Energetic method as an alternative for conventional method in fatigue life analysis of bituminous mixtures

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ABSTRACT

Fatigue test is now becoming more frequently applied for bituminous mixtures evaluation. European standards describe the tests methods and propose categories of resistance to fatigue. According to the standard EN 12697-24:2004 and AASHTO TP8-94 the conventional failure criterion shall be used to determine fatigue life of a bituminous mix, but other criteria are also permissible. This possibility is given because the conventional failure criterion is considered to be not objective. For example, 50% reduction of stiffness does not mean extensive fatigue cracking for one material, while in case of another material means significant micro- and macro-cracking. The alternative is the method based on dissipated energy concept. According to this method fatigue life is defined as the number of cycles until the moment when a sudden change in the total dissipated energy per cycle is observed. This paper presents the test results obtained with use of both method and shows advantages of using the energetic method. For the purpose of work a specific parameter: critical loss in stiffness modulus was introduced. It is defined as percentage value of stiffness modulus reduction during fatigue test at the moment when the energetic criterion is obtained. The analysis covers different types of asphalt mixes and grading, several asphalt binders and various test temperatures.

- *Keywords: fatigue life, fatigue law, dissipated energy*

1. INTRODUCTION

Resistance to fatigue of bituminous mixtures can be laboratory tested with use of several test methods. Specimens are subjected to cyclic loading at given testing conditions. Stiffness modulus is decreasing with number of cycles. A typical stiffness evolution is shown on figure 1, where three phases can be identified, Di Benedetto et al. (1997). Phase 1 covers the beginning of test, where the decrease in stiffness is rapid due to internal heating phenomenon. In phase 2 decrease in stiffness is slower and linear, until phase 3, when coalescence of micro-cracks starts and failure is very fast.

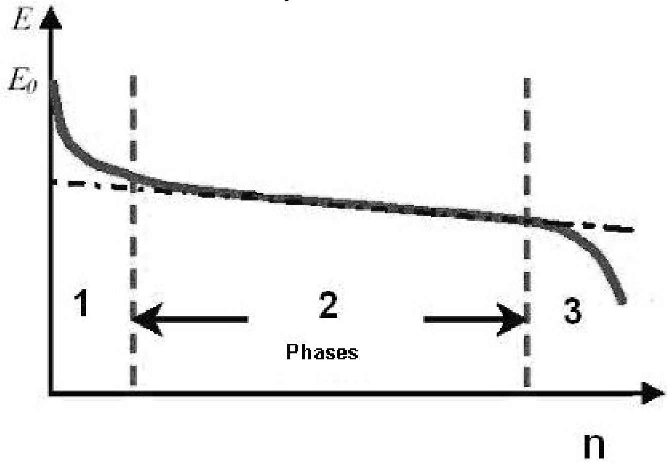

Figure 1 Typical phases in fatigue test

Fatigue life of a specimen is defined as a number of cycles corresponding with the chosen failure criterion. The conventional criterion defines failure, as a moment when the stiffness modulus has decreased to the half of its initial value. This criterion is supposed to be a subjective failure definition, that considers only the stiffness of a specimen, but not material properties and fatigue process itself. At specific testing conditions (high temperature and high strain amplitudes), the decrease in stiffness in phase 1 is sometimes very considerable. Applying of the conventional criterion may be the reason for differences in test results obtained with use of different test methods, Pronk (1997). Such factors as clamping method, homogenity of specimens, material properties, testing conditions etc. lead to the scatter of test results. Therefore analysis should be more complex as it is defined in the conventional criterion.

The new conception of fatigue life definition (N1) based on dissipated energy approach was presented in Madrid by Hopman, Hopman et al. (1989). Dissipated energy is mostly transformed into heat, but increase in temperature is rather small and cannot be completely responsible for the decrease of stiffness modulus, Pronk (1996). The rest of energy leads to the fatigue of specimen. During the test a sudden change in the evolution in the total dissipated energy can be observed and it indicates the beginning of the crack propagation phase (forming of a network of micro-cracks and macro-cracks, disintegration of the material), Pronk (1998, 1999).

According to the new definition, fatigue life (N1) is defined as the number of cycles, after which the ratio of dissipated energy deviates from the straight line, Pronk (1997). A typical plot for the strain controlled test is shown on figure 2. Fatigue life N1 can be estimated with use of two graphical methods A and B. However that are not precise and not easy to use. Method A leads to the overestimation, when in method B the result is subjective, depended on user, frequency of measuring points, etc.

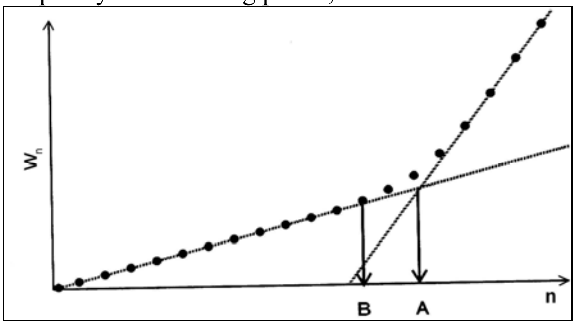

Figure 2 Ratio of the dissipated energy Wn versus number of cycles for the strain controlled test, Pronk (1999)

The alternative method was proposed by Rowe (2000), where fatigue life N1 is defined as the number of cycles corresponding to the maximum value of reduced energy ratio, which is as follows:

$$R_n = n \cdot E_n \quad , \qquad (1)$$

where:

Rn - reduced energy ratio,
n – cycle number,
En – stiffness after n cycles.

This method is easy to use and defines fatigue life in an unambiguous (mathematical) way. Figure 3 shows that N1 obtained with use of this method clearly relates to the beginning of final phase in fatigue test.

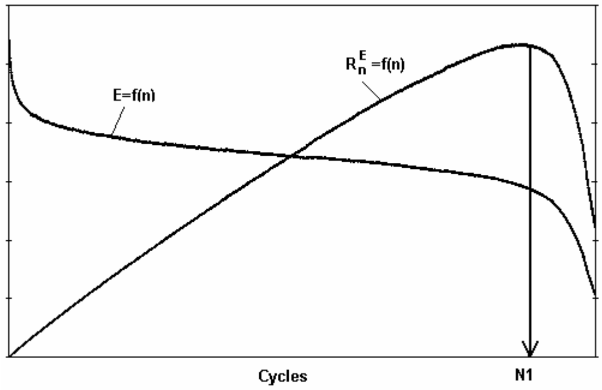

Figure 3 Evolution of stiffness and reduced energy ratio during fatigue test

Choice of fatigue criterion is a very critical decision. The conventional criterion is supposed to be arbitrary, doesn't take into account material differences, the result depends on the stiffness decrease in phase 1 due to the internal heating phenomenon. The energy criterion relates to the fatigue process itself and seems to be very promising. For example, it was proven that fatigue results from strain and stress controlled modes could be comparable, Pronk et al. (1990).

The aim of work is a comparison of fatigue test results calculated with use of the conventional and energetic method for different mixtures and constituent materials and various testing conditions. The archival wide database of fatigue test will be used.

2. TEST METHOD

Fatigue tests were performed by means of 4 Point Bending Test according to AASHTO TP8-94 (1994) with use of MTS universal material testing machine. Four point bending test consists in cycling bending of rectangular beam. Test conditions were as follows: temperature 0, 10 (the fatigue equivalent temperature for Poland, acc. to method developed by Deacon et al.,(1994)) and 20 °C; frequency 10 Hz; sinusoidal loading; constant strain mode. Fatigue life was calculated according to two methods: conventional (N) and energetic (N1). Test results were used to calculated parameters of fatigue law, which is define as follows:

$$N = A \cdot \varepsilon^{b}, \qquad (2)$$

where:
N – fatigue life,
ε - strain,
A, b – material parameters.

The parameter ε_6 is regarded as the characteristic of fatigue behavior of asphalt mixtures. It can be calculated from equation 2 and it is equal to the value of strain (for strain controlled mode) that leads to the fatigue life of 10^6 cycles. The loss of modulus d_n was introduced and defined as follows:

$$d_n = (1 - \frac{E_n}{E_0}) \cdot 100\%, \qquad (3)$$

where:
E_n – stiffness modulus after n-cycles,
E_0 – initial stiffness modulus.

The critical loss of modulus d_{kr} is obtained, when n is equal to fatigue life. For the conventional method $d_{kr(mk)}$ is always 50%, while for the energetic method $d_{kr(me)}$ is a result of an analysis.

3. ASPHALT MIXTURES

The analysis of fatigue test results covers a wide range of asphalt mixture, designed for base course and wearing course, most of them according to the polish standard PN-S-96025:2000. The mixes contain paving grade bitumen (D50 - different producers P, V, N and 50/70), polymer modified bitumen (OLE 30B, D70E), multigrade bitumen (MP 35/50) and special (MULTICOL, COLBASE, COLFLEX). Three types of mixes were tested: stone mastic asphalt (SMA), asphalt concrete (BA) and high modulus asphalt concrete (BAWMS).

Table 1 Asphalt mixes for wearing course

Mix (grading and binder)	Binder content, %m/m	Air voids content, %v/v	Marshall stability, kN	Marshall flow, mm
SMA 0/8 D50P	6,4	2,9	5,9	3,2
SMA 0/8 D50V	6,4	2,8	6,3	3,0
SMA 0/8 D50N	6,4	2,8	6,2	3,4
BA 0/12,8 MULTICOL	6,0	3,9	-	-
BA 0/6 50/70	6,9	5,0	-	-
BA 0/6 RILEM	6,85	5,0	-	-

Table 2 Asphalt mixes for base course

Mix (grading and binder)	Binder content, %m/m	Air voids content, %v/v	Marshall stability, kN	Marshall flow, mm
BA 0/25 D50P 3,5%	3,5	5,1	14,0	2,3
BA 0/25 D50P 3,8%	3,8	4,8	12,0	2,7
BA 0/25 D50P 4,1%	4,1	3,9	13,5	2,7
BA 0/25 D50P 4,0%	4,0	5,9	12,2	3,0
BA 0/25 D50V 4,0%	4,0	4,6	11,3	2,5
BA 0/25 D50N 4,0%	4,0	6,5	11,5	2,7
BA 0/25 OLE 30B	4,0	4,3	22,0	3,4
BA 0/16 D50P	4,8	4,6	10,0	3,1
BA WMS 0/16 D50P	4,2	5,6	14,5	3,0
BA WMS 0/16 OLE 30B	4,2	5,9	16,0	3,5
BA WMS 0/16 MP	4,2	6,0	12,0	3,2
BA 0/16 COLBASE	5,3	4,5	-	-
BA 0/16 D70E	4,8	3,7	11,0	3,0

4. FATIGUE TEST RESULTS

Tables 3 and 4 presents calculated parameters of fatigue laws for asphalt mixtures at different temperatures and on the basis of the conventional and energetic methods.

Table 3 Parameters of fatigue life for mixtures designed for wearing course

	Conventional method				Energetic method			
Parameters / Mixture	A	b	R^2	ε_6	A	b	R^2	ε_6
	-	-	-	μm/m	-	-	-	μm/m
Temperature 10˚C								
SMA 0/8 D50P	1,14E+24	-7,61	0,94	236	5,91E+22	-7,09	0,94	232
SMA 0/8 D50V	3,36E+14	-3,99	0,89	137	-	-	-	-
SMA 0/8 D50N	1,54E+17	-5,02	0,99	170	3,43E+16	-4,74	0,93	168
BA 0/12,8 MULTICOL	1,38E+25	-8,21	0,90	215	2,67E+25	-8,35	0,90	212
BA 0/6 RILEM	2,31E+18	-5,71	0,96	147	2,48E+18	-5,74	0,95	144
Temperature 20˚C								
SMA 0/8 D50P	3,34E+18	-5,43	0,71	306	-	-	-	-
SMA 0/8 D50V	4,88E+16	-4,52	0,97	232	-	-	-	-
SMA 0/8 D50N	9,26E+18	-5,31	0,98	274	-	-	-	-

Table 4 Parameters of fatigue life for mixtures designed for base course

Mixture \ Parameter	Conventional method A	b	R^2	ε_6	Energetic method A	b	R^2	ε_6
	-	-	-	μm/m	-	-	-	μm/m
Temperature 0˚C								
BA 0/25 D50P 4,1%	1,44E+19	-6,32	0,70	120	3,92E+16	-5,07	0,91	123
BA 0/25 OLE 30B	7,32E+23	-8,41	0,63	133	-	-	-	-
BAWMS 0/16 D50P	9,92E+13	-4,00	0,70	99	4,77E+13	-3,83	0,87	101
BAWMS 0/16 OLE 30B	1,40E+21	-7,17	0,57	129	-	-	-	-
BAWMS 0/16 MP	1,91E+23	-8,20	0,85	128	1,15E+21	-7,27	0,49	118
Temperature 10˚C								
BA 0/25 D50P 3,5%	2,60E+17	-5,63	0,76	107	3,44E+14	-4,26	0,73	101
BA 0/25 D50P 3,8%	9,50E+16	-5,29	0,44	119	1,74E+20	-6,81	0,60	124
BA 0/25 D50P 4,1%	1,08E+15	-4,27	0,77	130	1,57E+14	-3,93	0,70	122
BA 0/25 D50P 4,0%	2,09E+15	-4,69	0,91	97	1,17E+16	-5,03	0,89	101
BA 0/25 D50V 4,0%	2,86E+17	-5,61	0,59	110	4,76E+16	-5,27	0,66	106
BA 0/25 D50N 4,0%	1,05E+15	-4,55	0,84	96	1,05E+15	-4,60	0,86	92
BA 0/25 OLE 30B	1,20E+20	-6,41	0,54	157	1,22E+19	-5,99	0,46	153
BA 0/16 D50P	1,07E+23	-7,71	0,70	161	1,62E+22	-7,37	0,68	158
BAWMS 0/16 D50P	6,07E+33	-12,8	0,81	146	1,96E+30	-11,3	0,75	144
BAWMS 0/16 OLE 30B	4,69E+22	-7,41	0,69	178	6,46E+23	-3,62	0,76	179
BAWMS 0/16 MP	2,48E+23	-8,09	0,81	141	4,09E+16	-5,03	0,76	129
BA 0/16 COLBASE	9,91E+14	-4,18	0,90	142	7,69E+14	-4,15	0,91	138
BA 0/16 D70E	1,27E+28	-9,88	0,58	173	4,94E+23	-7,91	0,87	173
Temperature 20˚C								
BA 0/25 D50P 3,5%	7,56E+24	-8,75	0,76	144	2,84E+34	-13,0	1,00	156
BA 0/25 D50P 3,8%	7,43E+24	-8,45	0,91	171	2,04E+13	-3,33	0,67	156
BA 0/25 D50P 4,1%	1,26E+34	-12,1	0,65	208	3,41E+22	-7,20	0,73	198
BA 0/25 D50P 4,0%	4,76E+19	-6,14	0,63	169	4,06E+20	-6,56	0,72	169
BA 0/25 D50V 4,0%	4,61E+16	-5,17	0,94	116	1,88E+16	-5,00	0,98	113
BA 0/25 D50N 4,0%	3,27E+17	-5,52	0,84	122	1,59E+17	-5,37	0,98	122
BA 0/25 OLE 30B	2,17E+27	-8,68	0,76	287	4,50E+27	-8,77	0,76	294
BA 0/16 D50P	1,08E+16	-4,41	0,49	189	9,96E+14	-3,95	0,47	190
BAWMS 0/16 D50P	2,72E+20	-6,39	0,67	181	4,86E+17	-5,21	0,58	175
BAWMS 0/16 OLE 30B	6,94E+15	-4,26	0,71	203	2,05E+14	-3,62	0,58	198
BAWMS 0/16 MP	1,80E+14	-3,91	0,65	129	1,64E+13	-3,45	0,60	123

5. ANALYSIS OF CRITICAL LOSS OF STIFFNESS

Statistical analysis of the critical loss of stiffness for the energetic method should answer the questions about differences between the conventional and energetic method. If value of d_{kr} is lower than 50%, it leads to the conclusion that conventional method gives higher (overestimated) fatigue life. Statistical analysis consists in evaluation of statistical parameters of given population and preparation of histogram, probability distribution and distribution function. Different populations were analysed. First one covers all test results (300 specimens in total), all temperatures and all mixes. Then smaller populations were identified in order to evaluate an influence of different factors on the critical loss of stiffness. They are as follows:

- A – all results (300 specimens),
- T/0, T/10, T/20 – test results at different temperatures, adequately: 0, 10 and 20ºC,
- D50/0, D50/10, D50/20 – test results for asphalt concrete with D50 bitumen at a temperature of: 0, 10 and 20ºC,
- OLE/0, OLE/10, OLE/20 - test results for asphalt concrete with OLE 30B binder at a temperature of 0, 10 and 20ºC,
- BA and SMA – test results for asphalt concrete or SMA with paving grade bitumen at a temperature of 10ºC.

Analysis of all results shows that the mean average value of d_{kr} is 44,1% and for about 65% of specimens the conventional method gives higher fatigue life. Figure 4 and 5 presents the histogram and cumulative distribution function.

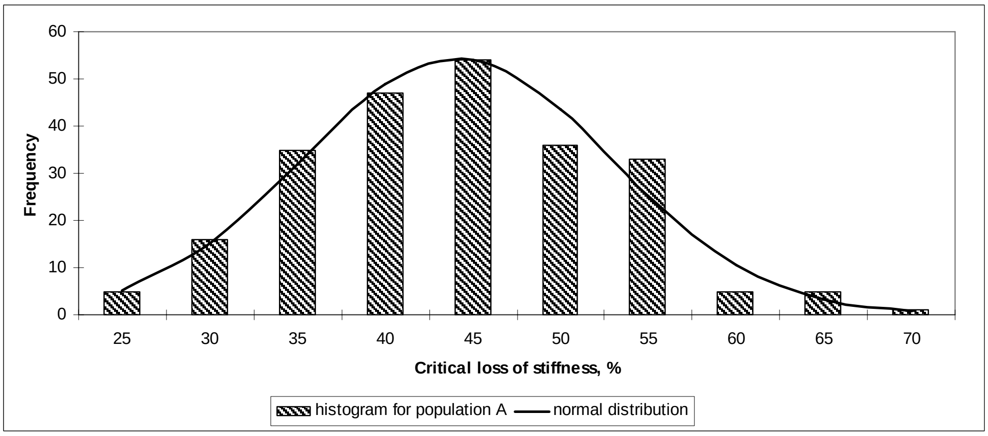

Figure 4 Histogram and normal distribution for population A

Figure 5 Cumulative distribution function for population A

Analysis of populations T/0, T/10 and T/20 allows to check temperature influence. It turned out that the critical loss of modulus is directly proportional to the test temperature. At a temperature of 0 and 10ºC about 80% of d_{kr} values are smaller than 50%, while at a temperature of 20ºC the critical loss of stiffness exceeds 50%. It can be concluded, that test temperature has the essential influence on the critical loss of stiffness and use of the conventional method, which is temperature independent, is not justified. This is especially important for lower temperatures, where fatigue process of asphalt pavement appears. The equivalent temperature for Poland for fatigue is 10ºC and it means that the conventional method leads to the overestimation of fatigue life.

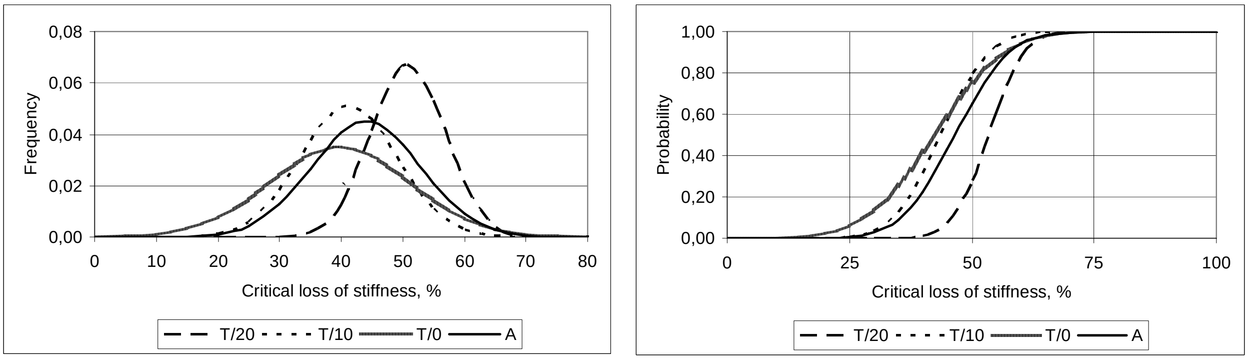

Figure 6 Cumulative distribution function for population A

Further analysis including asphalt concrete with D50 bitumen and asphalt concrete with DE30B polymer modified bitumen confirmed the observations on temperature influence. It should be also noticed that the conventional method gives lower values of d_{kr} in case of asphalt concrete with polymer modified bitumen. This is opposite to the observations of asphalt concrete with D50 bitumen for temperature 0 and 20ºC.

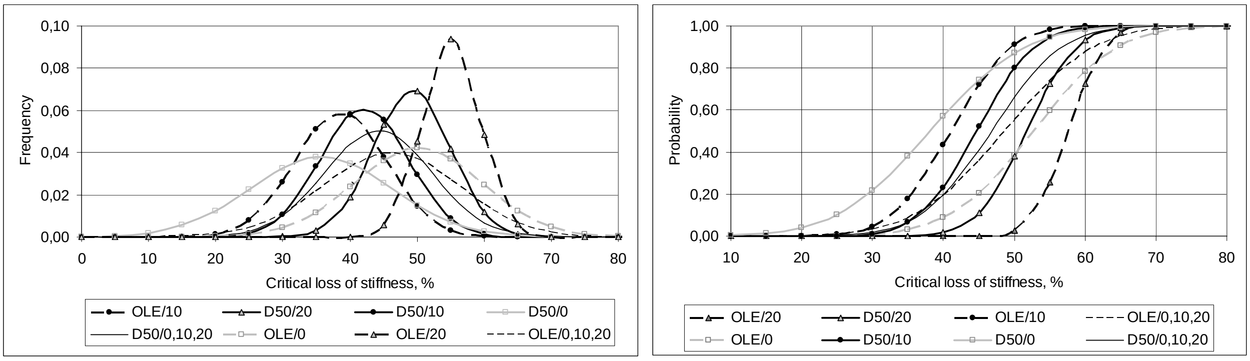

Figure 7 Cumulative distribution function for asphalt concrete with D50 bitumen and DE30B binder

Comparison of test results for asphalt concrete and SMA with paving grade bitumen at 10ºC indicates some differences in fatigue behavior. Mean values of the critical loss of stiffness were 42,2% and 49,7% accordingly. The probability of fatigue damage before reaching 50% of reduction in stiffness was 80% for asphalt concrete and 31% for SMA.

Figure 8 Cumulative distribution function for asphalt concrete and SMA with D50 bitumen at 10ºC

6. COMPARISON OF FATIGUE LIFE

Figure 9 presents correlation between fatigue life N and N1 obtained for all results, dashed line means proportion 1 to 1. The correlation coefficient is very high and it indicates that the conventional method gives higher results in general, but as it was proven in the statistical analysis it is not always true, especially for higher temperatures and polymer modified bitumen. Figure 10 shows calculated values ε_6 obtained from conventional and energetic method. Differences between these methods are not higher than 10%

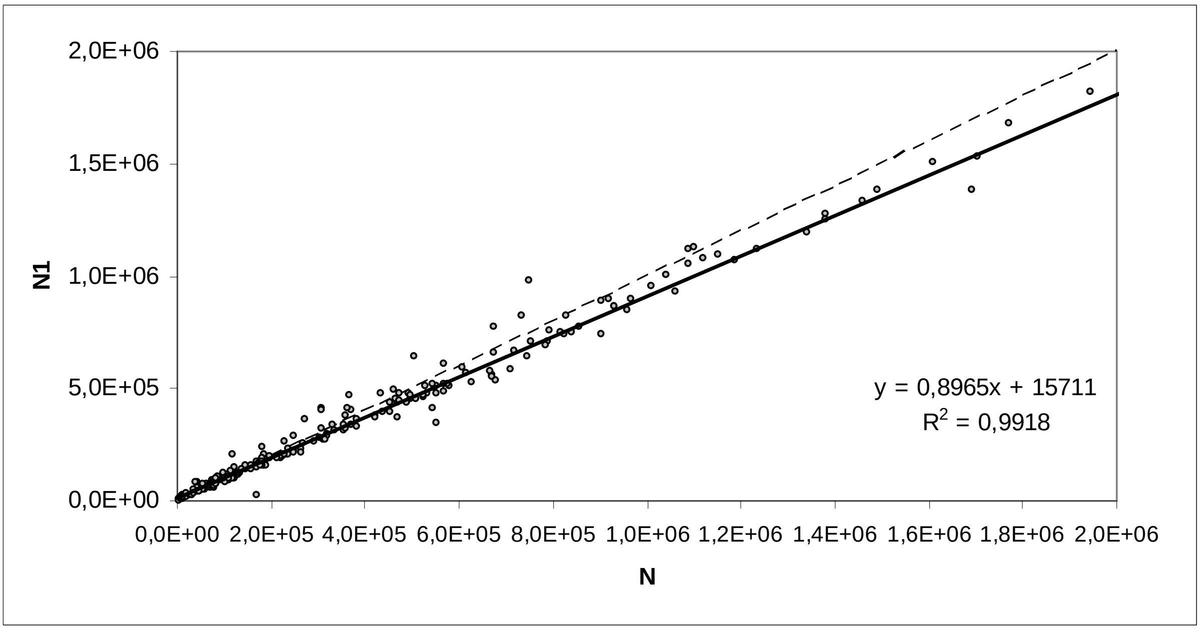

Figure 9 Comparison of fatigue life N and N1

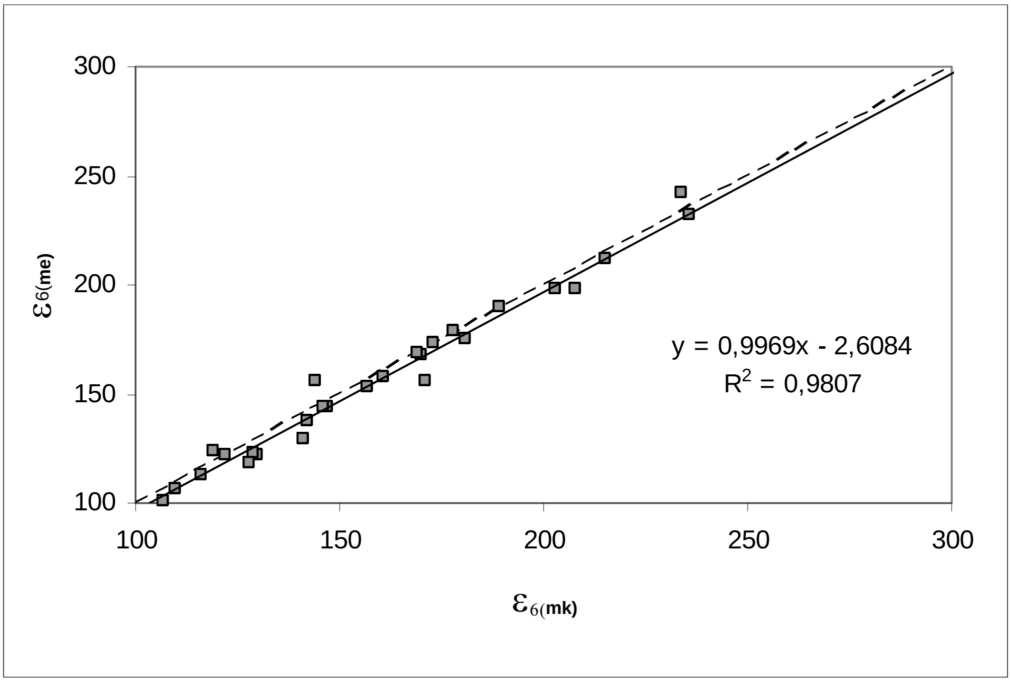

Figure 10 Comparison of ε_6 value obtained from conventional (mk) and energetic method (me)

7. SUMMARY

Definition of the failure in fatigue test of bituminous mixtures has essential influence on the results. The paper compares two alternative methods: conventional and energetic. The conventional method is supposed to be not objective and it was proved in presented analyses. There are several factors that influence the evolution of stiffness modulus during fatigue test: temperature, type of bitumen, type of asphalt mixture. The most important is temperature – an increase of temperature leads to an increase of the critical loss of stiffness. This is especially important for lower temperatures, for example 10ºC, which is the fatigue equivalent temperature for Poland, and at this temperature the conventional method overestimates mixture's fatigue life. For higher temperatures and for asphalt mixtures with polymer modified binder this method gives lower results than expected from energetic method. The energetic method based on the reduced energy ratio concept is easy to use. It enables to evaluate fatigue life on the basis of observation of fatigue evolution instead of change in stiffness as in conventional method. From the other side, the differences in ε_6 (which defines resistance to fatigue according to European Standard) are not larger than 10%, which is often less than fatigue test precision.

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