Simplified Testing Method for Evaluation of Asphalt Mixtures for their Susceptibility to Permanent Deformation

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ABSTRACT: The accumulation of permanent deformation in the asphalt surfacing layer is considered to be the major cause of rutting in flexible pavements. Thus testing and methods of evaluation of mixtures for their susceptibility to permanent deformation have become important issues. This article reports further development of a mixture evaluation procedure previously suggested by the authors. The study considered the use of a simplified testing method, in which a slightly modified NAT (Nottingham Asphalt Tester) is used to measure axial and radial strains resulting from loading of cylindrical asphalt specimens. Two types of mixtures, Ab 16 (asphalt concrete) and Ska 16 (stone mastic asphalt) are considered in the study. Tests were conducted on specimens produced in the laboratory using both the repeated load triaxial test and Nottingham Asphalt Tester. The results of the tests were used to rank the two mixtures in terms of their resistance to permanent deformation. The two mixtures were also laid as a surfacing layer on a main road in southern Norway and rutting measurements were conducted in the field. Although the major part of the rutting is believed to come from studded tire wear, the relative performance of the two mixtures in terms of total rutting agrees with the ranking provided by the tests and the suggested evaluation procedure.

KEY WORDS: Permanent deformation, testing, evaluation, rutting resistance index.

1 INTRODUCTION

Rutting in flexible pavements is caused by accumulation of permanent deformation in the layers of the pavement. The accumulation of permanent deformation in the asphalt surfacing layer is considered to be the major cause of the rutting in flexible pavements. This is a consequence of increased tire pressures and axle loads which subjects the material nearest to the tire-pavement interface to increased stresses. Thus procedures for evaluation of the resistance or susceptibility of the mixtures to rutting have become an important issue. Several test methods and procedures were proposed over the years for purpose of evaluating asphalt mixtures. However, a test and evaluation procedure that is simple and that correlates well with the field performance of mixtures is yet to be developed. This study aims to contribute in this endeavor.

The objective of this study is to further develop an asphalt mixture evaluation procedure that was proposed earlier by the authors based on triaxial test and strain decomposition approach. In this study the applicability of the procedure to different mixtures as well as its ability to correlate with the field performance is assessed. An effort is made to use a simplified testing procedure to obtain parameters used in the evaluation procedure. In this regard, the Nottingham Asphalt Tester (NAT) was slightly modified and used to measure both the radial and the axial strains. A simplified version of the evaluation parameter was developed to make it more practical. An attempt is also made to explain the rutting resistance parameter within the framework of fundamental theories for material behavior.

In the following sections the procedure is presented followed by its application to evaluate two different mixtures whose field performances were monitored.

2 THE RUTTING RESISTANCE INDEX

The rutting resistance index (RI) was developed based on strain decomposition approach (Garba, 2002). The strain decomposition approach involves decomposition of the total strain resulting from loading of asphalt concrete specimens into its components and modeling the components separately. Results of experiments have shown that asphalt mixture deformation consists of recoverable and irrecoverable components some of which are time-dependent and some time-independent. In general the total strain can be decomposed into four components and can be expressed as follows:

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_{ve} + \varepsilon_{vp} \tag{1}$$

where:
ε = total strain
ε_e = elastic strain, recoverable and time-independent
ε_p = plastic strain, irrecoverable and time-independent
ε_{ve} = viscoelastic strain, recoverable and time-dependent
ε_{vp} = viscoplastic strain, irrecoverable and time-dependent.

The procedure used to decompose the total strain was the same as that used by Uzan (Uzan, 1996). Figure 1 show a plot of the total strain in a typical creep and recovery test cycle on asphalt concrete specimen and illustrates the four components of strain described by Equation 1. The elastic, plastic, viscoelastic, and viscoplastic strain components can be incorporated into a comprehensive elasto-viscoplastic model. Following Uzan's approach, the creep compliance under step loading can be expressed as:

$$\frac{\varepsilon(t,N)}{\sigma} = D_e + D_p(N) + D_{ve}\frac{t^m}{1+at^m} + D_{vp}(N)t^n \tag{2}$$

where:
D_e = elastic compliance (time- independent)
D_p = plastic compliance (time-independent)
D_{ve}, a, m = viscoelastic parameters
D_{vp}, n = viscoplastic parameters
σ = the stress

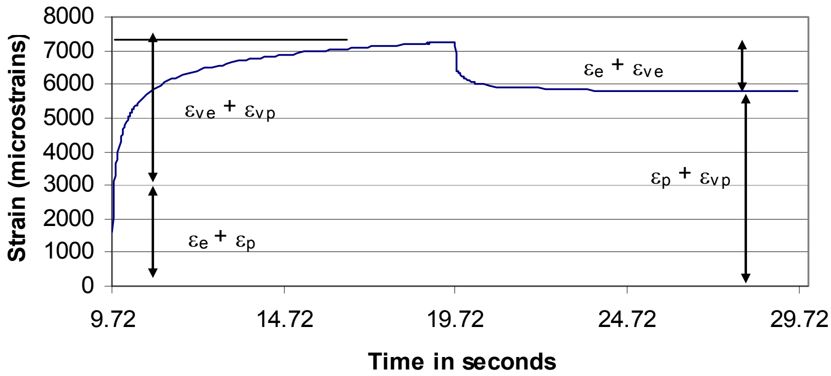

Figure 1: Total strain in a typical creep and recovery cycle

The values of the model parameters were calculated using results of triaxial creep and recovery test on asphalt concrete specimens with varying levels of binder content and void content. The objective was to identify the parameters that are sensitive to changes in mixture's volumetric composition, i.e. void content and binder content. The sensitivity analysis showed that, of the parameters that related to the permanent part of the deformation, D_p (1) and D_{vp}(1) are the most sensitive to changes in volumetric composition. The parameters D_p (1) and D_{vp} (1) refer to the first cycle plastic and viscoplastic compliances respectively. The parameters m and n are related to the time-dependent deformation of the material. These two parameters were found not to be sensitive to changes in volumetric composition but they might be sensitive to changes in binder type. However, as the specimens for the test under consideration were produced using the same binder type, their sensitivity to changes in binder type could not be verified.

The rutting resistance index was then defined using the parameters D_p, D_{vp}, m, n and an additional parameter, r, which is a ratio of incremental deviatoric permanent strain and incremental volumetric permanent strain. This ratio was found to be constant for the range of deformation involving contraction, i.e. decrease in volume. A more detailed description of the formulation of the rutting resistance index is provided in Garba (2002), Garba & Horvli (2002, 2004). The rutting resistance index was expressed as follows:

$$RI = \frac{H_{vp} H_P}{r(m+n)\left[H_{vp} + H_p\right]} \tag{3}$$

Where:

H_p = plastic modulus in the first cycle,
H_{vp} = viscoplastic modulus in the first cycle,
m, n = parameters defined in equation 2, and
r is expressed as follows:

$$r = \frac{\Delta \varepsilon_D}{\Delta \varepsilon_v} \tag{4}$$

Where:

$\Delta\varepsilon_d$ = incremental deviatoric permanent strain
$\Delta\varepsilon_v$ = incremental volumetric permanent strain

The ratio, r, is considered to be a measure of susceptibility to shear deformation. The rutting resistance index, RI, thus contains parameters that are related to both compaction and shear deformation. Compaction and shear deformation are the two mechanisms known to result in rutting in asphalt pavements. The index, RI, was found to be sensitive to changes in binder content and void content as shown in Figure 2.

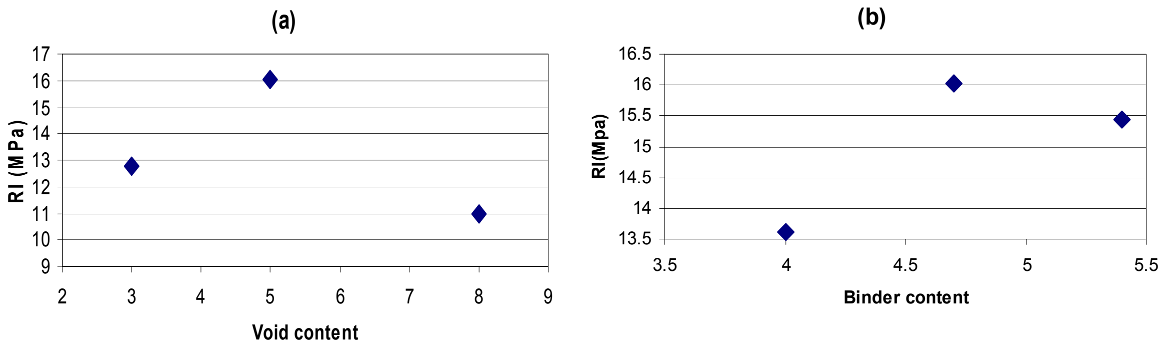

Figure 2: The rutting resistance index

2.1 A Simplified Formulation for the Rutting Resistance Index

The original formulation of the rutting resistance index was based on decomposition of the permanent strain in to the plastic (time-independent) and the viscoplastic (time-dependent) parts. A certain measure of susceptibility to deformation was defined as follows:

$$I = \lfloor D_p(1) + D_{vp}(1) \rfloor (m + n) \qquad (5)$$

Where $D_p(1)$, $D_{vp}(1)$, are first cycle plastic and viscoplastic compliance parameters respectively and m, and n are as defined in equation 2. The sum $D_p(1) + D_{vp}(1)$ gives the permanent part of the creep compliance in the first cycle. Replacing this sum with D_{perm}, equation 5 can be rewritten as:

$$I = D_{perm}(m + n) \qquad (6)$$

The inverse of I gives the resistance to deformation expressed as follows:

$$R = \frac{1}{D_{perm}(m + n)} \qquad (7)$$

Now introducing the ratio r into equation 7, the resistance index can be defined as:

$$RI = \frac{1}{rD_{perm}(m + n)} \qquad (8)$$

D_{perm}, the permanent creep compliance in the first cycle is the inverse of the plastic modulus (H_{perm}). The sum (m+n) was included on the assumption that the two factors may be sensitive to changes in binder type. For the purpose of simplicity, however, these two factors can be dropped. Equation 8 can therefore be expressed as follows using the plastic modulus:

$$RI = \frac{H_{perm}}{r} \tag{9}$$

This simplified resistance index can be calculated from the first cycle plastic modulus and the ratio r without the need for decomposition of strain. This form is also suited for analysis of continuous repeated load triaxial test as well as creep and recovery test.

2.2 Interpretation of the Rutting Resistance Index

The rutting resistance index contains the plastic modulus and the ratio of incremental permanent deviatoric strain to incremental permanent volumetric strain. In the theory of plasticity, the plastic modulus is often used as hardening parameter and it is well known that hardening is a property that is highly relevant to the resistance to permanent deformation. For asphalt concrete like materials, the plastic modulus in the first cycle of loading is considered to be an important parameter. Thus this parameter can be used as a measure of the initial deformation caused by compaction. The ratio of deviatoric permanent strain to volumetric permanent strain, referred to as dilatancy angle, defines the direction of plastic strain and it is often used as a flow rule in the theory of plasticity as illustrated in Figure 3 below.

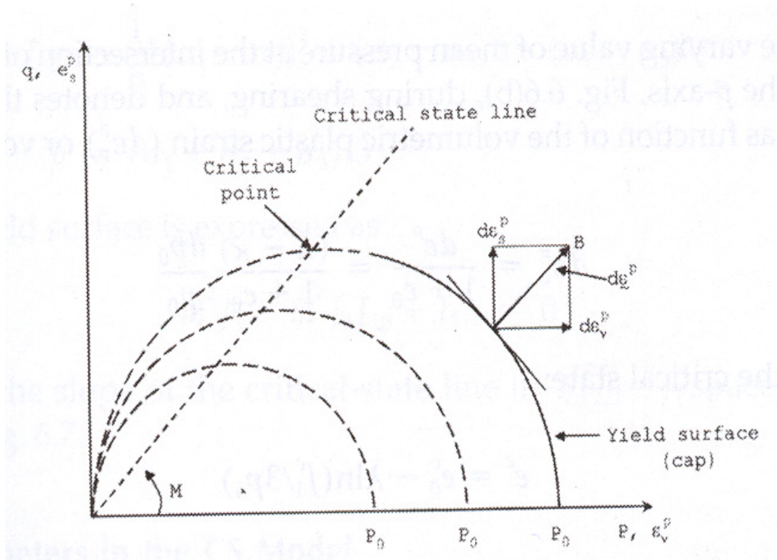

Figure 3: Shear and volumetric strains in relation to yield surfaces in q-p space (Desai 2001). $d\varepsilon^p_s$ and $d\varepsilon^p_v$ are incremental permanent shear and volumetric strains respectively.

A large dilatancy angle (a large value of the ratio of deviatoric to volumetric strain) indicates a plastic strain vector heading towards the critical state line or failure line, if such a line is defined. That is an indication that the material is susceptible to shear flow. Thus the ratio r measures the susceptibility of the material to shear deformation.

The rutting resistance index defined by equation 9 thus contains measures of resistance to compaction and shear deformation- the two mechanisms known to be the cause of rutting in asphalt pavements. Although the rutting resistance index was defined based on strain decomposition approach, which is considered to be not theoretically based, the two parameters contained in the index have physical meanings in the context of the more fundamental theory of plasticity. The rutting resistance index and its relation to void and binder contents (with in practical ranges) is illustrated in Figure 4.

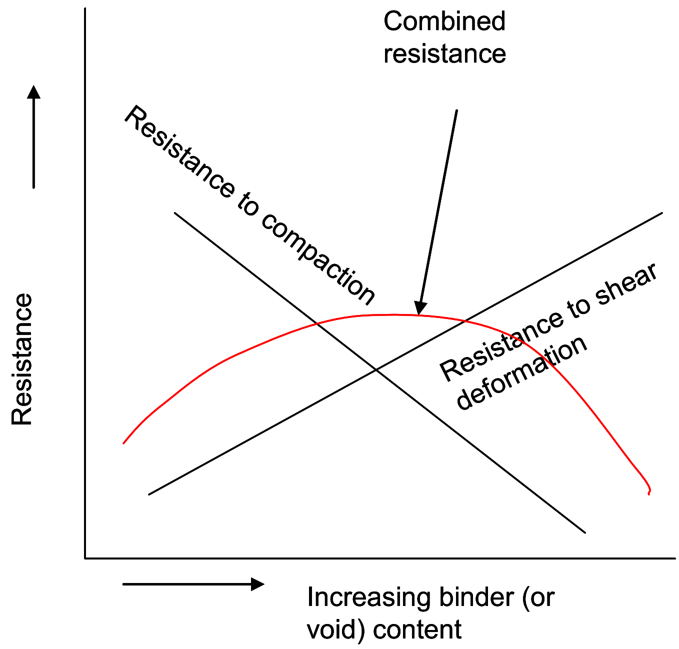

Figure 4: Illustration of the Rutting Resistance Index

Figure 5 shows the simplified RI values for asphalt concrete specimens with varying void content at two temperature levels. The specimens were tested under cyclic load triaxial test with frequency of 10 Hz. A sinusoidal deviatoric stress of 750 KPa and a constant confining stress of 150 KPa were applied. As can be seen from Figure 5, temperature has a dramatic effect on the RI values. The variation of RI with void content indicates that both high and low void levels can lead to materials with low resistance to rutting. In other words it points to the existence of a certain void content which gives the maximum resistance to rutting for the material under consideration.

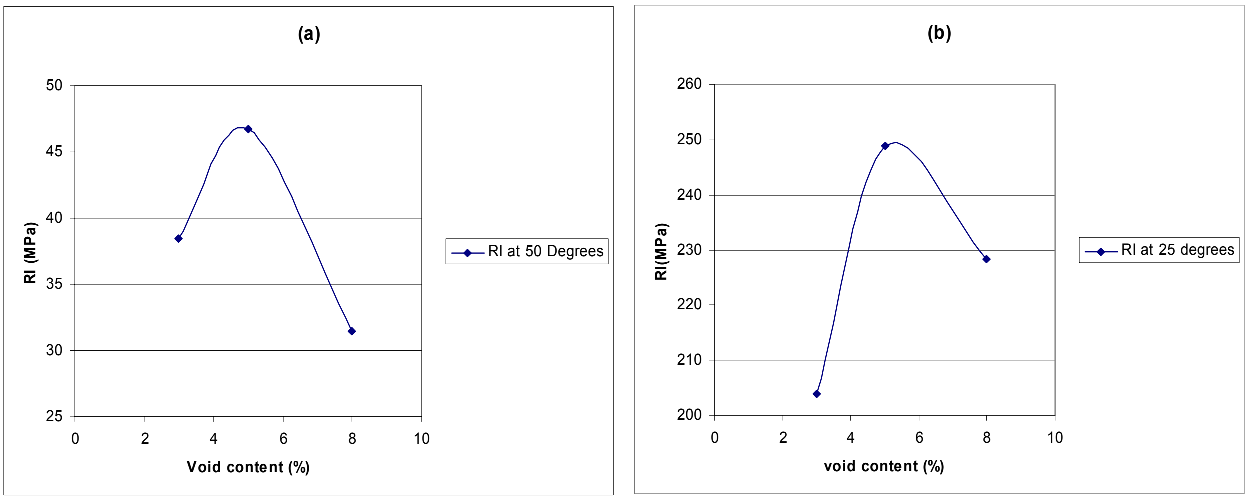

Figure 5: Variation of RI with void content, (a) at 50^{o}C and (b) at 25^{o}C. The specimens had binder content of 4.7%

3 APPLICATION OF THE RUTTING RESISTANCE INDEX

The rutting resistance index can be used to compare and rank mixtures according to their resistance to permanent deformation. As explained in the preceding sections, the rutting resistance index was originally developed based on triaxial creep and recovery test. Since such tests are relatively complicated and expensive, a simplified testing procedure is needed. To obtain the rutting resistance index one needs to measure both the axial and the radial strains resulting from loading of asphalt concrete specimens. In this study a simple testing method, which is based on a slightly modified Nottingham Asphalt Tester (NAT) was used to measure the axial and radial strains and obtain the rutting resistance index. Two asphalt mixtures were tested and ranked using this simple testing method and the rutting resistance index. In the following sections the materials used, the testing procedure and the results obtained are discussed.

3.1 Materials

Two asphalt mixtures were tested; an asphalt concrete mixture (Ab 16) and a stone mastic asphalt mixture (Ska 16). The maximum aggregate size for both mixtures was 16 mm and the mixtures were made from the same type of aggregate. Polymer modified binder, Pmb 60, was used in the asphalt concrete mixture while an unmodified penetration grade binder B70/100 was used in the Ska 16 mixture. Details of the composition of the two mixtures are given in Table 1. These two mixtures were also laid on a main road (E18) in southern Norway as part of a test section designed to study the development of rutting. The test section was laid in 2001 and rutting measurement was conducted twice per year; in early spring and late autumn.

For the purpose of this study the two mixtures were reproduced in the laboratory using the same materials used in the plant production for the test section. Test specimens were compacted using gyratory compactor. The target void content, as specified in the recipe, was 3.5%. The gyratory angle and number of gyrations were varied to find out the compaction procedure which gives average void content of about 3.5%. The test specimens had a diameter of 100mm and a height of 160 mm. After cutting 10mm from each end to obtain flat and parallel surfaces, the specimens had a height of 140mm, giving a height to diameter ratio of 1.4.

Table 1: Composition of mixtures

Mixture composition		Mixture type	
		Ab 16	Ska 16
Aggregate	Crushed rock Gravel Filler	77% 15% 8%	81% 10% 9%
Binder	Type Content	Pmb 60 5.7%	B70/100 6.3%
Anti-striping agent	Wetfix I	0.4% (of binder)	0.4% (of binder)
Fiber	Cellulose		0.3% (of aggregates)

3.2 Testing Procedure

Two types of tests were conducted on the specimens; a triaxial creep and recovery test and a confined creep and recovery test using a modified Nottingham asphalt tester (NAT). The tests were conducted at a temperature of $40^{o}C$ and three parallel specimens were tested for each case.

The triaxial creep and recovery test was conducted using an electro-hydraulic triaxial testing apparatus. The confining stress was kept constant at 150KPa. A deviatoric stress of 450KPa was applied in the form of a block (square) wave with 10 seconds loading and 10 seconds unloading (recovery). The specimens were conditioned in the test chamber until the desired temperature was obtained. Temperature in the chamber was monitored using a temperature transducer. Deformation data was recorded at frequent intervals during testing. The test was run for 200 creep and recovery cycles.

The permanent deformation test using the ordinary NAT is a simple test but has limitation in that it does not allow the measurement of radial (lateral) strain. Therefore, the apparatus and the software were modified in such away that the radial strain could be measured and recorded. The modification also allowed the testing of longer specimens than usually used in the standard NAT tests. The software modification was made by Cooper Research Technology Ltd (UK) according to our demand. In the modified NAT test confining stress was applied using vacuum. This allows the application of confining stress of up to 100KPa, but in the laboratory setup used in this study a vacuum pressure of only 70 KPa could be obtained. A deviatoric stress of 210 KPa was used to maintain the same stress ratio used in the triaxial test. The deviatoric stress was applied, in the form of a block wave with 10 seconds loading and 10 seconds unloading as in the case of triaxial testing and the test was conducted for 200 cycles, which takes 4000 seconds. Detailed data on the development of permanent deformation during loading and recovery during unloading was obtained for the first five cycles and for every fifth cycle thereafter. The modified NAT is much simpler than the triaxial test and appears to give satisfactory results. Figure 6 shows a test setup in the modified NAT.

3.3 Test Results

Data from the tests were used to compare the two mixtures. Comparison was made using the accumulated axial permanent strain and the rutting resistance index. Figures 7 and 8 show the accumulated axial permanent strain from the two tests. Results from the triaxial creep and recovery test (Figure 7) indicates that Ab 16 is more susceptible to permanent deformation than Ska 16. However the result from the modified NAT (figure 8) shows the opposite tendency, i.e., it shows Ska 16 to be more susceptible to permanent deformation. The difference between the two results might be due to the lower confining stress used in the modified NAT test as the Ska mixture is more sensitive to changes in confining pressure. Generally, however, this points to the fact that considering only axial (one dimensional) permanent strain in evaluation of mixtures can lead to erroneous conclusion. The fact that one dimensional analysis is insufficient for evaluation of mixtures for their susceptibility to permanent deformation has been shown by earlier tests (Garba and Horvli 2004).

The rutting resistance index was calculated using results of the two tests and is shown in Figure 9. For both tests the index showed that Ab 16 mixture has better resistance to permanent deformation than the Ska 16. The rutting resistance index values for the two tests are however different indicating the dependence of the index on the stress. Figure 10 shows the performance of the two mixtures in the field in terms of the measured rutting. The field measurements were conducted using two methods; a beam instrumented with an LVDT (Linear variable differential transducer) developed by SINTEF and a surface condition measurement system (vehicle) known as ALFRED which is equipped with ultrasonic sensors.

Figure 6: Test setup in the modified NAT

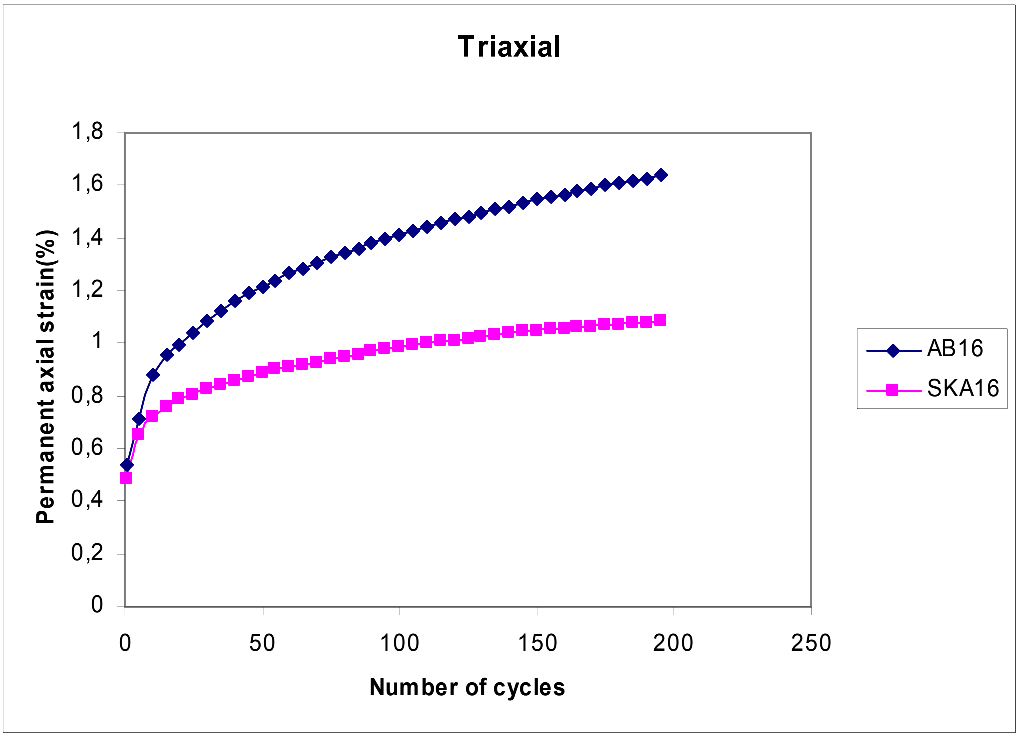

Figure 7: Accumulated axial strain under the triaxial creep and recovery test

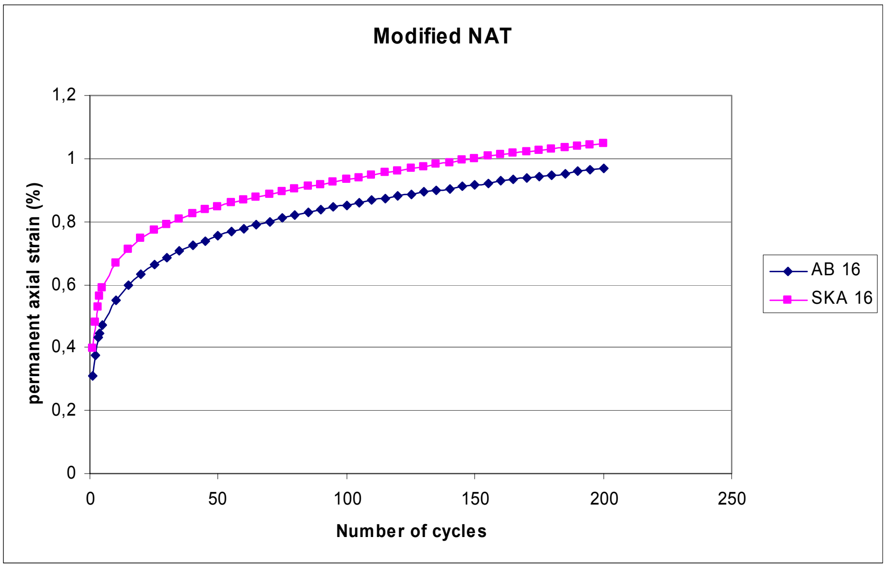

Figure 8: Accumulated axial permanent strain under the modified NAT test

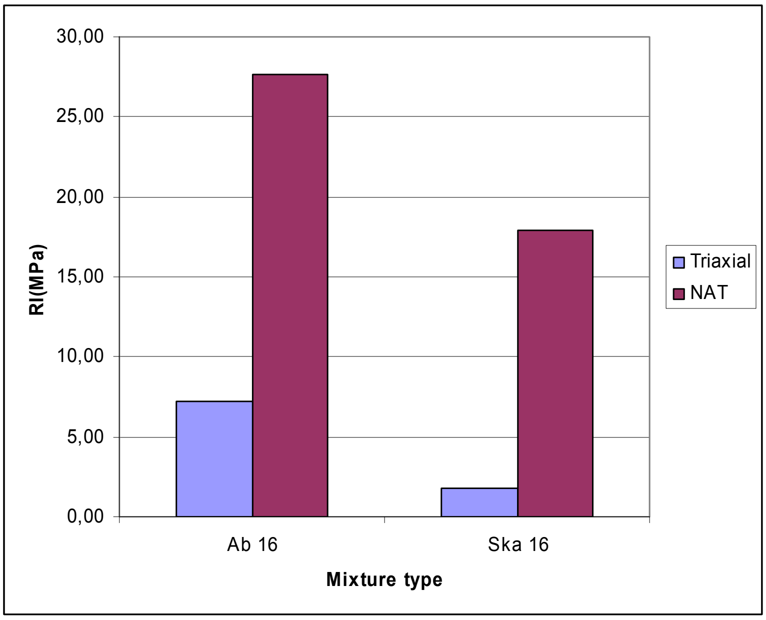

Figure 9: Rutting resistance index for the two tests

Both measurements indicate that the Ab 16 section had slightly less rutting than the Ska 16 section. The difference becomes more significant, however, when one considers the fact that significant portion of the rutting comes from studded tire wear during winter season. Because Ska 16 has greater proportion of larger size aggregate materials, it has better resistance to the studded tire wear. Had it not been for the deformation related rutting, one would have less rutting on the Ska 16 section compared to the Ab 16 section. Therefore, the observed difference in rutting confirms that the Ska 16 mixture does have lower resistance to permanent deformation compared to Ab 16, in agreement with laboratory evaluation based on the rutting resistance index. Visual inspection of the sections by one of the authors also showed some sideway movement of materials in the wheel track in the Ska 16 section.

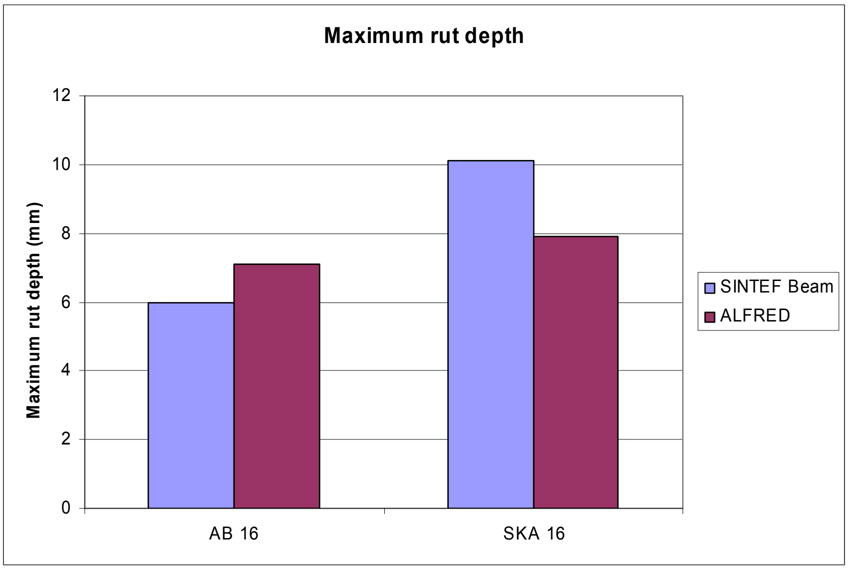

Figure 10: Result of rutting measurement in the field

4 CONCLUSIONS AND RECOMMENDATIONS

This study investigated the use of a simplified testing method for evaluation of the resistance of asphalt mixtures to permanent deformation. A simplified form of the rutting resistance index reported earlier by the authors was used to compare two mixtures. The test was conducted using a modified Nottingham Asphalt Tester and a triaxial testing apparatus. The ranking obtained using rutting resistance index agrees with field observation. Testing with the modified NAT is simple and appears to be satisfactory for evaluation of mixtures with respect to their resistance to rutting. Further study involving large number of tests is recommended to determine the variability of the rutting resistance index and its applicability in mixture design and evaluation.

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