Performance-based optimization of tire rubber modified asphalt mixtures

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ABSTRACT: A quantity of approximately 45.000 tons of waste tires is burnt in incineration plants in Austria per year. New recycling technologies enable the production of high quality rubber and fiber products from recycled car tires. One field of application may be the use of recovered fibers and rubber products for the modification of asphalt mixtures for road pavements. Successful use of rubber modifications of asphalt mixtures is reported in literature, but no sufficient information is provided on a systematic approach for mix design of rubber modified asphalts based on performance oriented test methods. This paper deals with this question, and reports of an on-going research project, where a new type of fiber and/or rubber modified stone mastic asphalt (SMA) is developed on the basis of a systematic performance-based test procedure. Both, bitumen and asphalt performance are considered. At first, rheological binder tests, i.e. Bending Beam (BBT), Dynamic Shear Rheometer (DSR) and Rotational Viscosimeter (RV), are used to optimize the performance properties of the rubber modified binder. The rubber modification of the binder was done in the laboratory as *wet process*. Consequently, laboratory specimens of rubber modified asphalt mixture are exposed to performance-based tests, i.e. the Tensile-Stress-Restrained-Specimen-Test, the Uniaxial-Stress-Test, the Triaxial-Stress-Test, and the Nottingham-Asphalt-Test. Here also the *dry process* was investigated, where specially granulated rubber is mixed with the hot minerals before the bitumen is added. By means of these test methods, a prediction of the in-service performance of the asphalt mixture is possible, in regard to the low-temperature behavior, the stiffness properties, and the resistance to rutting. In a further step it will be analyzed, if the new asphalt mixture is a technically equivalent alternative, but economically favorable to conventional techniques.

KEY WORDS: tire rubber modification, modified binder, recycling of waste tires, performance-based testing, mix design.

1 INTRODUCTION

Given several million end-of-life vehicles in Europe per year, recycling of waste tires may contribute to a reasonable reduction in consumption of energy and resources. Recycling will help to achieve the requirements in the directive 2000/53/EC from the European Council: By 2006, for all end-of-life vehicles reuse and recycling should increase to a minimum of 80%.
Waste tires are fiber-reinforced composites, with a strong adhesion between the fibers and the rubber matrix, thus making the separation process rather time-consuming. One of the most modern recycling plants for waste tires is operated by GVG, Gummiverwertungsgesellschaft

GmbH., in Ohlsdorf, in the province of Upper Austria. Waste tires are cut and ground via several steps, and steel, rubber and fiber fractions are generated. One main quality aspect in the plant is an accurate sorting and separation of rubbers from passenger cars and truck tires, know for their different composition and properties. The recovered products are of high quality and can be used for a variety of construction materials, such as asphalt mixtures for road.

Although the successful use of different rubber-modifications for asphalt mixtures is reported in literature, it does not provide sufficient information on a systematic approach for mix design for use of recycled rubber in stone mastic asphalt (SMA). This is subject of the project, presented in this paper. Research work at the Vienna University of Technology's Institute for Road Construction and Maintenance focuses on the development and assessment of appropriate test methods for optimizing new types of asphalt mixtures with regard to their in-service life (Lackner et al. 2004; Spiegl et al. 2005). Currently a performance-based optimization procedure is implemented for the testing of a new tire rubber modified SMA type of asphalt. Its performance is further compared with conventional SMA mixtures used in Austria. Laboratory tests comprise both, performance based binder and asphalt testing. The results of these tests will allow to forecasting the in-service performance of the asphalt mixture, with regard to the low-temperature and fatigue behavior, and the resistance to rutting. On the basis of these test efforts it will be feasible to evaluate, if rubber modified SMA is a technically equivalent alternative, but economically favorable to existing techniques.

This paper emphasizes on the scientific approach to a performance-based mix design procedure developed for this new type of asphalt mixture, which is modified by products recovered from waste tires. Preliminary results of currently on-going binder and asphalt mix testing are presented.

2 SYSTEMATIC APPROACH AND LAYOUT OF THE EXPERIMENTAL PROGRAM

The research study comprises several steps of investigation. Firstly, appropriate products gained from different tire recycling process steps in the recycling plant are selected, according to their comparability to conventional additives and by means of engineering judgment. Depending on the selected production process of the asphalt mixture, the optimum quantity of additives in the bitumen respectively in the asphalt mixture is determined by means of performance-based laboratory experimentation. Optimization-parameters are found on both scales of observation, bitumen and asphalt mixture, which allow to compare the material properties of different types of asphalt with different contents of additives, and furthermore, to predict in-service performance properties. Therefore, testing criteria for performance-based laboratory experimentation are selected with regard to the predominant types of deterioration of asphalt road pavements, which are (surface initiated) low-temperature cracking, permanent deformation by rutting, and material fatigue failure. This stepwise approach of investigation is detailed below (Figure 1).

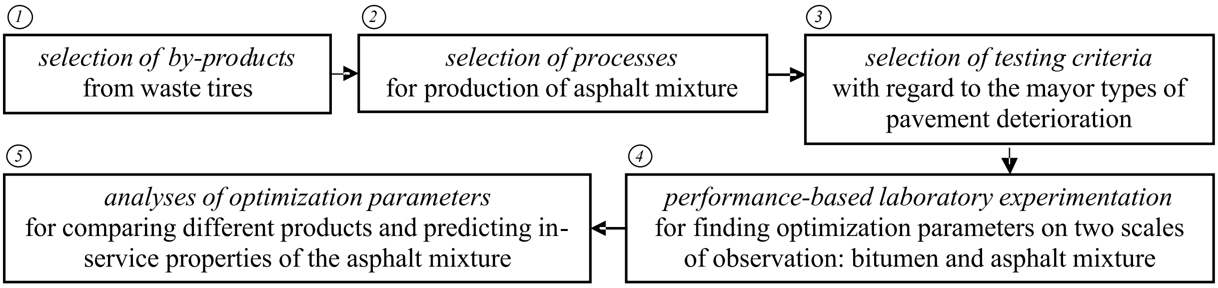

Figure 1: Systematic approach on the investigation of tire rubber modified asphalt mixtures.

2.1 Selection of recycling products and asphalt production processes

Special types of asphalt mixtures, like SMA, used for highly trafficked road pavements contain industrial fibers as additives (e.g., VIATOP®, or Arbocel®, both ground cellulose), in order to increase load capacity and temperature resistance. These industrial fibers may be substituted by less expensive products recovered from waste tires, since the morphology of industrial fibers and of fibers obtained from tire recycling is comparable. The average width is about the same and the average length of the recycled fibers can be adjusted accordingly. Due to the natural origin of ground cellulose the distribution of fiber width is very broad and a large portion of fibers are below 0.1 mm length. In contrast, fiber morphology of recycled fibers is much better (Bartl et al. 2004).

Because of the known positive effects of rubber additives on the performance characteristics of asphalt mixtures, a fully separation of fibers and rubber seems to be unnecessary from a technical point of view, and hence, the recovering process in the tire recycling plant is more easy. For this reason, the following products have been selected in this study: a *fiber & rubber blend*, consisting of fibers and of 50 mass-% residual rubber, and *rubber 1* and *rubber 2*, two fiber-free rubber products of different grain sizes. All products are exclusively gained from waste tires in the GVG recycling plant.

Two different processes of introducing the additives into the asphalt mixture are pursued, the *wet process*, where the product is directly mixed into the bitumen, and the *dry process*, where the product and the bitumen are added to the aggregate one after the other during the mixing process. In both cases a bitumen of the type B50/70 is used. The grading of the mineral aggregate is predetermined similar to the one of a noise-absorbing SMA recently used for Austrian highways with a maximum grain size of 11 mm.

For the current experimental stage of research, these fabrication processes are executed by means of usual laboratory devices only, but the applicability on the construction-site is already planned ahead.

Since the workability of the created modified asphalt mixture strongly depends on type and quantity of the additive in the mix, during the experimental stage, the maximum content of additives is predetermined due to the limitations of the laboratory equipment. In preliminary mix testing the quantity was raised stepwise (low-high-max) until the workability of the mixture was no longer given, and thus, the maximum possible content is found empirically.

2.2 Testing criteria and performance-based experimentation

In order to predict in-service performance, the bitumen and the asphalt mixture are exposed to a number of time-lapse laboratory tests, where traffic and environmental distress are simulated in accordance with field conditions, and where the failure mechanism of the test is similar to the one observed for road pavements. According to the three mayor types of pavement failure, the tests focus on the material's resistance to low-temperature cracking, to permanent deformation, and to stiffness and fatigue behavior. Optimization parameters and curves are determined by analyzing the test results, which enable the ranking of different products on the basis of the in-service behavior prediction. By means of iterative steps of testing and changes in the asphalt mix composition the SMA is comprehensibly optimized.

2.2.1 Binder testing

The US SUPERPAVE systematic for binder specification (AASHTO, 2003) is applied to comparing the performance characteristics of the modified binders to those of conventional ones. The Dynamic Shear Rheometer (DSR) is used to determine the shear-modulus G* and the phase shift angle δ in the temperature range from 46 to 82°C. The ratio G*/sin δ [kPa] can be used as optimization parameter to evaluate the stableness of the bitumen binder. The higher the ratio the higher is the resistance against deformation of the bitumen binder and thus also the manufactured asphalt mixture. For un-aged bitumen this ratio must not fall below 1.0 kPa. Viscosity, an optimization parameter to predict constructional workability, is measured by means of a Rotational Viscometer (RV). The viscosity of un-aged binders must not exceed 3000 mPa·s at 135°C temperature.

The modified samples of un-aged bitumen are also tested using a Bending Beam Rheometer (BBR), in order to assess the resistance to low-temperature cracking. Data from BBR are used to calculate two optimization parameters, the low-temperature creep stiffness S (determined at a loading time of 60 s) and the slope of response, called m-value (slope of $\log_{10}$ stiffness versus $\log_{10}$ time at 60 s), that corresponds to the material's relaxation und creep properties.

2.2.2 Asphalt mix testing

Laboratory specimens of asphalt mixtures are exposed to extreme low-temperature conditions, by means of the Tensile-Stress-Restrained-Specimen-Test (TSRST) and the Uniaxial-Tensile-Stress-Test (UTST), and to hot-temperature conditions, by means of the Triaxial-Cyclic-Compression Test (TCCT). Stiffness and fatigue properties are analyzed with the help of a 4-Point-Bending-Beam-Test (4-Point-BBT) and the Nottingham Asphalt Test (NAT).

During TSRST the length of the specimen is kept constant and the deformation of the specimen is restrained, while the temperature is decreased with a constant pre-specified cooling rate (10°C/hour). This process continues until the tensile stress exceeds the material's tensile strength and, hence, the specimen fractures, and the optimization parameters fracture temperature and the corresponding fracture stress are found.

The UTST is an isothermal process at specified temperatures. After stress-free cooling of the asphalt to the testing temperature, the UTST is performed by applying a constant strain rate (1 mm/min) until the specimen fractures.

In order to assess the risk of low-temperature cracking, the stress induced by thermal shrinkage is compared with the respective tensile strength. Combining the results of TSRST and UTST the tensile strength reserve is found, a traditionally used optimization parameter for low-temperature cracking (Arand et al. 1984).

For predicting the material's resistance to rutting, triaxial cyclic compression tests according to prEN 12697-25 (2003) are performed. Asphalt specimens are exposed at a constant temperature of 40°C to a sinusoidal axial load at constant cell pressure, while the cumulative axial strains versus number of load cycles are registered.

A 4-Point-BBT is performed, according to prEN 12697-24 (2003) and prEN 12697-26 (2003), in order to calculate the stiffness moduli and to predict fatigue properties. The Master curve of the complex stiffness modulus and the Wöhler fatigue curve are derives. Recovered stiffness moduli by means of 4-Point-BBT are finally compared to those received from NAT, according to prEN 12697-26 (2003).

Figure 2 gives a layout of the overall experimental program used for the performance-based testing of SMA, modified with products from waste tires.

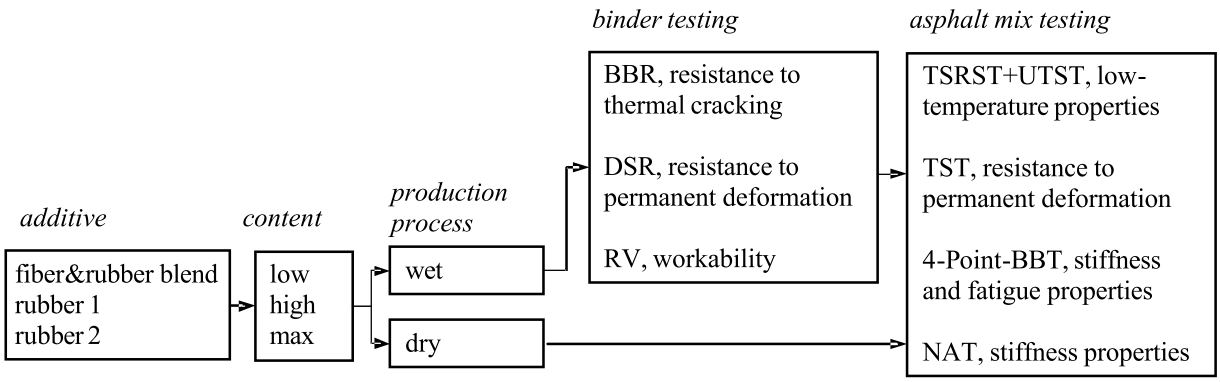

Figure 2: Layout of the experimental program.

3 INTERPRETATION OF RESULTS FROM LABORATORY TESTING

Within the framework of this on-going project some results are already obtained from performance-based binder and asphalt mix testing on fiber and rubber modified SMA. These results, which are discussed below, are promising as regards the performance characteristics of the new asphalt mixture on the one hand, and as regards the applicability of the mix design methodology on the other.

For a better understanding of performance trends, the quantity of the additive in the bitumen respectively in the asphalt mixture is varied. This variation is indicated in the figures by using the abbreviations *low*, *high* and *max*, where the latter indicates the maximum possible content known from laboratory experience.

3.1 Results from binder testing

Test results from DSR, RV and BBR are available for un-aged bitumen B50/70 modified by two different additives, *fiber composite* and *rubber 2*.

3.1.1 Bitumen modified by fiber & rubber blend

Results from DSR clearly indicate, that the bitumen's stiffness not unexpectedly is increased by adding fiber & rubber composites from recycled car tires. For pure bitumen the threshold value of $G^*/\sin\,\delta$ = 1.0 kPa is reached at approximately 68°C temperature (Figure 3a), representing the temperature which is linked to early failure of the asphalt pavement by permanent deformation (rutting).

For highly fiber composite modified bitumen the critical value is shifted to higher temperatures, up to approximately 76°C temperature (Figure 3a, *high*). Hence, asphalt mixtures using fiber composite modified bitumen are expected to be more resistant to rutting than without modification.

However, as shown in Figure 3b the viscosity is increased at the same time, worsening the workability. Since the viscosity of un-aged binders must not exceed 3000 mPa·s at 135°C temperature, the addition of fiber composite is limited.

Results from BBR indicate the low-temperature characteristics (Figure 3c and Figure 3d). Stiffness increases if the bitumen is modified with the fiber composite, as for a specific level of stiffness a temperature-shift of up to approximately 2°C is found. The m-value decreases at the same time, for a specific level of the m-value the temperature-shift is up to approximately

4°C. Hence, the addition of fiber composite to bitumen obviously rather worsens its low-temperature properties.

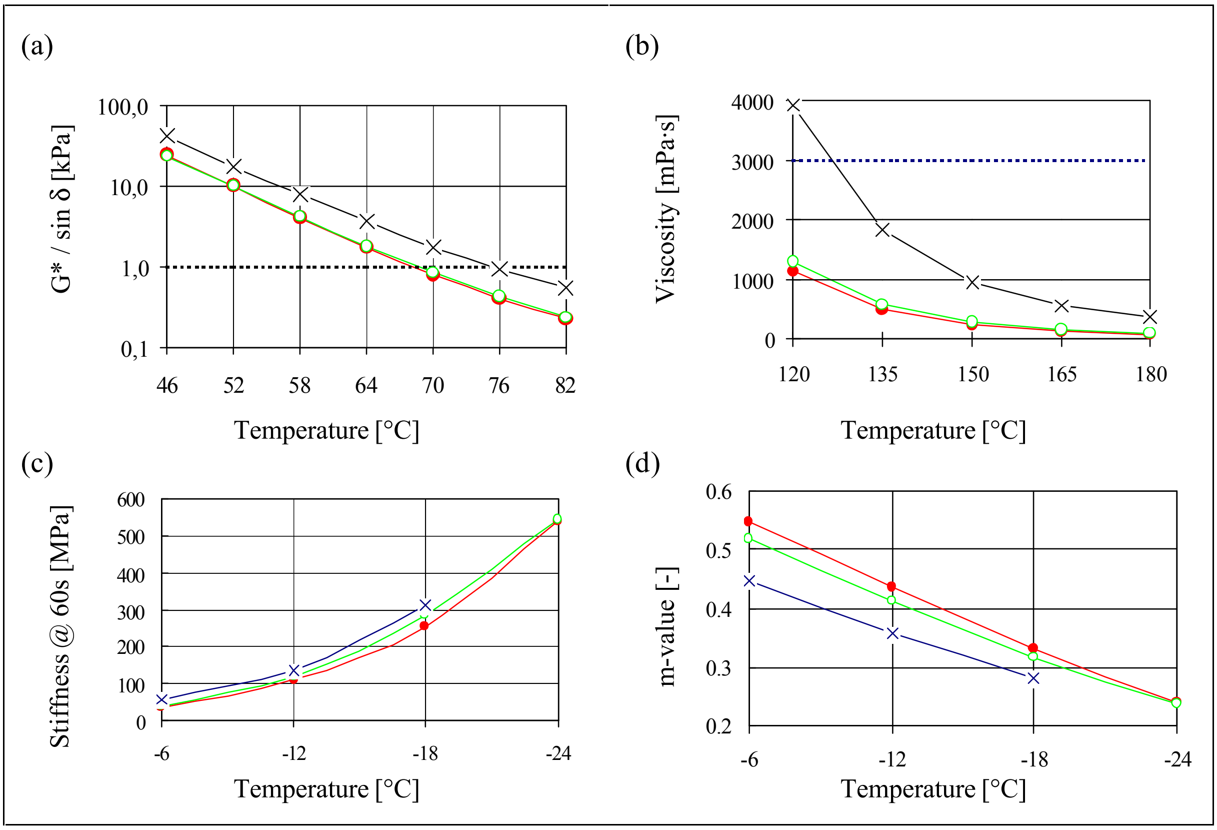

Figure 3: Content of fiber & rubber blend in pure bitumen B50/70:
no low high.
(a) G*/sin δ vs. temperature. frequ. 1.6 Hz; gap length: 1.0 mm; must not fall below 1 kPa.
(b) Viscosity vs. temperature. Pumping viscosity must not exceed 3 000 mPa·s at 135°C.
(c) Stiffness @ 60s vs. temperature. (d) m-value vs. temperature.

3.1.2 Rubber modified bitumen

Compared to the fiber & rubber blend the resistance to rutting for *rubber 2* modified bitumen without fibers is apparently better. Results from DSR show, that the critical value of G*/sin δ = 1.0 kPa is shifted about 20°C at least (Figure 4a)! However, viscosity increases tremendously at the same time, and makes workability rather difficult as far as conventional construction techniques are considered (Figure 4b).

Low-temperature characteristics are improved by rubber modification, as can be seen from BBR-results. Stiffness at low-temperatures decreases for rubber modified bitumen, as for a specific level of stiffness a temperature-shift of up to approximately 4°C is found (Figure 4d).

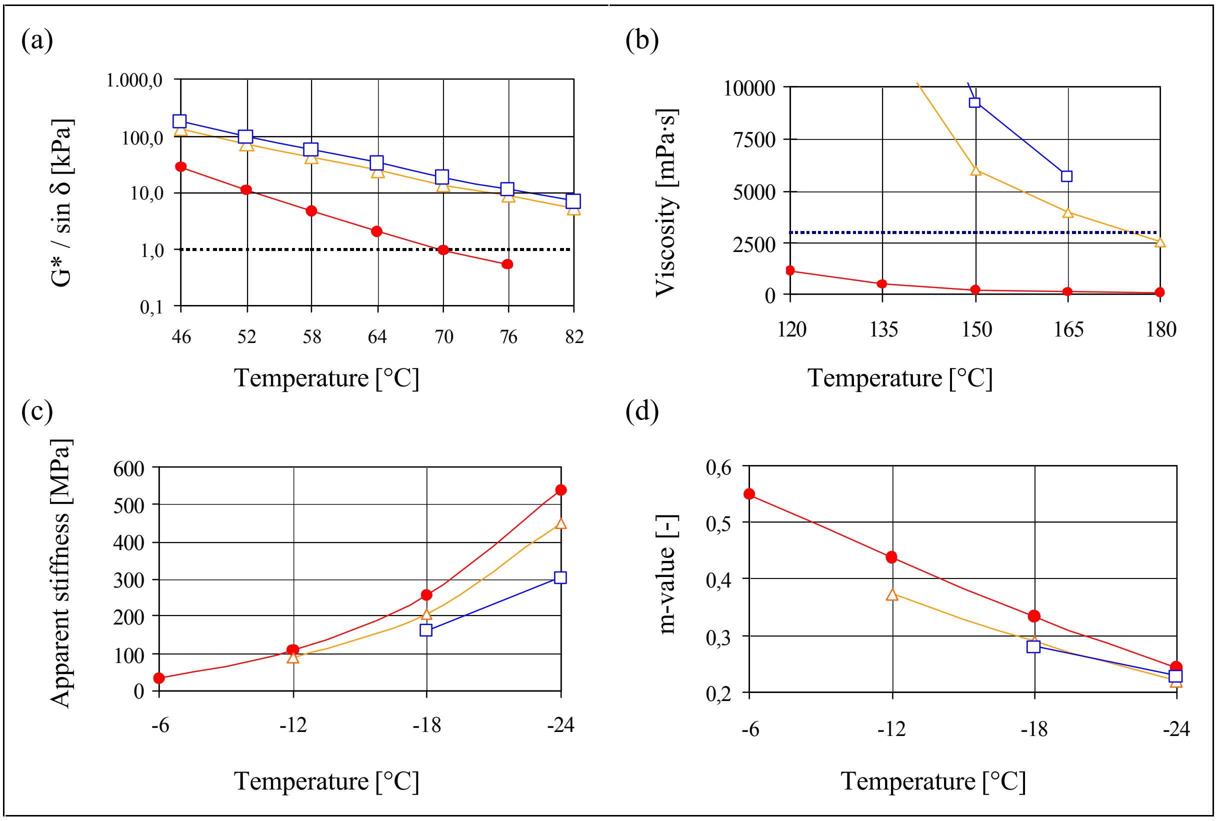

Figure 4: Content of *rubber 2* in un-aged pure bitumen B50/70: 0 high max.
(a) G*/sin δ vs. temperature. Test frequency 1.6 Hz; slit: 2.0 mm; must not fall below 1 kPa.
(b) Viscosity vs. temperature. Pumping viscosity must not exceed 3 000 mPa·s at 135°C.
(c) Apparent stiffness vs. temperature. (d) m-value vs. temperature.

3.2 Results from asphalt mix testing

Test results of asphalt mix testing are available from TSRST, UTST, TST and NAT for SMA modified by *rubber 1* in a dry process.

Figure 5 gives the results for low-temperature experimentation, TSRST (tensile strength) and UTST (stresses from cooling). Optimization parameters, i.e. fracture stress, corresponding fracture temperature, and tensile strength reserves, are in the same range for both, rubber modified and conventional SMA. Hence the low temperature behavior of rubber modified SMA is expected to be rather equivalent to the one of a conventional one with pure bitumen B50/70.

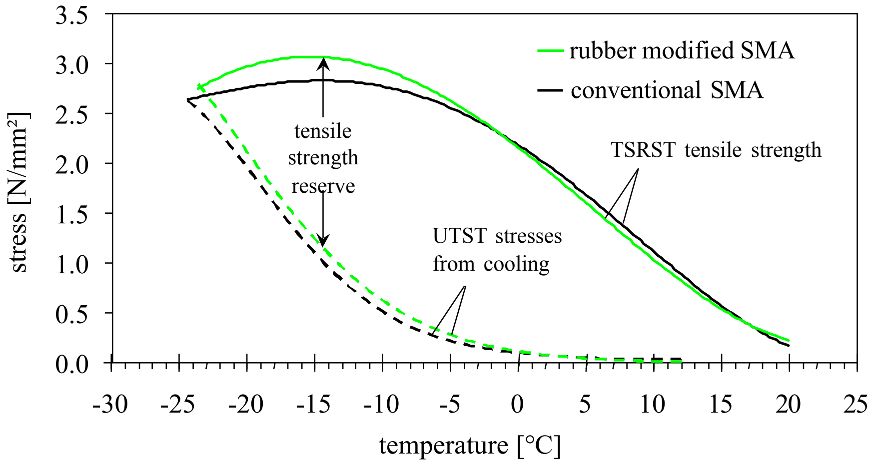

Figure 5: Results from TSRST and UTST indicating low-temperature behavior.

Triaxial stress tests (TST) are performed at 40°C temperature and a sinusoidal axial load of 5 Hz frequency, in order to determine the material's resistance to rutting at hot weather conditions and at low traffic speeds. According to the recommendations given in the prEN 12697-25 (2003) the sinusoidal cyclic axial load was chosen to vary between 250 and 850 kPa @ a constant confining pressure of 250 kPa. As a test result the cumulative axial strains are plotted versus the number of load cycles. The resulting performance for different asphalt types clearly indicates, that a rubber modified SMA is more resistant to a conventional, and furthermore that its performance characteristics are comparable to a SBS modified SMA. After 10000 load cycles the cumulative axial strains for rubber modified and SBS modified SMA are about 0,8% smaller than for a conventional mixture (Figure 6).

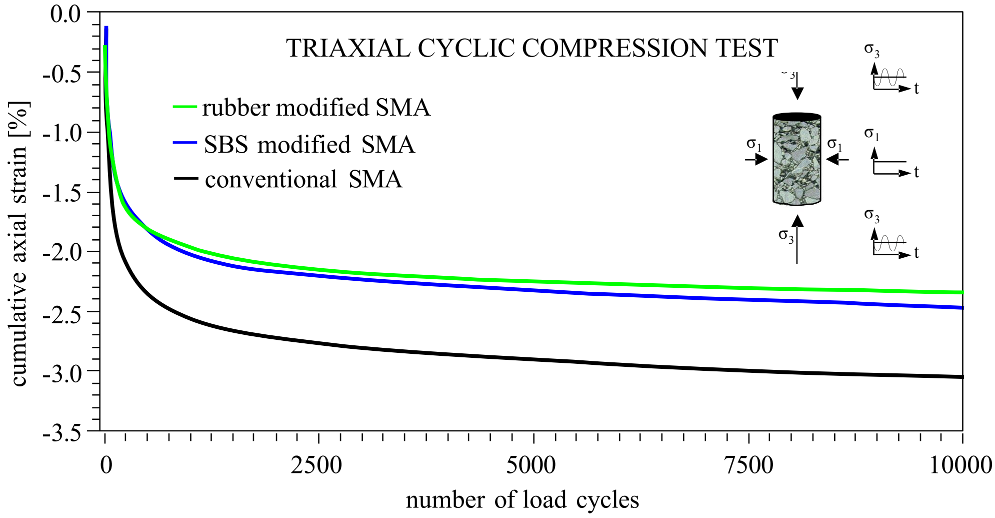

Figure 6: Results from TST indicating permanent deformation behavior (resistance to rutting).

Stiffness properties are investigated for rubber modified and SBS modified SMA by use of the Nottingham Asphalt Tester for temperatures from 2 to 20°C. In such a temperature range usually no thermal cracking is expected. As shown in Figure 7 the rubber modification significantly changes the stiffness properties. If compared to SBS modified SMA, the stiffness modulus is increased depending on the specific temperature by a factor of 1.6 to 2.8.

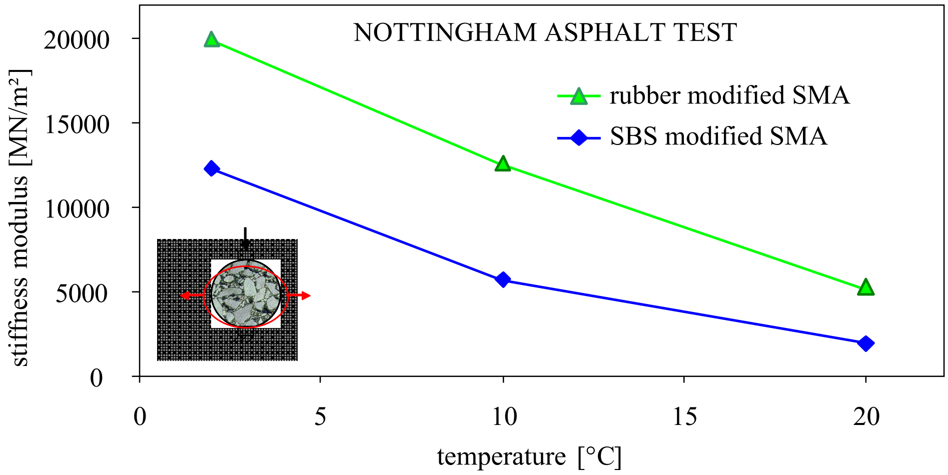

Figure 7: Results from NAT indicating stiffness behavior.

4 CONCLUSIONS AND OUTLOOK

A new type of noise reducing stone mastic asphalt SMA is tested, that is modified by fiber and rubber products originating from waste tires. For mix design a systematic performance-based test procedure has been followed. Both scales of observation are considered, bitumen and asphalt mixture and the *wet* and *dry* production process.

From the test results on bitumen modified with a fiber & rubber blend, it can be concluded, that the addition of the tested fiber composite changes the properties of the modified bitumen significantly. First test series show that the modification of the bitumen with fiber & rubber blend rather worsens the low temperature properties, but significantly improves the high temperature properties at the same time. Since the improvement at high temperatures is more distinct, the temperature range of application for the modified bitumen can be shifted, which may be an important advantage especially in warm climates.

As regards similar tests on rubber modified bitumen, the improvement of high temperature properties is even more distinct for the tested pure rubber modification of the bitumen than for the fiber & rubber composite. And supplementary, the disadvantage of down grading the low-temperature properties is not observed in case of pure rubber modification. However, a major increase of viscosity makes workability rather difficult as far as conventional construction techniques are considered.

Performance-based tests on specimens of a rubber modified type of SMA that were produced on the basis of the *dry* process, are carried out, in order to predict the low-temperature and stiffness properties, and the new material's resistance to rutting. From these tests it can be concluded, that the low-temperature characteristics of the tested rubber modified asphalt mixture are comparable to those of a conventional SMA. The rubber modified SMA can therefore be regarded as a technically equivalent alternative.

As regards the high temperature performance, the tested rubber modified SMA (*dry* process) shows a better resistance to permanent deformations in a triaxial cyclic compression test, than SMA produced with unmodified bitumen. Its behavior is technically equivalent to the one of a SBS modified SMA.

If compared to a SBS modified SMA, stiffness properties between 2 and 20°C temperature are clearly increased by the tested rubber modification (*dry* process). The increase in stiffness is regarded as technical advantage, which may lead to a longer in-service life. This intention is certainly to be proved in subsequent fatigue tests.

As a conclusion of the performance-based testing on rubber modified SMA it can be pointed out, that the tested rubber modification is a technically equivalent alternative to a conventional modification, and in warm climates without severe winters it may be even favored. In addition, if the rubber additive is used instead of industrial cellulose fibers, usually added to conventional SMA, the new type of rubber modified SMA may be economically favorable to conventional techniques.

Based on these first promising results, further work is to be carried out, in particular on rubber modified asphalt mixes. Further research will focus on the effects of rubber particle surface and grain size and fiber length distribution on the mix performance. Finally the production process is to transfer from laboratory to on-site conditions, where new techniques of processing may be required.

5 ACKNOWLEDGEMENT

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REFERENCES

AASHTO, 2003. American Association of State Highway and Transportation Officials, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. 23rd Edition.

Arand, W., Steinhoff, G., Eulitz, J. and Milbradt, H., 1984. Verhalten von Asphalten bei tiefen Temperaturen [Low-temperature behavior of asphalts]; Entwicklung und Erprobung eines Prüfverfahrens. Forschung Straßenbau und Straßenverkehrstechnik, Bundesminister für Verkehr, Abteilung Straßenbau, 407, Bonn-Bad Godesberg. In German.

Bartl, A., Hackl, A., Mihalyi, B., Wistuba, M., and Marini, I., 2004. *Recycling of Fiber Materials*. Invited paper for the 7th World Congress on Chemical Engineering, 10-14 July, 2005, Glasgow, United Kingdom.

EN 12697-24, 2003. Bituminous mixtures - Test methods for hot mix asphalt - Part 24: Resistance to fatigue. European Standard.

EN 12697-26, 2003. Bituminous mixtures - Test methods for hot mix asphalt - Part 26: Stiffness. European Standard.

Lackner, R., Blab, R., Jäger, A., Spiegl, M., Kappl, K., Wistuba, M., Gagliano, B., and Eberhardsteiner, J., 2004. Multiscale modeling as the basis for reliable predictions of the behavior of multi-composed materials. Progress in Engineering Computational Technology, Saxe-Coburg Publications, ISBN 1-874672-22-9.

prEN 12697-25, 2003. Bituminous mixtures - Test methods for hot mix asphalt - Part 25: Cyclic compression test. European Pre-Standard.

Spiegl M., Wistuba, M., Lackner, R. and Blab, R., 2005. Evaluation of temperature associated cracking in asphalt concrete by means of performance based laboratory testing. Accepted paper for the 7th International Conference on Bearing Capacity of Roads and Airfields, 27-29 June 2005, Trondheim, Norway.