Rutting behaviour of flexible pavements aggregate bases measured with small-scale laboratory heavy vehicle simulator

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Abstract: Rutting of flexible pavement structures when submitted to repeated heavy-vehicle loading is a complex phenomenon. In northern environment where thick granular layers are included in flexible pavement structures to reduce frost action, most of surface rutting occurs in unbound granular materials. This long-term permanent deformation damage can be studied with heavy vehicle simulator. A small-scale laboratory heavy vehicle simulator was developed at Laval University over the last few years and this paper presents the first results obtained for the characterization of the rutting behavior of flexible pavement bases. Standard aggregate bases, as well as base layers containing 70 % RAP and geogrid were tested. The results obtained are in good agreement with literature on permanent deformation and geogrid reinforcement. The rutting sensitivity of RAP bases is compared to standard aggregate base layer and the structure behavior improvement caused by the geogrid is also quantified.

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1. Introduction

Flexible pavement rutting is a distress caused essentially by the accumulation of permanent deformation within each layer of the pavement layered system. In northern climate such as the one encountered in the Province of Quebec, flexible pavement structures are usually thick in order to ensure good behaviour regarding frost action. Because of that, most of the flexible pavement structures is composed of granular materials. One of the main hypothesis for early mechanistic-empirical pavement design regarding rutting was that it is associated with the vertical strain experienced at the top of the subgrade [1], which is the weakest layer of the pavement layered system. However, because of the important thickness of flexible pavements in Quebec, it is reasonable to assume that an important proportion of pavement structural rutting is due to the accumulation of permanent deformation within the granular base and subbase layers. The researches of Pidwerbeski [2], who discussed that 30 to 80 % of surface rutting is attributable to the pavement granular layers, support this assumption. The accumulation of permanent deformation within granular assemblies under repeated wheel loading is the result of the complex elastoplastic mechanical behaviour presented in Figure 1. When submitted to cyclic deviatoric stress σ_d such as the one experienced in flexible pavement structures, granular materials strain is composed of a recoverable strain ε_R^1 and a permanent strain ε_P^1, the recoverable strain representing the elastic component of the total strain. For adequate pavement design and normal pavement operation conditions, the permanent deformation rate tends to stabilize according to the number of load cycles *N* as shown in Figure 2 (line A). However, for inadequate structure design, or when the axial stress σ_1 or the water content *w* significantly increase, the permanent strain rate according to the number of load cycles may increase and the materials may become unstable or reach failure (Figure 2 line B and C).

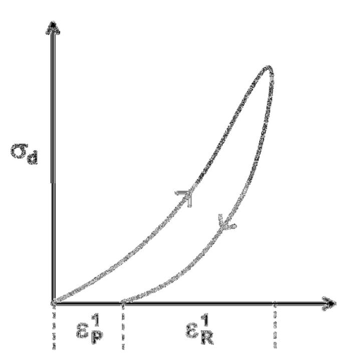

Figure 1. Granular materials elastoplastic behaviour [3]

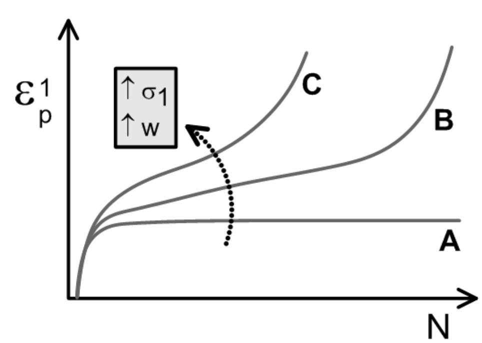

Figure 2. Accumulation of permanent deformation according to the number of load cycles [3]

One of the most popular pavement design procedure used over the last decades, the American Association of State Highway and Transportation Officials empirical method [4], considers rutting damage as part of a complex pavement quality index, the Pavement Serviceability Index *PSI*. Permanent deformation accumulation within the granular layers was part of the index decrease, which is associated with decreasing quality or serviceability of the pavement structure. Nowadays, as mechanistic-empirical pavement design procedures tend to become the recommended practice, there is a need to consider more adequately the granular layers elastoplastic behaviour for flexible pavement design in order to predict structural rutting of the structures. The permanent deformation behaviour of pavement granular materials may be obtained by cyclic triaxial testing of compacted aggregate samples, measurement of aggregate layers rutting under repeated loading of a heavy vehicle simulator (HVS) or by long-term measurement of aggregate layers rutting of instrumented pavement sections. Permanent deformation testing using cyclic triaxial tests is still far less common than resilient modulus characterization and few practical test methods exists for long term behaviour characterization. However, these tests remain quite simple, accessible and fast when compared with HVS tests or long-term monitoring of instrumented pavement sections. Recent research efforts in Quebec were focused on permanent deformation testing of base granular materials using the triaxial apparatus [3, 5, 6, 7, 8, 9] and the Ministry of Transportation is actually developing a test method for the characterization of this behaviour. However, triaxial testing presents some limitations regarding scale effect or principal stress reorientation. It is recognized that prediction of pavement granular layers rutting using triaxial permanent deformation data will lead to an underestimation of this performance parameter [10]. The department of civil engineering at Laval University owns a laboratory size, small-scale heavy vehicle simulator which was under development over the last decade. This research tool is described with details in Juneau et Pierre [11]. As the researches performed to date with this simulator were focused on unpaved roads, this paper presents the results of the first tests performed on flexible pavement structures. The rutting of the base layer is measured for this study and the results are compared with triaxial permanent deformation tests.

2. Equipment, materials and methods

The small-scale laboratory heavy vehicle simulator used at the Laval University civil engineering department is presented in Figure 3. It consists of a wheel of 450 mm diameter and 150 mm tire thread loading a pavement sample of 0.6 x 1.8 x 0.6 m^3 (Width x Length x Height). The tire thread is similar to conventional commercial vehicle but the print is approximately 60% due to the smaller diameter. The tire pressure can be set at more than 800 kPa. The wheel maximum speed is 6 km/h, constant over the central third of the sample length. Approximately 400 000 load cycles per week can be applied to a pavement sample. The axial force is applied using air-spring bellow and a maximum load of 20 kN can be applied. The load is set following a calibration of the air-spring bellow pressure according to the force measured with a load cell (Figure 4). Lateral displacement of the tire is allowed according to a normal distribution. The lateral coverage of the pavement surface is 450 mm. The tire pressure (80 psi) and air-spring bellow pressure (20 psi) used were selected in order to obtain a surface stress of 560 kPa. This choice was made following measurements of surface contact area using image analysis of tire prints for various tire and air-spring bellow pressures (Figure 4).

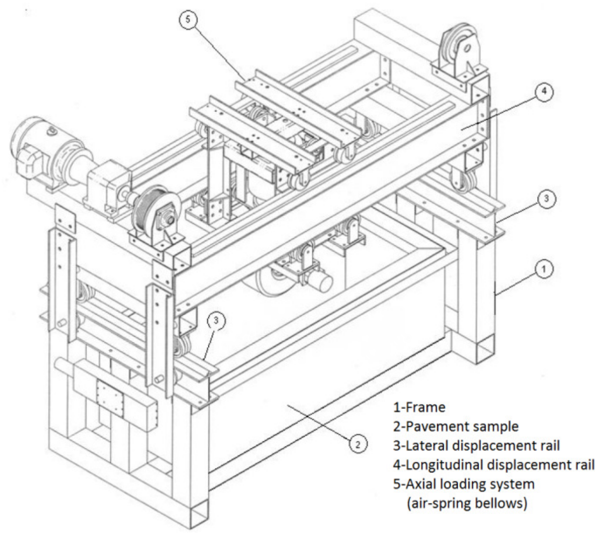

Figure 3. Small-scale laboratory heavy vehicle simulator of at Laval University (Juneau and Pierre 2008)

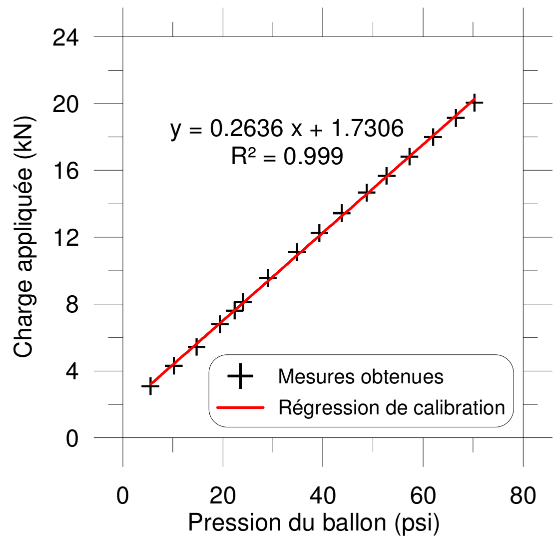

Figure 4. Calibration of the air-spring bellow to determine the applied load (Poupart 2012)

The flexible pavement rutting tests were performed for three pavement samples. The pavement samples included a 245 mm base and 55 mm thick asphalt concrete, as presented in Figure 5. Given the imposed surface stress conditions, this design allowed obtaining similar vertical stresses in the base layer than the ones experienced for typical flexible pavement structures. The first pavement sample was made of a standard grauwacke base granular material. The other pavement samples were made by mixing a limestone granular base with recycled asphalt pavement (RAP) particles, which grain-size distribution is also similar to base granular materials. The mix was set to 70% RAP and 30% Virgin aggregate. One of the two pavement sample containing RAP in the base layer was built with a geogrid at a depth of 180 mm within the base. The permanent deformation occurring within the base was measured with 50 x 50 mm^2, 6 mm thick, steel plates positioned at the top of the base layers prior asphalt concrete compaction. Holes were drilled into asphalt concrete to the steel plates to measure their relative displacement (permanent deformation of the base layer) according to a reference point during the tests and surface rutting was also measured using standard technique (Figure 6). Because of the height of the pavement mold (0.6 m), a special configuration was used to fill the mold and complete the building of the layered structures. As the objective was to measure the rutting occurring in the base layers and given the permanent deformation measurement method, it was necessary to ensure that no permanent deformation occurred lower than the base layer. Moreover, it was necessary to ensure that the layers positioned under the aggregate base presents an elastic behaviour with a deflection at the bottom of the base layer that is in the same range of the one experienced for typical flexible pavement structures in Quebec. Experience in Quebec suggests a deflection value of 0.2 mm at the top of the subbase in typical flexible pavement structures. In order to meet these construction criteria, the bottom 300 mm of the pavement mold was filled with 275 mm of concrete slabs and 25 mm thick rubber mat (Figure 5). Preliminary analysis using multilayered linear elastic software revealed that this pavement sample configuration was adequate for the research needs.

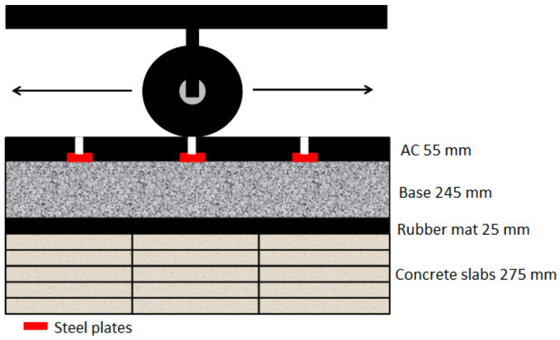

Figure 5. Pavement samples typical structure (Poupart 2012)

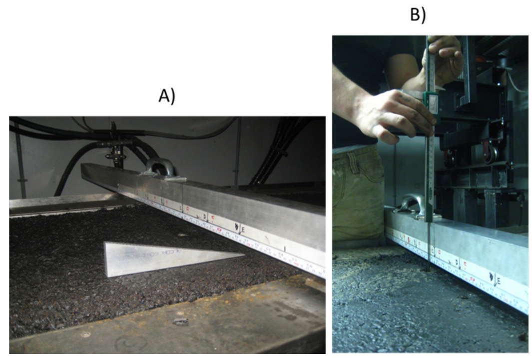

Figure 6. A) Measurement of surface rutting (standard technique); B) Measurement of base layer permanent deformation

The pavement samples were submitted to 50000 load cycles. The base layers were compacted in three layers of approximately 80 mm at similar water contents of 4%. The asphalt concrete, as well as the base materials, were compacted using an electric vibrating plate. Permanent deformation of the base layer and surface rutting were measured at the following load cycles : 0, 1, 50, 100, 200, 350, 500, 1000, 2000, 3500, 5000, 10000, 20000, 30000, 40000, 50000. The Huurman model [12], also referred to as the Dresden model, was selected [5, 9] to model the permanent strain occurring in the base layers according to the number of load cycles. This model is expressed

(1)
$$\varepsilon_p^1 = a\left(\frac{N}{1000}\right)^b$$

in which *a* is the modelled permanent strain after 1000 load cycles and *b* the modelled permanent strain rate.

3. Results and discussion

The experimental results obtained from this study focused on rutting performance of pavement granulars materials used as pavement bases. The main results are presented as graphs showing the relationship between the permanent deformation and the number of load cycles. The results are presented in Figure 7, Figure 8, Figure 9, Figure 10 and Figure 11. The results presented in Figure 7 and Figure 8 are the experimental results obtained for the grauwacke and 70%RAP bases. Moreover, the results obtained from permanent deformation tests using cyclic triaxial loading at equivalent vertical stress and similar water content are presented with the HVS results. It shows that, from the results obtained, the final permanent deformation obtained using the small-scale laboratory HVS is approximately 50 to 350% higher than the one obtained from the triaxial tests. It is in good agreement with the data found in the literature that suggests that permanent deformation obtained through HVS tests is typically 2 to 3 times higher than the one obtained using cyclic triaxial testing.

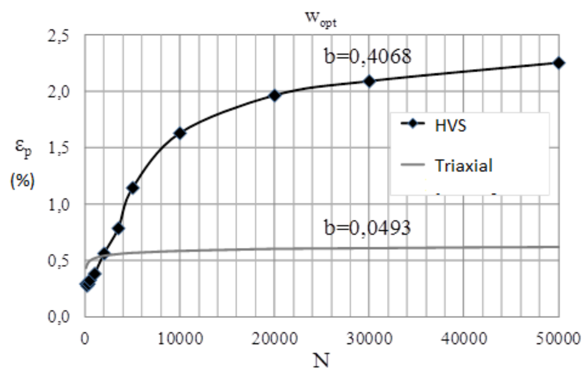

Figure 7. Grauwacke HVS test results compared with triaxial test results

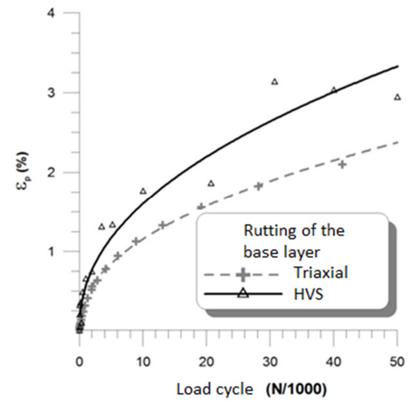

Figure 8. HVS test results for base layer containing 70%RAP compared with triaxial test results

The test procedure followed during HVS tests allowed obtaining direct measurement of surface rutting and permanent deformation occurring in the base layer. Therefore, it was also possible to obtain asphalt concrete layer rutting by a simple difference between both values. Figure 9 presents the results of the permanent deformation that was measured in asphalt concrete and base layers for the pavement samples containing RAP. As it is observed, most of the long-term surface rutting is attributable to the behaviour of the base layer, since the relationship between permanent deformation and the number of load cycles are very similar for surface rutting and base permanent deformation. From the results collected, it appears that the rutting of the asphalt concrete layer solely occurs very early during the loading history. For the three tested pavement samples, asphalt concrete permanent deformation was in the range of 2 to 4 mm. The results collected during the tests also allowed measuring the rut profile developing during long-term wheel loading of the pavement samples, as shown in Figure 10 for the bases containing RAP. As it can be observed, the pavement structure containing a geogrid presents a more constrained rut basin than the pavement structure without any reinforcement technique. As a matter of fact, the rut transversal profile shows a greater surface deformation radius for the pavement sample with 70%RAP without a geogrid. The geogrid also limits the permanent deformation more efficiently in the area where there is less wheel loading, as the sample without geogrid presents permanent strain 130% higher at the sample edges and 230% higher at the sample center when compared to the sample containing a geogrid.

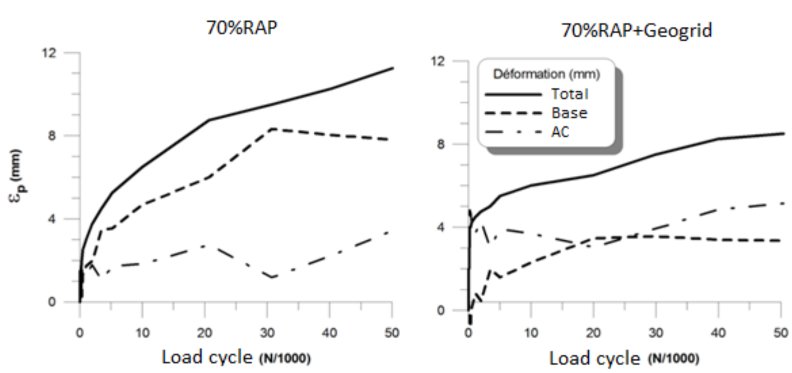

Figure 9. Examples of total surface rutting separated as rutting of asphalt concrete and base layers

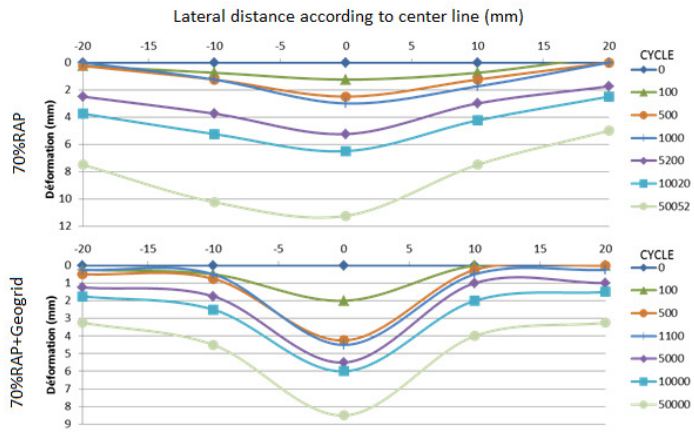

Figure 10. Typical transversal profile of surface rutting

The experimental results, as the ones presented in Figure 7 and Figure 8, were modelled with the power relationship presented in equation 1. The process allowed obtaining the regression parameters *a* and *b*, *a* being the modelled permanent deformation after 1000 load cycles and *b* the permanent strain rate. The models obtained are presented in Figure 11 for the three tested pavement samples. When the grauwacke base and the 70%RAP are compared, the well-known rutting sensitivity of bases containing high RAP percentage is emphasized, as *a* and *b* are 1,11 times higher for the pavement sample containing the 70%RAP base, resulting in a final permanent deformation 1,33 times higher after 50000 load cycles. However, a significant effect of the geogrid is measured when the pavement sample containing a geogrid is compared to the same pavement sample without any geogrid. As a matter of fact, for the base with a geogrid, the *a* value, *b* value and final permanent deformation are 69, 74 and 42 % the values measured on the pavement sample that was not built with a geogrid. The effect of the geogrid on the rutting behaviour of the flexible pavement is in the same range than what was measured [13, 14], the technique showing an interesting potential as a stabilization technique.

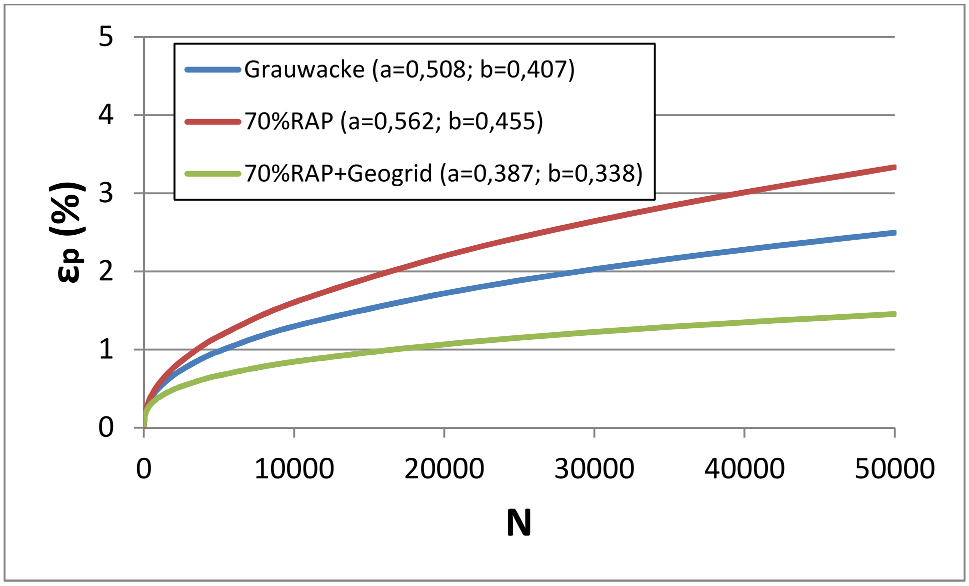

Figure 11. Results modelled for the three tested pavement samples

4. Conclusion

Rutting behaviour of flexible pavement bases was investigated using a small-scale laboratory heavy vehicle simulator. Conventional unbound granular material was tested, as well as a granular material containing a high RAP proportion (70%). This rut sensitive aggregate base was tested with and without a stabilization technique. For this study, the selected rutting stabilization technique is a geogrid. The experimental results were modelled using the Dresden model. A significant difference was found between the small-scale laboratory HVS results and standard cyclic triaxial tests, revealing the fundamental differences between both loading methods. The rutting sensitivity of the base layer containing 70%RAP was noticed when compared to conventional aggregate base. However, the use of a geogrid significantly improved the behaviour of the base containing 70% RAP in terms of post compaction, permanent deformation rate and final permanent deformation. These tests were the first performed on flexible pavement structures using the Laval University small-scale laboratory heavy vehicle simulator. More tests will be performed in the next months to continue gathering information and data on the rutting behaviour of flexible pavements.

Acknowledgements

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