Determination of Stone-Mastic Asphalt Concrete Durability

D A Yastremsky, T N Abaidullina, P V Chepur

Industrial University of Tyumen, 38 Volodarskogo St., Tyumen 625000, Russia

E-mail: Yaster.dmitry@yandex.ru

Abstract. The paper is focused on determination of durability of the stone-mastic asphalt (SMA) concrete, containing various stabilizing additives: "Armidon" (authors’ development) and "Viatop". At the first stage of experiments, the APA method was used to determine the rutting in the SMA containing these additives. Strength test for only top layers of asphalt concrete surface is insufficient for the calculation of the pavement fatigue resistance limits. Due to this fact, a comprehensive approach was employed which incorporates the interaction of the surface and subgrade natural soil. To analyze the road surface stress-strain state and to determine the durability margin, a numerical model was used (describes the processes of fatigue life). The model was developed basing on the finite element method (FEM) in the ANSYS program. Conducted studies and numerical calculations allowed obtaining the minimum and maximum stress values in the structure affected zones and in the zones of plastic deformations occurrence in artificial and natural bases. It allows predicting deformation processes during repeated wheel loads caused by moving vehicles. In course of studies, the results of static stresses in the pavement were also obtained.

1. Introduction

Existing asphalt concrete testing methods stipulated by the Russian Federation state standards do not allow one to fully assess the durability of the material in service and to reliably predict the pavement service life [1-2]. National regulations define asphalt concrete durability basing on maximum loads at failure, while the surfacing material is subjected to cyclic loads of much less critical values. Therefore, to evaluate the durability of the road surface materials and their ability to resist operational effects, authors carried out a set of tests to determine rutting resistance at positive temperatures of the Stone Mastic Asphalt (SMA) concrete – a material used under high traffic density and which is an independent kind of asphalt concrete [3].

SMA was developed in 1966 in Germany and since 1970 has become widely used in road construction. It was named «Splitsmastixasphalt» (SMA) [4-5].

Continuously increasing cyclic wheel-load inevitably causes rutting in SMA which includes several specific stages. At the first stage, additional compaction of mixture occurs, where increment of rut depth depends on the material residual porosity. The next stage is creep – increasing the number of wheel-runs causes strain accumulation, which leads to rutting. The rut depth in this case depends on the binder type, particle size distribution, grain shape etc.

2. Materials and methods

Asphalt concrete resistance to rutting was determined by means of the Asphalt Pavement Analyzer (APA), Pavement Technology Inc. in accordance with the AASHTO TP 63 methods (APA method).
The methods were developed by the American Association of State Highway and Transportation Officials and have become widely known and accepted throughout the world.

The APA method involves determining the rut depth caused by the force moving along the air hose of the metal wheel (Figure 1a). Predetermined pressure was maintained in the hose. Thus, real operating conditions for the surface material are simulated [7].

Methods of assessing the asphalt concrete fatigue life have also become widely accepted in European countries. These methods are regulated by EN 12697-24 standard in Europe and by AASHTO TP 8 and AASHTO T 321 standards in the United States.

Strength test for only top layers of the asphalt concrete surface is insufficient for the calculation of the resistance limit points of pavement fatigue. Due to this fact, a comprehensive approach was employed which incorporates the interaction of the surface and subgrade natural soil. To analyze the roadway surface stress-strain state and to determine the durability margin, a numerical model was used (developed by authors basing on the finite element method (FEM) in the ANSYS program) [8].

3. Experiment

To determine the rutting with the APA method, a series of SMA-20 samples was prepared by using AVCII vibropress (75 mm in height and 150 mm in diameter) of the bitumen-concrete mixture with the stabilizing additives (SA) "Viatop 66" (Germany) and "Armidon" (Russia – authors’ design). Basic materials selection and their optimum amount were determined in the authors’ work [9].

The test duration was limited to 12,000 cycles of the wheel-run with applied wheel load of 0.69 MPa. The pressure in air hoses was set to 700 ± 35 kPa. The rut depth was automatically recorded throughout the entire test period. The temperature of samples and the test chamber was 50 °C.

Two compositions of bitumen-concrete mixtures were prepared. For each composition, 12 samples were prepared and tested through. The maximum value of rutting for each composition was taken as the average value for all the twelve samples tested. Figure 3 displays the test results on the formation and deepening of the rut in the SMA-20 samples with the "Viatop 66" and "Armidon" additives at a temperature of 50 °C.

To calculate the fatigue stress by means of the numerical model made in the ANSYS 16.0 program, one can use a variety of empirical methods including the theory of Gerber, Goodman and Soderberg which are used for mean stress observing. Goodman and Soderberg theory is to be applied to brittle materials. Since stone mastic asphalt concrete is a plastic material, the most suitable in this case is the Gerber theory. This theory equally describes the negative and positive mean stress, in contrast to Goodman and Soderberg theory, which cannot be applied to negative mean stress. This is due to the
ability of compression mean stress to inhibit the fatigue cracks growth so that the conservative effect of negative mean stress is ignored [10].

To perform the most accurate stress-strain analysis of the roadway elements and to construct the finite element model, one should know the physical and mechanical properties of all the structural layers of the pavement and the subgrade. For this end, a series of conventional studies was conducted [11-12]. The results of the studies are presented in the previous work [13]. Analysis of the obtained data allowed making a design scheme presented in Figure 2. The scheme comprises the soil body with thickness of over 10 meters, a bottoming and the asphalt-concrete pavement consisting of three layers as stated in reference documentation. The pavement surface was loaded along four ruts, each 600 mm in width according to [2]. The length of simulated road segment was 30 meters with the total width of 30 meters including slopes. Boundary conditions limit the movement of the 6th and 7th layers side walls, as well as the footing base - the 7th layer.

The model consists of the following elements: SOLID 186 elements (in soil body), SHELL 181 elements (in three layers of asphalt concrete), CONTA 174 and TARGE 170 (for setting the contact interaction of layers), SURF 154 (used for vehicle load effect application). In total, the model comprises 12 zones of «bonded» type contact interaction. After dividing into the finite element mesh, 136 000 elements and 247 330 nodes were generated.

![Figure 2. A design scheme of a highway structure. An elasto-plastic model of multilayer surface and subgrade: 1 – stone mastic asphalt (SMA – 20) concrete - 0,05 m; 2 – porous asphalt concrete (grade I) of coarse-grain mix - 0,07 m; 3 – porous asphalt concrete (grade I) of coarse-grain mix – 0,06 m; 4 – macadam base - 0,34 m; 5 – coarse sand - 2,48 m; 6 – low-plastic loam - 5,0 m; 7 – semisolid loam - 6,0 m.](image)

4. Results
The AASHTO TP 63 (APA) method specifies the maximum allowed rut depth - 12 mm after 8000 cycles. During the experiment, the rut did not reach the peak value even after 12000 cycles of wheel-runs (the peak value of rut for compositions with "Armidon" additive was 9.16 mm, and with "Viatop 66" additive - 9.7 mm) (Figure 3). Thus, it was found that the ability of SMA-20 with "Armidon" stabilizing additive (SA) to resist the plastic deformation during repeated wheel loads is higher by 6% than the same ability of SMA-20 with "Viatop 66" SA.
Figure 3. Rut depth dependence on the number of wheel-runs and additive type

The FEM based mathematical model was developed and used to provide a more detailed study of the road structure dynamic deformations and of the way the "Armidon" and "Viatop 66" stabilizing pulp and paper additives affect the SMA-20 properties. Figure 3 displays the test results of the SA effect on accumulation of the residual deformations.

Highway experts and scientists, who at that time developed theoretical and practical bases of methodology and instructions for non-rigid pavements design and construction, suggested that a subgrade, a road base and a surface would only work at the elastic stage without accumulating plastic (residual) deformations. However, in reality in most cases all materials and layers of the road structure behave as the elastic-viscous-plastic materials and zones gradually accumulating residual deformations according to the cyclic creep law, which ultimately leads to the surface local unevenness and rutting on the road tracks [14].

FEM calculations of the multilayer road structure, performed in the ANSYS 16.0 software package, showed the following results:

1– Fatigue life, that is the limiting number of wheel-runs cycles to failure was $N \geq 5765 \, 000$ runs.

2– Using the SN approach theoretical calculations, the safety factor for durability was determined

$$n_{SF}^N = N_b / N ,$$

where $N$ is the current durability; $N_b = 10^9$.

It is determined that $n_{SF}^N \leq 1.9$.

3 – The safety factor for stress amplitudes was determined (2):

$$n_{SF}^{\sigma} = \sigma_{at} / \sigma_{eqv} ,$$

where $\sigma_{at}$–principal stress of the peak values tensors;

In accordance with (2), it is determined that value $n_{SF}^{\sigma}$ is within the 1–3.67 interval (fig. 3a).

4 – After reduction of the uniaxial loading cycle reduced characteristics to the symmetric cycle of equivalent damage (fig. 3b), equivalent stress amplitude $\sigma_{eqv}$ was obtained which lies in the range of 2.44-10.19 MPa (3)

$$\sigma_{eqv} = \frac{\sigma_{at}'}{1 - \left( \frac{\sigma_{at}'}{\sigma_{u}} \right)^2} ,$$
where $\sigma^l_a$ – principal stress of the peak values tensors;

**Figure 4:** a - Safety factor for stress amplitudes, b - Equivalent stress amplitude obtained after reduction of reduced characteristics of the uniaxial loading cycle to the symmetric cycle of equivalent damage
5. Conclusion

1. Experiments showed that the SMA-20 containing "Armidon" SA has the increased values of operational properties. Its ability to resist the plastic deformation during repeated wheel loads is higher than the same ability of SMA-20 with "Viatop 66" SA by 6%.

2. A mathematical model of the rutting in the asphalt concrete surface was developed. The model describes the fatigue life processes. On the tested SMA surface segment, the distribution of safety factors values was as follows: safety factor for durability ($n_{SF}^N \leq 1,9$), safety factor for stress amplitudes ($n_{SF}^\sigma$, on an interval of 1-3.67). Numerical calculation determined the distribution of equivalent stress amplitudes: ($\sigma_{equiv}$, on an interval of 2,44-10,19 MPa).

3. Conducted studies and numerical calculations allowed one to obtain the minimum and maximum stress values in the road structure affected zones and in the zones of plastic deformations occurrence in the artificial and soil base. It allows predicting deformation processes during repeated wheel loads caused by moving vehicles. In the course of the studies, the results of static stresses in the pavement were also obtained.

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