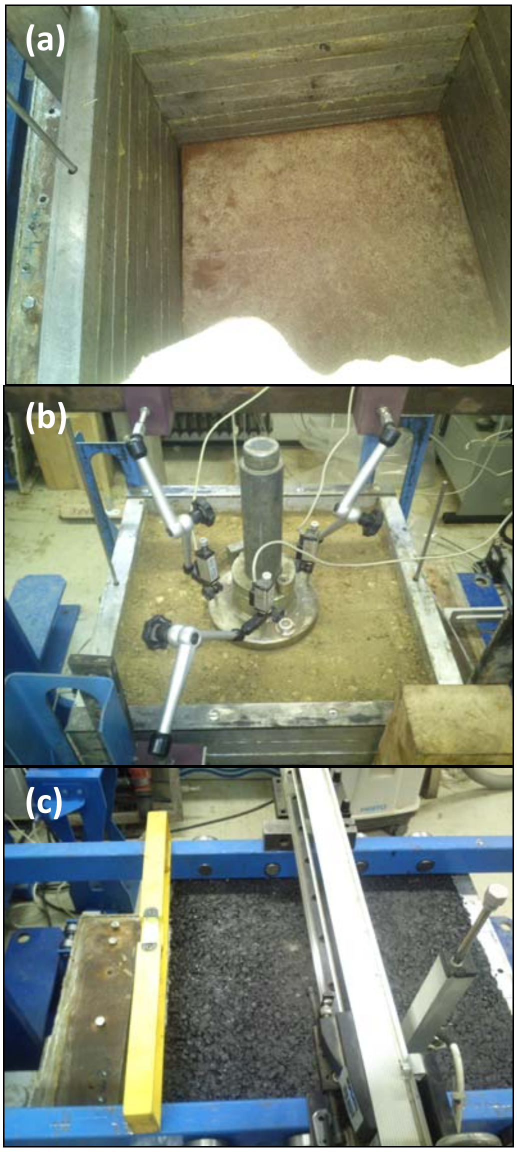

Figure 5. Three layers of the specimen during its preparation: (a) the elastic foam, (b) the unbound bearing layer during the plate loading test, and (c) profile measurements being performed on the surface asphalt layer.

2 .3 *Test procedure*

Before the loading test was begun, profile measurements were performed on the surface asphalt layer. Next, the test specimen was cyclicly loaded with a multi-stage stress path similar to that shownin Figure 1. The loading period was 12 s per cycle. Each stage consisted of a certain number of load cycles. The loading amplitudes are presented in Table 1.

3 RESULTS

Profile measurements were performed after every 1000 load cycles in order to evaluate the cumulative residual deformation of the pavement structure.

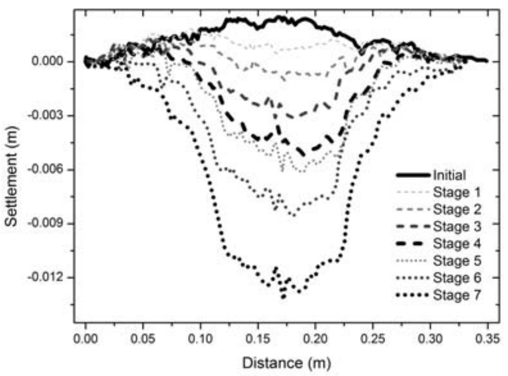

Figure 6. Rut depth measurements after completion of each loading stage.

The results of the profile measurements are presented in Figure 6. It can be seen that the surface was slightly raised initially before the test began. As the loading proceeded, a rut was formed under the tyre. Ruts generally appear due to wear and low load-bearing capacity of the pavement structure. In the first few loading stages the rut depth was almost negligible, whereas in the following stages it noticeably increased, together with the load.

The final rut that was formed after stage 7 is shown in Figure 7. It can be seen that some wearing of the surface layer occurred, but most of the settlement was due to the residual settlement of the pavement structure.

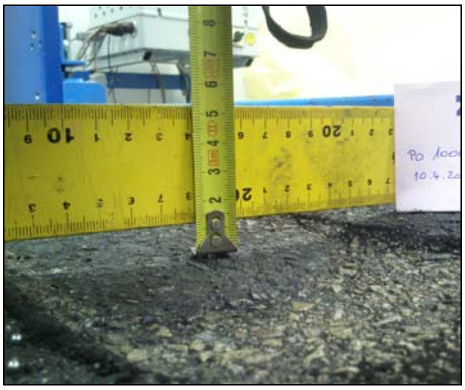

Figure 7. View of the rut which developed under the loading wheel at the end of the test.

4 CONCLUSIONS

A new testing device, referred to as a Traffic Load Simulator (TLS), has been constructed at the Slovenian National Building and Civil Engineering Institute (ZAG), whose aim is the performance of laboratory tests of full-scale pavement structures subjected to traffic loadings. Special attention was paid to adequate simulation of the traffic loading, and particularly to the rotation of the principal stress axes, which typically occurs during traffic loading.

Specimens of paved road sections, 0.4 m long, 0.4 m wide, and 0.51 m deep, were constructed for the purpose of laboratory research which is presented in this paper. In order to take into account the particularities of traffic load simulation with principal stress axis rotation, the specimens were constructed inside 17 rigid aluminium frames. Free non-frictional movement of all the frames were permitted in the horizontal direction, except the bottom frame, which was loaded in the horizontal direction. Loading in the vertical direction was applied by means of a tyre which was fixed to a hydraulic piston, which also supported the specimen in the horizontal direction. Synchronized vertical and horizontal cyclic loading applied by two computer-controlled hydraulic pistons simulate traffic load, with rotation of the principle stress direction. The impact of such traffic loading upon the development of ruts is also presented in this paper.

This kind of full-scale laboratory element test enables more realistic evaluation of rut development in pavement structure. Thus it can be useful in design of new types of pavement structures as well as in prediction of pavement sustainability.

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