Evaluation of durability of the asphalt-concretes under static fatigue

Victor Zolotaryov[1, a], Imad Ali Al-Shalout[2, b]

[1] *Department Of Technology Road Building Materials, KHARKOV NATIONAL AUTOMOBILE ROAD UNIVERSITY, Kharkov, Ukraine*

[2] *Civil Engineering Department, Zarqa University, Zarqa, Jordan*

[a] vvm@khadi.kharkov.ua

[b] emad_alshalout@yahoo.com

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ABSTRACT

Forecasting the durability of asphalt- and polymer concretes which is actual in the aspect of the eternal (or high durability) roads concept is executed in recent years on the basis of the testing results under cyclic loading on bending with constant amplitudes of stress or deformation.

Such tests are rather complicated, expensive and ambiguous because of the difficulties with providing symmetrical loading with respect to the zero value stress.

It is far easier to determine the asphalt concretes lifetime from the begining of loading till the total destruction of the sample by means of double-point loading via series of constant loads (the static fatigue while creeping). As a result a dependences similar to Woehler diagrams are received. Analysis of literature reveals that dependences of a number of cycles and times of destruction via stress for the same objects have close values of exponents (they are almost similar) in case of relatively congruous stressed states and temperatures.

In this case the objectively equitable lifetimes of various asphalt-concretes can be achieved under the equal levels of stressed state which are defined by the ratio of the quantity of stress which is imposed on the asphalt concrete sample to the asphalt-concrete strength at the preset speed of deformation.

The available lifetimes range from 10 seconds to many days. This allows to detect the lifetimes under near-critical stresses which correspond to the boundary of the transition to the linear viscoelastic behavior of asphalt concretes at a wide range of temperatures as well as under the simultaneous effect of stresses and liquid corrosive media (water, water solution of deicing agents, oil and lubricants etc.).

Keywords: Durability, Fatigue Cracking, Mechanical Properties, Modified Binders, Testing

1. INTRODUCTION

Traditionally, number of cycles which asphalt mix withstands under the bending with constant loading levels and deformations is used as this criterion [1, 2]. To ensure objectivity of the criterion, it is paramount to comply with the test conditions under which the number of cycles would approach to the in-situ number of passages, asphalt concrete would typically experience throughout pavement operational stage. According to different literature sources, the number of cycles may vary from 80×10^6 to 200×10^6 [3]. A fulfillment of in-situ conditions is rather problematic because it requires a long period of time and high reliability of the equipment applied in the testing. To achieve a shorter testing time, it is feasible to either increase loading or strain magnitudes (Figure 1). However, it is then more challenging to make sure that stresses (σ_L) and strains (ε_L) remain within the linear visco-elastic region as shown in Figure 1, thereby diverging from the primary test condition. A linear deformation limits could be determined by carrying out either dynamic or static test at variable strain rates [4] or loading durations [5]. In both cases, the experiment is conducted covering a broad frequency sweep [4] or stresses (5) ranging from very small values until a direct proportionality between stresses and strains is no longer maintained/observed. Based upon a deviation tolerance of 10-15 % from the linearity state, critical stresses (σд) and strains (εл) are afterwards estimated.

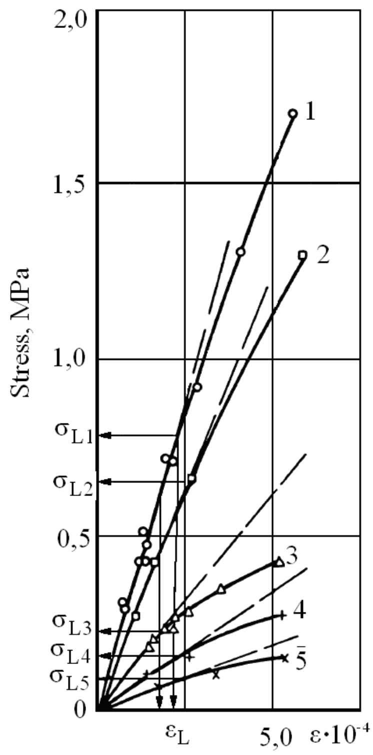

Figure 1: The stresses (σ) as a function of strains (ε) relationship for the asphalt concrete of the type A at the temperature 20 ºC with the bitumen BND 60/90 at deformation frequencies in Hz: 1 - 20; 2 - 5; 3 - 0,5; 4 - 0,05; 5 - 0,01

Linear deformation limits are dependent on frequencies, temperature, asphalt mix composition, the bitumen type and other factors (Table 1 and 2).

The degree of deformation that corresponds to a linearity range, increases with respect to bitumen penetration and its content increase, transition process from oxidised to a distilled bitumen state or due to introduction of polymer additives and their content increase (Table 1 and 2). Effectively, similar dependencies can be attributed to critical stresses with an exception for bitumen content impact. For fatigue tests it is crucial so that the ratio of σ_L to the asphalt mixture flexural strength (R_f) varies in a similar manner. These ratios range between 0,06 (for low-viscous bitumens) and 0,22 (for high-viscous bitumens and PMB).

Table 1: ε_L and σ_L values at frequency 0,5 Hz and temperature 20 ºC of asphalt mixtures with unmodified bitumen

Property indexes	Penetration, 0,1 mm				Bitumen content, %				Bitumen type		
	40/60	60/90	90/130	130/200	4,25	5,0	5,75	6,0	“gel”	“sol-gel”	“sol”
$\varepsilon_L \times 10^{-4}$	3,5	2,5	2,0	1,8	1,8	2,5	3,0	3,7	1,2	4,0	4,8
σ_L, MPa	0,42	0,22	0,11	0,94	0,15	0,22	0,30	0,19	0,11	0,52	0,67
R_f^{20}, MPa	2,6	2,0	1,7	1,4	1,8	2,0	2,05	-	1,3	2,3	2,65
σ_L / R_f	0,16	0,11	0,062	0,060	0,08	0,11	0,14	-	0,08	0,22	0,25

Stresses, that are close to the linearity limit, are very small and it is difficult to fulfil them under cycle fatigue test. Besides, the results of cyclic tests can be affected by way the loading is applied (e.g. sinusoidal, cyclic in the form of square-like pulse or ramp pulse); the degree of induced load relative to a zero stress value in the specimen; loading frequencies under sinusoidal loading; loading regimes (loading and rest periods), where loadings that are different to sinusoidal. High loading rates could be accompanied by temperature rise, thereby causing a drop in stiffness of the asphalt mixture. As a result of aforementioned test parameters, it is often infeasible to perform adequate comparison amongst the results obtained in different laboratories [2, 6].

Table 2: ε_L and σ_L values at frequency 0,5 Hz and temperature 20 ºC of asphalt mixtures with unmodified bitumen and modified bitumen by polymers of SBS type

Property indexes	Bitumens of different penetration and BMP modified by 3 % of polymer								Bitumen with polymer content, %				
	46	BMP 30	70	BMP 46	116	BMP 60	176	BMP 6	0	3	5	7	10
$\varepsilon_L \times 10^{-4}$	2,25	2,5	1,5	2,2	1,25	1,5	0,9	1,5	1,25	1,5	2,2	2,65	2,85
σ_L, MPa	0,54	0,72	0,28	0,48	0,17	0,28	0,09	0,26	0,17	0,28	0,54	0,55	0,53
R_f^{20}, MPa	2,61	2,95	2,3	2,58	2,13	2,41	1,96	2,26	2,13	2,41	2,52	2,56	2,60
σ_L / R_f	0,21	0,24	0,12	0,19	0,08	0,12	0,051	0,12	0,08	0,12	0,21	0,22	0,20

Shortcomings that occur, when dealing with repeated loading tests, could be eliminated if using creep tests until failure under a series of continuous loading, is reached. It is consequently possible to determine the static fatigue (i.e. asphalt mixture life time) relationship as a function of variable stresses. This implies that such tests could avoid leading to unpredictable impact on the asphalt concrete fatigue index originating from the rest intervals between cycles. The test is easy to conduct and closely enables to approach to the concept of "durability" [1, 7].

2. EXPERIMENTAL STUDIES

The adopted methodology consists in estimating the flexural strength (R_f) of rectangular beams with application of four-point bending test at specified temperature (in this case being set at 21 ºC) and loading rate (3 mm/min). Afterwards, set of beams are subject to continuous loading action resulting in stresses (σ_d) being equal to 0,1; 0,2; 0,3; 0,4; 0,5 out of flexural strength. Series of beam specimens have been divided into 4-5 sets. The first set of specimens were subject to a load to generate a stress σд equal to 0.4 R_{20}; lifetime is, at the same time, recorded from the point of the load application to the failure mode. All other specimens are subsequently investigated establishing stress magnitude at (0.1; 0.2; 0.3; 0.5) R_{20}. A test data is then presented in terms of relationship between lifetime (t) and σ_d on a logarithmic scale. The slope of these dependencies is characterized by power (m) in compliance with an equation

$$t = A \cdot \sigma_d^{-m} \quad (1)$$

Asphalt concrete lifetime characteristic is very sensitive with regards to composition and structure of the asphalt concrete as well as properties of constitutes it is made up of. This relationship is readily seen, when plotting the mixture lifetime as a function of stresses for a range of bitumens with various penetrations (Figure 2). For instance, considering the stress level of 0,7 MPa, the asphalt mixture lifetime produced with different bitumens with penetration (at 25 ºC) being equal to 64×0,1 mm, 103×0,1 mm, 160×0,1 mm, would respectively decreases by 17; 56; 329 times in comparison with the asphalt mixture on the bitumen with penetration 43×0,1 mm. This difference would grow as the magnitude of generated stresses is lower. In this connection the penetration values for above-mentioned bitumens correlate as 1,49; 2,40; 3,71 and respective bending strength ratios – as 1,4; 1,6; 2,33.

These ratios decline multifold when turning to the static fatigue test with the same stress level for different asphalt mixture. At $\sigma_d/R_f = 0,2$ they are equal to 4, 10, 19 and these values, as in the previous case, are decreasing when stress level increase but their magnitudes are much closer to virtual asphalt mixture long-term performance ratios. These ratios are in a good agreement with viscosity ratios (2,8, 10, 20 times) of bitumens with different penetration derived in [8].

Considered approach allows differentiate effects of a range of factors on durability of asphalt mixtures. A special attention is given to analysis of durability, when polymer modified bitumen is added to the mixture. Introduction of 3 % of SBS into bitumens with penetration 64×0,1 mm, 103×0,1 mm, 160×0,1 mm extends asphalt mixture lifetime by 2,15; 2,25 and 3,23 times respectively, which is substantially higher than gains in strength that accordingly went up by 1,39; 1,35; 1,6 times (Table 3).

As an example, lifetime bituminous mixture with 40 % of aggregate and 5 % of bitumen with penetration 46×0,1 mm, being compacted up to the residual void content of 4,6 % and 8 %, in the case of 0,5 MPa loading level, would be $5,0\times10^4$ sec and $1,0\times10^4$ sec respectively (the ratio is 5), whereas if exerting identical stress level ($\sigma_d/R_f = 0,2$) – $2,5\times10^4$ and $1,26\times10^4$ (the ratio is about 2).

Throughout the service life pavement bituminous surface courses are exposed not only to loadings action but also liquid corrosive mediums. In the EU, evaluation of moisture damage is commonly undertaken by applying the M. Duriez method (EN 12697-12). Similar methodology is used in the Ukraine and Russia, but preliminary immersion time (15 days) is twice longer for preliminarily water-saturated specimen. This methodology and compressive failure of the saturated specimen do not properly capture pavement in-situ response. The static fatigue method allows eliminate this deficiency by simultaneously bending asphalt mixture specimens and exposing them to a liquid medium. This implicates that in the lower part of the specimen tensile stresses would cracks, which in turn would facilitate penetration of medium into cracks and further occurring defects, which are overlooked in the case of normal stresses under compression. Water and diesel fuel have been envisaged to illustrate the aggressive medium impacts.

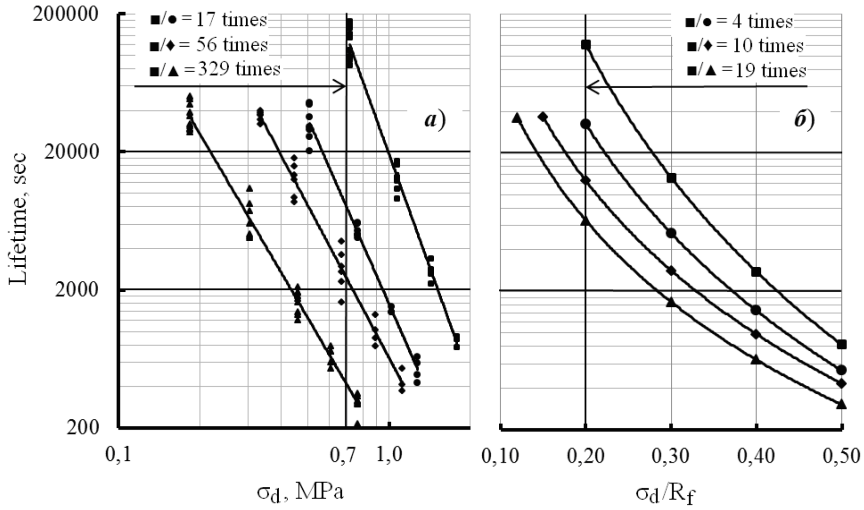

Figure 2: The relationship between asphalt mixture lifetime of the "G" class based on four unmodified bitumens as a function of stresses generated by a constant loading (a) and stress state level (b):
■ – B (43); ● – B (64); ♦ - B (103); ▲- B (103)

Table 3: Comprative results of asphalt mixtures static fatigue based on unmodified bitumen and modified bitumen with 3 % of SBS at σ_d/R_f = 0,2

Indexes	Bitumen binder with penetration, 0,1 mm					
	Bitumen 64	PMB 52	Bitumen 103	PMB 74	Bitumen 160	PMB 107
Flexural strength, MPa	2,50	3,48	2,23	3,01	1,53	2,45
Lifetime, sec $\times 10^{-3}$	32	69	12	27	6,5	21
Lifetime ratio	1	2,15	1	2,25	1	3,23

The PMB with 3 % polymer content prolongs the lifetime in the presence of moisture as follows: for bitumen 64×0,1 mm penetration by 2,1 times, 103×0,1 mm by 2,2 times, 107×0,1 mm by 3,4 times (Table 4). In this regard, corresponding flexural strength increases by 1,4; 1,35; 1,6 times respectively. To more objectively assess polymer influence on the asphalt mixture liquid resistance, it is reasonable to make comparison of lifetimes of those mixtures which are fabricated with a bitumen of close penetration grade. Taking an average penetration of two PMB (52×0,1 mm and 74×0,1 mm) equal to 63×0,1 mm, a mean asphalt mixture lifetime would equate to $41{,}5\times10^3$ sec, while the lifetime of the asphalt mixture with unmodified bitumen of 64×0,1 mm grade, would reduce down to $27{,}5\times10^3$ sec, in other words the durability of the polymer modified asphalt mix is 1,5 times greater. In the event of the mixture with bitumen 103×0,1 mm penetration and the mixture based on the PMB 107×0,1 mm penetration, lifetime of the latter combination is by 1,7 times higher. Addition of a surface-active agent into the PMB increases the asphalt mixture lifetime in the presence of moisture by 1,27 times compared with the asphalt mixture with the PMB having 107×0,1 mm penetration, whilst in comparison with asphalt mixture with unmodified bitumen of 103×0,1 mm grade, performance is larger by 2,2 times.

Table 4: The influence of liquid mediums on the asphalt mixtures and PMB asphalt mixtures lifetime

Medium	Index	Bitumen with penetration, 0,1 mm						
		B 64	PMB 52	B 103	PMB 74	B 160	PMB 107	PMB + 0,7 ASA 102
Water	Lifetime, 10^3 sec	27,5	59,2	10,7	23,9	5,5	18,5	23,5
	T_{BMP}/t_B	1	2,1	1	2,2	1	3,4	4,3
Diesel fuel	Lifetime, 10^3 sec	7,8	23	4,4	10,2	2,35	7,5	-
	T_{BMP}/t_B	1	2,9	1	2,3	1	3,2	-

The effect of combustive and lubricanting liquid (diesel fuel) dramatically reduces the asphalt mixture lifetime at σ_d = 0,29 (Table 4). It should be noted that when bitumen penetration changes from 64×0,1 mm to 103×0,1 mm and 160×0,1 mm, the lifetime decreases from $7{,}8\times10^3$ sec to $4{,}4\times10^3$ sec and $2{,}35\times10^3$ sec, respectively (i.e. by 1,8 and 3,4 times).

It is found that by adding 3 % of polymer into the bitumens extends the polymer modified mixture lifetime in case of the diesel fuel damage by 2,9; 2,3 and 3,2 times, respectively. Given the fact that polymer alters bitumen properties shifting it to a more consistent state, which basically improves asphalt mixture performance, it is more appropriate as in the case with water, to evaluate unmodified and modified mixture performance by looking at bitumens with close penetration grade. It is therefore possible to correlate the mixture lifetime between unmodified bitumen having 64×0,1 mm penetration ($7,8\times10^3$ sec) and the PMB-based mixture ($16,1\times10^3$ sec) having 52×0,1 mm and 74×0,1 mm penetration (the average is 63×0,1 mm). In particular, this has indicated that the mixture lifetime would be extended by 2,1 times. Regarding the mix with unmodified bitumen 103×0,1 mm penetration and PMB 107×0,1 mm penetration, the lifetime of the former appeared to be shorter as compared with the latter by 1,7 times. A failure of bituminous mixes under cyclic and static fatigue test is verified by a clear similarity between exerted stresses and number of cycles/lifetime for both these tests, i.e. a power «m» is equal in fitted equations. Identical results have been presented in [1]. Furthermore, it has been noted in [1], that at cyclic/sinusoidal loading degree being set at 61 % of the permanent stress, there could be seen a relationship common for both loading modes. Obviously, setting the stress level at 61 % is not a unique loading scenario, nevertheless, according to [1], it is sufficiently enough to justify the developed static fatigue/durability assessment methodology.

CONCLUSIONS

In order to ensure that lifetime performance parameter is comparable, it is necessary to verify whether the ratio of stresses within a specimen to a flexural strength is equal for a range of considered mixtures. Stresses that fall within linear viscoelastic limits are regarded as acceptable. The stresses in the linearity limits range are expected to increase as a result of bitumen penetration decrease and addition of SBS polymer into bitumen in amounts of 3 to 7 %.

For the same stress conditions, a change in the asphalt mix lifetime that takes place to due to various causes, is much greater than in the strength parameter. It has been identified that a rise in penetration from 64×0,1 mm to 160×0,1 mm would lead to a drop in the mixture performance lifetime by 4,9 times, whereas the flexural strength will fall by just about 1,6 times. Addition of 3 % of polymer into previously mentioned bitumens increases lifetime under bending by 2,1 and 3,2 times respectively, while the flexural strength inclines by 1,4 and 1,6 times.

By means of the static fatigue technique, it is straightforward to take account of simultaneous effect of loading and moisture damage (or other aggressive fluid). It could be pointed out that the performance lifetime of the mix with 64×0,1 mm bitumen penetration is 5 times and 3,4 times longer, respectively, in the case of moisture and diesel fuel damage, compared with the mixture with less viscous bitumen of 160×0,1 mm grade.

A modified bitumen will embed an improved performance to resist water damage increasing durability by 2,1 times and 3,4 times for bitumen with 64×0,1 mm and 160×0,1 mm penetration grade, respectively. The effectiveness of polymer against diesel fuel impact for the same bitumens is in the range from 2,9 to 3,2 times.

It could be concluded that the discussed experimental findings have clearly shown that the static bending fatigue test is capable to adequately and effectively evaluate/distinguish durability of diverse asphalt mixtures with modified or unmodified bitumens.

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