

1 **The influence of combination of binding agents on fatigue properties of**  
2 **deep cold in-place recycled mixtures in Indirect Tensile Fatigue Test**  
3 **(ITFT)**

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12           **Abstract**

13           The publication presents fatigue properties of cold recycled mixtures for eight  
14 combinations of binding agents (cement and bituminous emulsion). Cold recycled  
15 mixtures were evaluated in Indirect Tensile Fatigue Test (ITFT) at the temperature of  
16 20°C in controlled stress mode. As a function of horizontal stress, fatigue life is strongly  
17 influenced by combination of the binding agents. When fatigue life is analyzed as a  
18 function of initial horizontal strain, the difference between different combinations  
19 decreases. In all cases, the influence of a specific binding agent is more visible for  
20 combinations with lower total amounts of the two agents.

21           **Keywords:** cold recycling; recycling; mineral cement emulsion mixtures; cement;  
22 bituminous emulsion; fatigue; Indirect Tensile Fatigue Test (ITFT)

## 23 **1. Introduction**

### 24 1.1. Background

25 Deep cold in-place recycling is one of the most widely used eco-friendly technologies  
26 for reconstruction of old and deteriorated road pavements [1–3]. The most commonly used  
27 binders for aggregate material include combinations of cement, cement-based binders,  
28 bituminous emulsion and foamed asphalt [4–6]. Laboratory and field investigations showed  
29 that the proportion between the binding agents has significant influence on properties of ready  
30 cold recycled mixtures [7–12]. Literature encompasses numerous research projects focused on  
31 the influence of binding agents on mechanical properties, such as stiffness modulus, strength  
32 or frost and water susceptibility, especially for short periods of curing. However, these  
33 properties do not fully describe the behavior of cold recycled mixtures in the pavement  
34 structure. Cold recycled mixtures in pavement structure, as in most cases they are used as  
35 road bases, where loads are distributed on a larger area in comparison to asphalt courses.  
36 Therefore, not only the basic mechanical properties, such as strength and stiffness modulus,  
37 are important to proper performance of this layer, but also fatigue properties, which  
38 correspond to the impact of numerous small loads from all vehicle passes in the pavement  
39 life. The influence of combination of binding agents on fatigue behavior of cold recycled  
40 mixtures still has not been fully investigated. It is a very important factor, taking into  
41 consideration the dual behavior of cold recycled mixtures. Depending on the amount of a  
42 specific binding agent, a cold recycled mixture may present a more ductile behavior (when,  
43 due to higher bituminous emulsion content, the bituminous bonds are dominating) or a more  
44 brittle behavior (when, due to higher cement content, the hydraulic bonds are dominating)  
45 [13]. The presented research shows results for a whole spectrum of mixtures: from brittle to  
46 flexible. It is an important, as most of the research presented in the literature are conducted for  
47 cold recycled mixtures with bituminous emulsion used as the primary binding agent [14–21].

48 Moreover, due to usage of different fatigue test methodologies, results from different research  
49 projects are difficult to compare in order to determine the influence of specific factors: such  
50 as composition of the mixture, gradation of the mixture, amount of RA or time of curing.

## 51 1.2. Fatigue behavior of cold recycled mixtures

52 Resistance to fatigue damage is one of the most important factors for all materials  
53 used in pavement structure, due to the cyclic loading from traffic. In the case of cold recycled  
54 mixtures, a proper and clear analysis of this factor is hindered not only by the complex  
55 behavior resulting from viscoelastic properties of emulsion and elastic properties of cement,  
56 but also by constant changes in properties due to ongoing processes of aging and cement  
57 hydration. [16, 18-21]

58 Literature review shows that fatigue of cold recycled mixtures is typically tested in  
59 Indirect Tensile Fatigue Test (ITFT) at various test conditions. A short summary of earlier  
60 fatigue tests, including the tested materials, methodology and results, is presented in Table 1.  
61 Tests are most commonly performed in controlled stress mode [15–18,20], which illustrates  
62 the real field conditions of the base course, where the cold recycled mixtures are usually  
63 employed. Cold recycled mixtures are used as base courses in pavement constructions with  
64 sufficient subgrade bearing capacity, which, in connection with the presence of a stiff  
65 hydraulically bound layer, leads to a reduction in vertical deflections and an increase in stress  
66 generated in the layer. For this reason, a controlled stress test is recommended. Nevertheless,  
67 Indirect Tensile Fatigue Tests in controlled strain mode were performed as well [14]. Fatigue  
68 tests using four point bending (4PB) are also found in the literature [19,21,22], but require  
69 special treatment during the preparation phase (for example, sieving off aggregate above a  
70 specific dimension). This kind of “pre-treatment” makes it easier to prepare the specimen, but

71 it also raises doubts about usability of the results in relation to the “full mixture” in field  
 72 conditions.

73 Another problematic question which arises during fatigue testing is the period of time  
 74 after which the specimen should be tested. Presence of cement and bitumen emulsion in the  
 75 mixture makes it impossible to directly implement methods and specifications made for  
 76 asphalt mixtures, such as EN 12697-24 [23] with 4-6 weeks of storing of the specimen before  
 77 the test. In most fatigue tests conducted on cold recycled mixtures, the specimens are assumed  
 78 to be fully cured, but the procedure of cold recycled mixture curing varies across different  
 79 countries. In some territories the specimens are cured for 28 days in typical laboratory  
 80 conditions, with temperature around 20°C and typical moisture. In other cases the procedure  
 81 is shortened to several days of curing at an increased temperature. While the procedures may  
 82 be comparable for typical CEM I Portland cement, questions arise when another type of  
 83 binding agent is used. The recommended load ranges are also varied, as the use of different  
 84 amounts and types of binding agents results in production of mixtures within a wide spectrum  
 85 of performance.

86 **Table 1.** Summary of fatigue tests based on literature review

Research author	Tested mixture (basic data)	Fatigue properties	Test scheme	Other remarks
Bocci et al. [14]	cement 2% emulsion 3% gradation 0/16 50% RA	$y = 130.32x^{-0.09}$ $\epsilon_6 = 33.1 \mu\text{strain}$ $a = 0.111$	ITFT	Test temperature 20°C Test mode: not specified Axis: $\epsilon$ [ $\mu\text{strain}$ ] – N
Yan et al. [15]	cement 1.5% emulsion 3.5% gradation 0/26 100% RA	$y = 2E-10x^{-3.5233}$	ITFT	Test temperature 20°C Test mode: controlled stress Axis: $\log \epsilon$ [-] – $\log N$
Stimilli et al. [16]	cement 2% emulsion 4% gradation 0/20 90% RA	$y = 282.70x^{-0.095}$ (laboratory specimen) $y = 223.40x^{-0.075}$ (field specimen, sec. 1) $y = 215.72x^{-0.096}$ (field specimen, sec. 2)	ITFT	Test temperature 20°C Test mode: controlled stress Axis: $\epsilon$ [ $\mu\text{strain}$ ] – N
Leandri et al. [17]	cement 2.0% emulsion 4.2% gradation 0/16 100% RA	$y = 1069.56x^{-0.19}$	ITFT	Test temperature 20°C Test mode: controlled stress Axis: $\log \epsilon$ [ $\mu\text{strain}$ ] – $\log N$
Buczyński [18]	cement 3.0% emulsion 3.0 / 5.0% gradation 0/31.5 RA amount not stated	$\frac{250\text{kPa}}{y = 55.950e^{2E-06x}}$ (5% emulsion) $y = 37.858e^{2E-06x}$ (3% emulsion) $\frac{375 \text{ kPa}}{y = 89.007e^{0.0002x}}$ (5% emulsion) $y = 50.591e^{1E-05x}$ (3% emulsion)	ITFT	Test temperature 20°C Test mode: controlled stress Axis: $\log \epsilon$ [ $\mu\text{strain}$ ] – $\log N$
Taherkhani et al. [19]	cement 0–3.0% emulsion 2.5–4.5% gradation 0/25	$N_F = 6x10^{29} \cdot \sigma^{-11.48}$ (0% cement) $N_F = 2x10^{27} \cdot \sigma^{-10.16}$ (1% cement) $N_F = 3x10^{25} \cdot \sigma^{-9.045}$ (2% cement)	4PB	Test temperature 10°C Test mode: controlled stress Axis: according to EN standard

	100% RA	$N_f = 4 \times 10^{16} \cdot \sigma^{-4.785}$ (3% cement)  $\log N - \sigma$ $y = 1E+26x^{-9.8310}$ (0% cement) $y = 2E+25x^{-9.1861}$ (1% cement) $y = 2E+25x^{-8.9914}$ (2% cement) $y = 5E+16x^{-4.7997}$ (3% cement)		
Lin et al. [20]	cement 2% emulsion 3.5% gradation 0/30 100% RA	$N_f = 1.1 \cdot \sigma^{-8.394}$ (ITT) $N_f = 7.4E+16 \cdot \sigma^{-4.915}$ (4PB, 28 days curing) $N_f = 2.2E+20 \cdot \sigma^{-6.048}$ (4PB, fully cured)	ITT 4PB	Test temperature: 15°C Test mode: controlled stress (ITT) Test mode: controlled strain (4PB)
Ebels [21]	cement 0.0–1.0% emulsion 2.4, 3.6% gradation 0/19 25% RA	emulsion 3.6%, cement 1.0% 300 $\mu$ str – 88 200 cycles 250 $\mu$ str – 560 000 cycles 200 $\mu$ str – 172 000 cycles 140 $\mu$ str – 2 400 000 cycles 120 $\mu$ str – 1 700 000 cycles	4PB	Test temperature: 5°C Test mode: controlled strain Test frequency, 10 Hz

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### 88 1.3. Aims and scope

89 The main aim of the described research is to present and compare the fatigue behavior  
90 of eight cold recycled mixtures containing the same mineral aggregate and different  
91 combinations of binding agents. The combinations of binding agents were selected to present  
92 both bitumen-dominated mixtures, intermediate mixtures and cement-dominated mixtures. All  
93 the mixtures were tested in the Indirect Tensile Fatigue Test at the temperature of 20°C.

## 94 2. Materials and methods

### 95 2.1. Materials and preparation

96 For all the investigated cold recycled mixtures, one grading curve was designed  
97 according to the Polish requirements [24,25]. The mixture consisted of reclaimed asphalt  
98 pavement 0/31.5 (70%), continuously graded 0/31.5 aggregate (18%) and 0/2 fine aggregate  
99 (12%). Portland cement CEM I 32.5R and cationic bituminous emulsion C60B10 were used  
100 as binding agents. The bituminous emulsion contained neat 70/100 bitumen. The amounts of  
101 both binding agents used in this research were 2%, 4% and 6% in various combinations. For  
102 each value of cement content the optimum water content was determined using the modified

103 Proctor method. The amount of water added to mixtures with different combinations of  
 104 cement and bituminous emulsion was calculated taking into consideration water from the  
 105 emulsion as well as the influence of bitumen from emulsion. The amount of added water  
 106 equals optimum water content decreased by water from emulsion and half of binder content in  
 107 emulsion. In this research mineral aggregate and reclaimed asphalt pavement were dried, so  
 108 there was no need to reduce the addition of water by material humidity (which should not be  
 109 omitted during plant production). The mixture with 4% of cement and 4% of emulsion was  
 110 damaged during the preparation of the specimen and was not included in this research.  
 111 Grading curves of the designed mixtures are presented in Figure 1. Basic data regarding  
 112 composition of mixtures obtained during the design process are presented in Table 2.

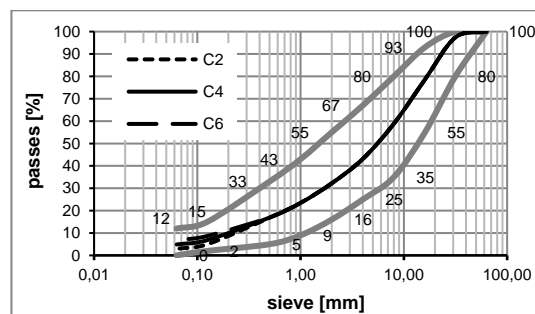


Fig. 1. Grading curve of mineral mixtures.

Table 2. Basic data of the tested mineral-cement-emulsion mixtures

Mixture designation	Cold Recycled Mixture							
	C2E2	C2E4	C2E6	C4E2	C4E6	C6E2	C6E4	C6E6
Cement content, [%]	2	2	2	4	4	6	6	6
Emulsion content, [%]	2	4	6	2	6	2	4	6
Optimum water content, Proctor modified method [%]	7.0			7.0		7.1		
Proctor density [Mg/m <sup>3</sup> ]	2.135			2.138		2.140		
Water added to the mix [%]	5.6	4.2	2.8	5.6	2.8	5.7	4.3	2.9
Air voids in Marshall samples (2 x 75 blows), [%]	14.3	17.1	16.7	13.9	15.8	12.8	13.4	13.1
Stiffness modulus ITSM, 5°C, 28 days (MPa)	5867	4799	5985	8615	6140	not tested	not tested	not tested
Indirect tensile strength ITS, 5°C, 28 days (MPa)	0.64	0.74	0.94	1.18	1.08	not tested	not tested	not tested

119 All the tested mixtures were prepared in a laboratory mixer according to the EN 12697-  
120 35 standard [26]. The specimens were compacted in a gyratory compactor according to the  
121 EN 12697-31 standard [27]. The limiting compaction ratio was set as 99%. The specimens  
122 were compacted to height of 170 mm and diameter of 100 mm. Loss of water with some  
123 amount of fines was observed during compaction. 28 days after compaction lower and upper  
124 surfaces were cut to obtain height of 150 mm.

125 Before fatigue testing, specimens were used for long-term modulus testing [28,29]. Since  
126 the earlier tests were nondestructive, the same material – already after over 4 years of curing –  
127 was used for fatigue testing, in order to gather valuable data on performance of mixtures with  
128 various combinations of binding agents after longer curing periods. After such a long time,  
129 the processes of water evaporation, hydration of cement and aging of bitumen in emulsion are  
130 slower than at the early stages of curing and have minor impact on mechanical properties, and  
131 therefore – on fatigue properties. Three test specimens of approximately 50 mm in height  
132 were cut from every gyratory sample. The amount of bitumen from emulsion in the cold  
133 recycled mixtures is visible in the color of the samples. Mixtures with 2% of cement and 2%,  
134 4% and 6% of bituminous emulsion are shown in Figure 2. Figure 3 shows the natural  
135 heterogeneity of cold in-place recycled mixtures. The random distribution of mineral  
136 components with such diverse gradation in the mix should be taken into consideration in the  
137 analysis of the uniformity of results. Heterogeneity of cold in-place recycled mixtures is also  
138 visible in high variability of void content and compaction index (as shown in Table 3). Those  
139 differences originated from the internal structure of the tested material rather than from the  
140 chosen method of compaction. The method used for determination of bulk density (geometric  
141 method), could have influenced the obtained values as well. Chipping of material from the  
142 sides and the bottom of the specimen could have resulted in an increase in the obtained results  
143 of void content and a decrease in the value of the compaction index.





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**Fig. 2.** A typical view of cold in-place recycled mixtures. Samples from left: C2E2, C2E4, C2E6.



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**Fig. 3.** A display of natural heterogeneity of cold in-place recycled samples. Four samples from one mix type (C6E2).

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## 2.2. Methods

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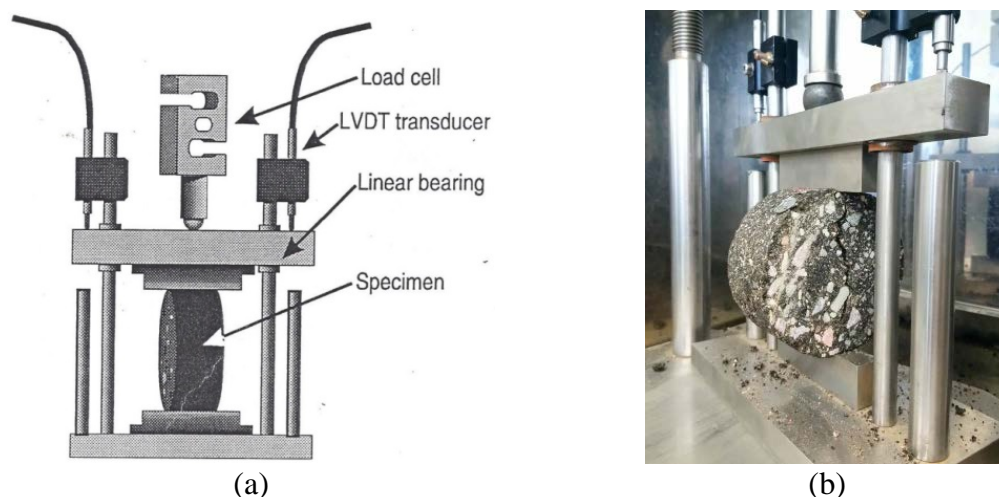
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The Indirect Tensile Fatigue Test was conducted according to the BS DD ABF standard [30]. The scheme of the test and specimen installation in the test machine are presented in Figure 4. Instead of three selected levels of loading with a few repetitions of each, as described in the EN 12697-24 European specification, varied levels of loading were

156 used to obtain fatigue curves, as described in [30]. The test was conducted in controlled stress  
 157 mode, with horizontal stress values ranging from 100 up to 620 kPa depending on mixture  
 158 composition. Due to varying binding agent content, the indirect tensile strength of the  
 159 mixtures varied as well. Therefore, the stress levels used in fatigue tests were also different  
 160 and were chosen during testing, depending on the results obtained. Stress used for the first  
 161 sample for every tested combination was set to 300 kPa. Afterwards, a test at another stress  
 162 level was conducted, taking into account the number of cycles obtained from the previous  
 163 test. Stress level was increased or decreased by 20 kPa. Stress levels were selected to obtain a  
 164 number of cycles from 10 to 100,000. Fatigue tests for a given combination of binding agents  
 165 were conducted to obtain a minimum of eight valid results for eight different stress levels.  
 166 One specimen was tested for one stress level. Test temperature was equal to 20°C.



167 **Fig. 4.** (a) – Scheme of the test setup [30], (b) – view of the sample after the ITFT test.

### 168 3. Results and discussion

169 Detailed data including bulk density, void content, compaction index and ITFT results  
 170 are presented in Table 3. The regression parameters obtained from the Indirect Tensile  
 171 Fatigue Test are presented in Table 4 and in Figures 5 and 6. For description of the fatigue  
 172 curve, the following power functions were used:

$$173 \quad \sigma = a \cdot N^b \quad (1)$$

174 where  $\sigma$  is the applied horizontal stress (MPa),  $N$  is the fatigue life (number of loading  
 175 cycles),  $a$  and  $b$  are regression parameters;

176 
$$\varepsilon_{init} = a \cdot N^b \quad (2)$$

177 where  $\varepsilon_{init}$  is the calculated initial strain,  $N$  is the fatigue life (number of loading cycles),  $a$  and  
 178  $b$  are regression parameters.

179 **Table 3.** Detailed tests results

Mixture designation	Sample no.	Bulk density [Mg/m <sup>3</sup> ]	Void content [%]	Compaction index [%]	ITFT @20°C	
					Stress level [kPa]	Number of cycles to failure
C2E2	431/5/1	2.156	12.6	101	100	8200
	431/3/2	2.076	15.9	97	120	9100
	431/6/1	2.103	14.8	98	150	75000
	431/4/1	2.051	16.9	96	150	1100
	431/1/2	2.004	18.8	93	170	600
	431/3/1	2.144	13.1	100	200	7300
	431/9/1	2.062	16.5	96	220	500
	431/2/1	2.054	16.8	96	250	100
	431/8/1	2.071	16.1	97	250	1300
	431/2/2	2.078	15.8	97	270	30
	431/1/1	2.152	12.8	100	300	600
C2E4	432/1/2	1.942	20.4	96	180	9900
	432/6/1	2.003	17.9	99	200	17000
	432/8/2	1.956	19.8	97	220	900
	432/9/2	1.945	20.3	96	240	700
	432/4/2	1.937	20.6	96	260	200
	432/3/2	1.937	20.6	96	280	200
	432/5/1	2.020	17.2	100	300	2500
	432/7/2	1.969	19.3	97	320	80
	432/5/2	1.941	20.5	96	340	90
	432/9/1	1.949	20.1	96	360	90
	432/8/1	2.011	17.6	99	380	400
432/7/1	1.987	18.6	98	400	200	
C2E6	440/1/1	2.028	16.0	101	200	22000
	440/8/1	2.003	17.0	100	220	6100
	440/7/2	1.976	18.1	98	240	2200
	440/8/2	1.967	18.5	98	260	1000
	440/6/1	1.998	17.2	99	280	1600
	440/2/1	1.997	17.3	99	300	1500
	440/6/2	1.972	18.3	98	320	200
	440/9/1	1.971	18.4	98	340	400
	440/7/1	2.016	16.5	100	360	600
	440/4/1	2.045	15.3	102	380	1000
	440/3/1	1.965	18.6	98	400	400
C4E2	441/1/2	2.051	17.1	96	280	17000
	441/1/1	2.086	15.7	98	300	13000
	441/3/1	2.080	15.9	98	320	5600
	441/9/1	2.098	15.2	98	340	2200
	441/9/2	2.053	17.0	96	360	2300

	441/7/2	2.055	16.9	96	380	1700
	441/6/2	2.066	16.5	97	400	700
	441/4/2	2.021	18.3	95	420	500
	441/6/1	2.134	13.7	100	440	6000
	441/4/1	2.132	13.8	100	460	2900
	441/5/1	2.100	15.1	99	480	2900
	441/2/1	2.116	14.5	99	500	400
C4E6	447/6/2	1.951	19.3	96	260	12000
	447/8/1	2.067	14.6	102	280	18000
	447/1/1	2.044	15.5	100	300	16000
	447/5/2	1.970	18.6	97	320	2200
	447/9/2	1.969	18.6	97	340	1500
	447/8/2	1.967	18.7	97	360	3300
	447/9/1	2.059	14.9	101	380	9700
	447/3/1	2.004	17.2	98	400	4100
	447/4/1	2.029	16.1	100	420	1900
	447/5/1	1.977	18.3	97	440	1300
	447/3/1	2.004	17.2	98	460	3100
	447/1/2	1.964	18.8	96	480	800
447/4/2	1.959	19.0	96	500	300	
C6E2	454/5/2	2.085	15.9	96	480	76000
	454/9/1	2.119	14.6	98	500	18000
	454/5/1	2.140	13.7	99	520	34000
	454/2/1	2.131	14.1	99	540	5900
	454/8/1	2.117	14.6	98	560	1900
	454/6/2	2.072	16.5	96	580	4400
	454/3/2	2.094	15.6	97	600	1400
454/8/2	2.032	18.1	94	620	100	
C6E4	451/8/2	2.044	16.6	96	360	86000
	451/3/2	2.019	17.7	95	380	11000
	451/1/1	2.076	15.3	98	400	35000
	451/1/2	2.023	17.5	95	420	3000
	451/6/2	2.036	17.0	96	440	6600
	451/4/2	2.015	17.8	95	460	1900
	451/5/1	2.052	16.3	97	480	5600
	451/4/1	2.060	16.0	97	500	1900
	451/6/1	2.127	13.3	100	520	7100
	451/7/1	2.083	15.0	98	540	1900
451/9/1	2.066	15.7	97	560	900	
C6E6	450/9/2	2.002	17.4	95	340	14000
	450/7/2	1.994	17.7	95	360	4200
	450/5/3	2.101	13.3	99	380	38000
	450/1/1	2.053	15.3	98	400	6500
	450/5/2	2.006	17.2	95	420	2100
	450/9/3	2.077	14.3	99	440	16000
	450/8/3	2.062	14.9	98	460	5000
	450/4/3	2.076	14.4	99	480	6000
	450/8/2	2.002	17.4	95	500	1000
	450/4/2	2.008	17.2	95	520	1000
	450/9/1	2.030	16.3	96	540	1400
	450/8/1	2.052	15.3	97	560	800
	450/6/1	2.042	15.8	97	580	800
450/4/1	2.029	16.3	96	600	1100	

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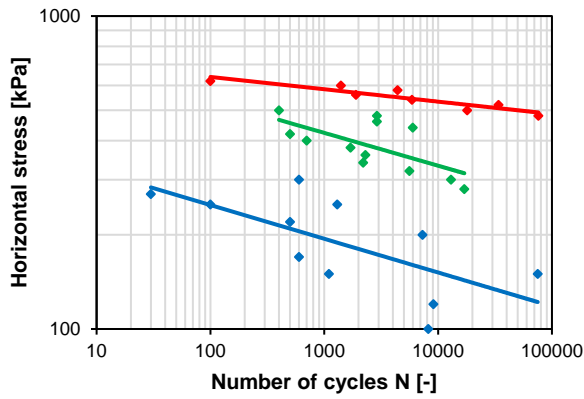
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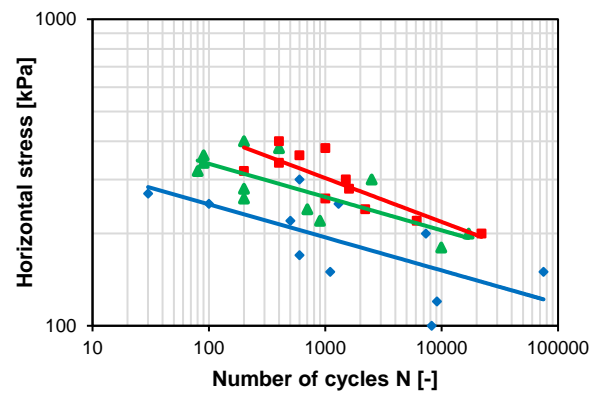
**Table 4.** Indirect Tensile Fatigue Test results

Mixture designation	Cold Recycled Mixture							
	C2E2	C2E4	C2E6	C4E2	C4E6	C6E2	C6E4	C6E6
Bitumen (from emulsion) to cement ratio	0.6	1.2	1.8	0.3	0.9	0.2	0.4	0.6
Horizontal stress range min, MPa	100	180	200	280	260	480	360	340
Horizontal stress range max, MPa	300	400	400	500	500	620	560	600
Regression parameters for equation (1)								
a	409.01	577.02	814.40	873.66	1103.40	766.10	956.84	1160.40
b	-0.108	-0.109	-0.143	-0.105	-0.135	-0.039	-0.086	-0.114
Regression parameters for equation (2)								
a	448.10	709.99	667.11	360.25	395.02	197.47	312.17	425.80
b	-0.156	-0.181	-0.177	-0.146	-0.124	-0.046	-0.101	-0.124

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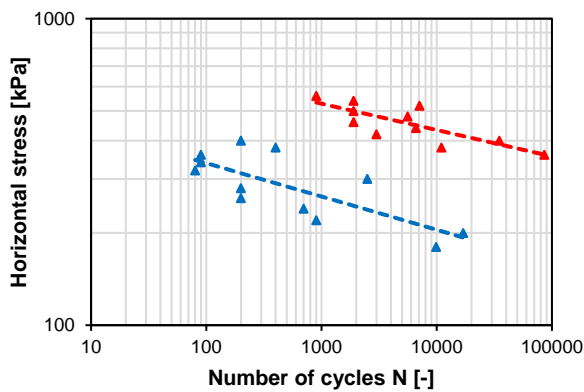


◆ C2E2    ◆ C4E2    ◆ C6E2

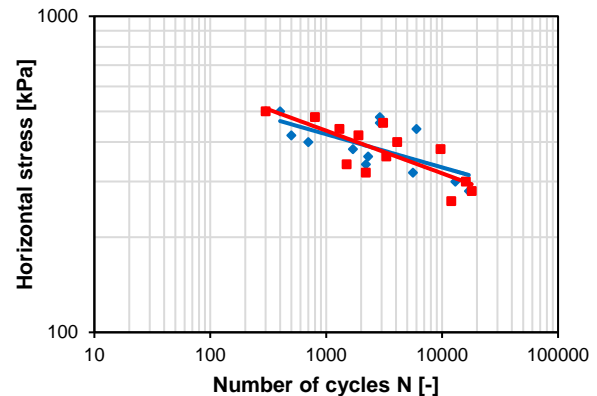


◆ C2E2    ▲ C2E4    ■ C2E6

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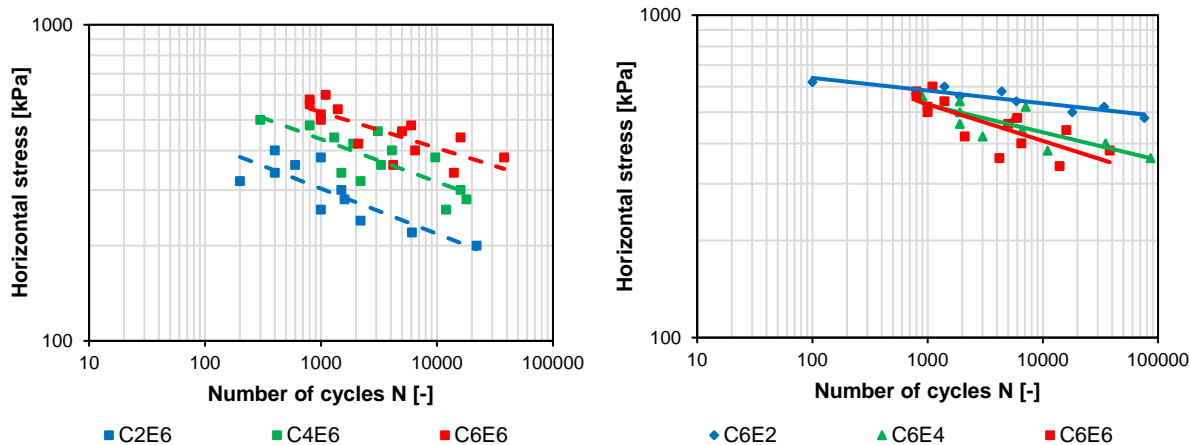


▲ C2E4    ▲ C6E4



◆ C4E2    ■ C4E6

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**Fig. 5.** Summary of the Indirect Tensile Fatigue Test for all the tested mixtures as a relationship between horizontal stresses and number of fatigue cycles.

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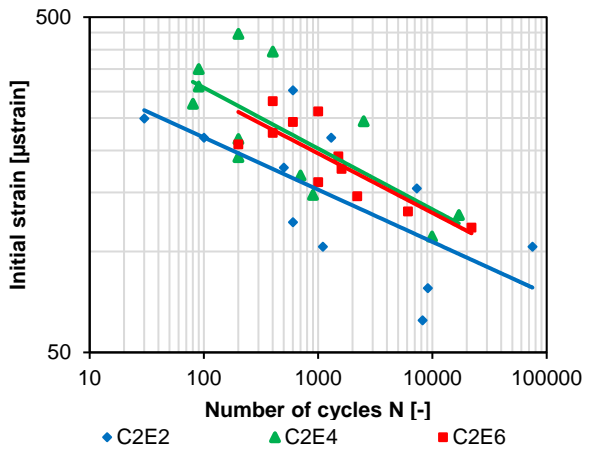
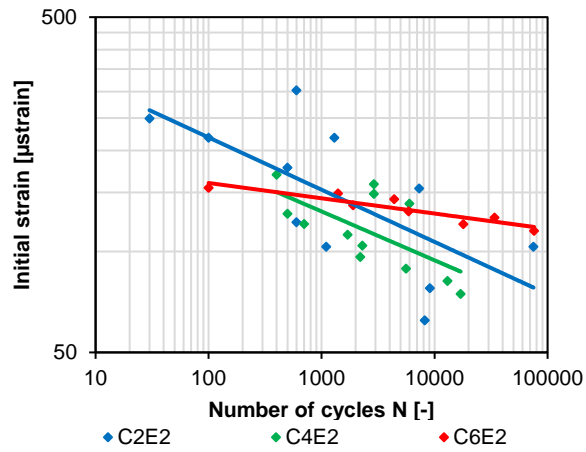
205

Results presented in Figure 5 were separated to present the influence of both binding agents. The left side of the figure presents the results for constant amounts of bituminous emulsion (top to bottom: 2%, 4% and 6%), whereas the right side presents the results for constant amounts of Portland cement (from top to bottom: 2%, 4% and 6%). Upon analysis, the results obtained for constant amounts of bituminous emulsion show evident relationships. In all tested cases, when the amount of bituminous emulsion is constant, the fatigue life of cold recycled mixture increases with an increase in the amount of cement. The fatigue curves are almost parallel to each other. However, aside from that general conclusion, relations regarding the range of test results are also visible. It is observable that with an increase in the amount of bituminous emulsion the range of all test results narrows down. Adding a higher amount of cement results in a lower increase in the fatigue life for higher content of bituminous emulsion. For example, for 2% of bituminous emulsion, an additional 2% of cement increases the fatigue life by around 2 orders of magnitude (which corresponds to additional 100 kPa of stress to obtain the same number of fatigue cycles). In the case of 6% of bituminous emulsion, the increase in the fatigue life for each additional 2% of cement is equal to around half-order of magnitude (which corresponds to additional 50–60 kPa of stress to obtain the same number of fatigue cycles).

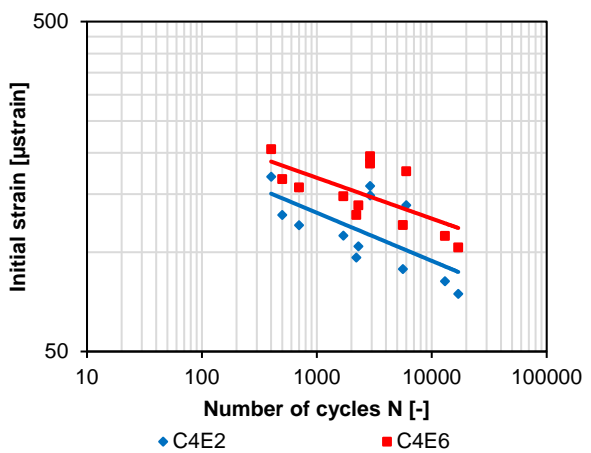
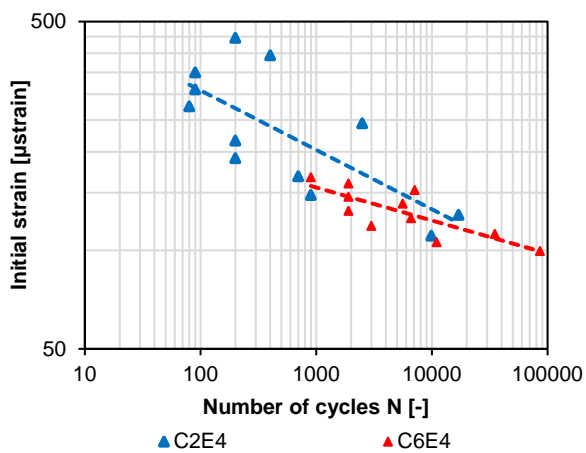


206 The reason for narrowing of the range of the obtained fatigue test results is noticeable  
207 when the results for constant amounts of cement are analyzed. The influence of bituminous  
208 emulsion content is not as regular and simple as it was in the case of cement content. For 2%  
209 of cement, an increase in the amount of bituminous emulsion results in a small increase in the  
210 fatigue life, by around a half-order of magnitude for an additional 1% of bituminous  
211 emulsion. For 4% of cement, an increase in the amount of bituminous emulsion does not have  
212 visible influence on the fatigue life. Unfortunately, due to problems with preparation of the  
213 C4E4 specimen series, it was impossible to verify whether it was just a coincidence or a  
214 general behavior. However, based on the analysis of results for higher cement content, it may  
215 be assumed as a general trend that for 6% of cement additional amount of bituminous  
216 emulsion results in a decrease in the fatigue life.

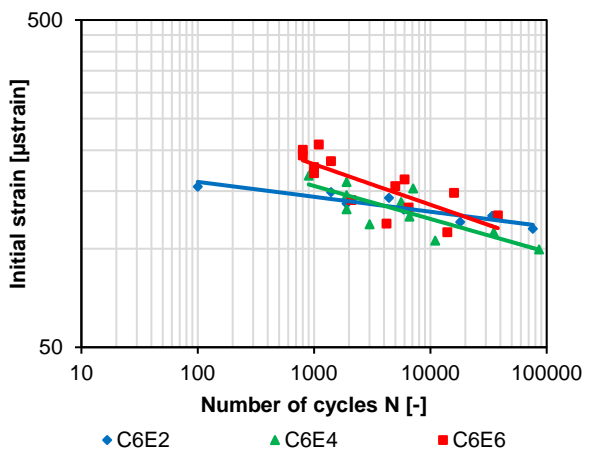
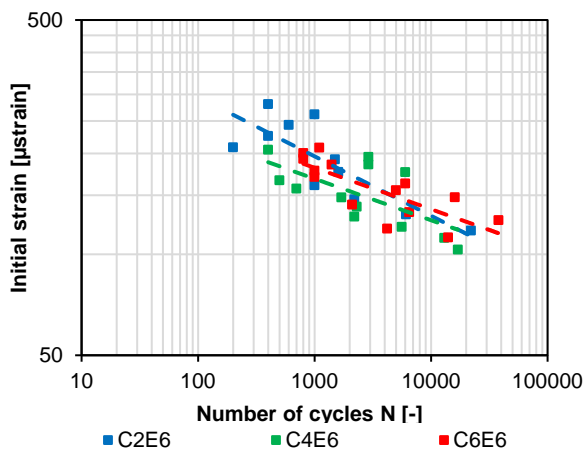
217 While the influence of cement on the increase in the fatigue life in controlled stress  
218 mode may be connected to the increase in values of stiffness modulus due to an increased  
219 cement content, the same cannot be stated for the influence of emulsion. Results presented in  
220 Table 2 as well as previous research [28,29,31] show that an increase in the amount of  
221 bituminous emulsion generally results in a decrease in stiffness modulus for all the chosen  
222 constant amounts of cement and for all the tested curing periods. While the difference is  
223 smaller in the case of 2% of cement, and in some cases the test results overlap, the change is  
224 evident for higher amounts of cement.



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**Fig. 6.** Summary of the Indirect Tensile Fatigue Test for all the tested mixtures as a relationship between initial strain and number of cycles.

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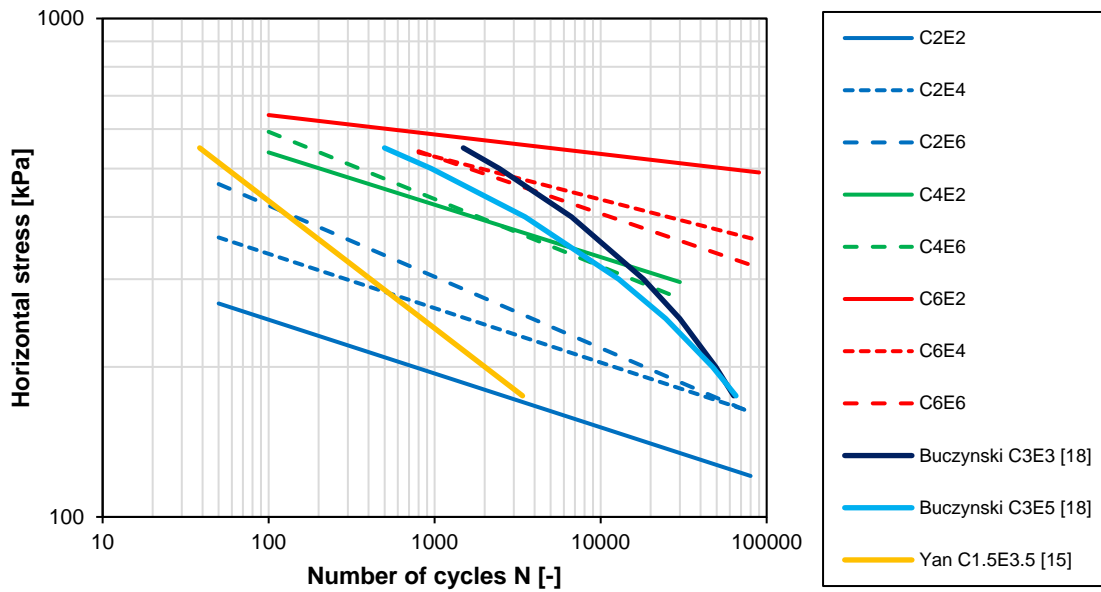
A similar manner of presentation was used in Figure 6. The left side of the figure presents the results for constant amounts of bituminous emulsion (top to bottom: 2%, 4% and 6%). The right side presents the results for constant amounts of Portland cement (from top to



233 bottom: 2%, 4% and 6%). Upon analysis, the obtained results do not show relationships as  
234 evident as those noted for the fatigue life shown as a function of horizontal stresses. In this  
235 case, only some general trends can be observed. As the stiffness moduli of the mixtures are  
236 now included in the fatigue analysis, the differences between specific combinations decrease.  
237 Nevertheless, trends are still visible. For a constant amount of bituminous emulsion, an  
238 increase in cement content does not significantly change the fatigue characteristics. For a high  
239 amount of emulsion (6%), the results for all cement amounts are the same. In the case of  
240 lower amounts of emulsion (2% and 4%), the fatigue properties deteriorate slightly with the  
241 addition of cement. More noticeable differences are visible in the case of a constant amount of  
242 cement. In the case of lower amounts of cement (2% and 4%), increasing bituminous  
243 emulsion content improves fatigue properties. In the case of a high amount of cement (6%),  
244 additional amount of bituminous emulsion does not significantly change the fatigue properties  
245 of the mixtures. While the variability of the obtained results is relatively high – as may be  
246 expected in the case of recycled materials – it is noticeable that with an increase in the amount  
247 of both binding agents the variability of the results decreases. It is possible that with higher  
248 amounts of cement and bituminous emulsion the influence of the mastic and its properties on  
249 mechanical behavior is more significant than the influence of RA and mineral aggregate.

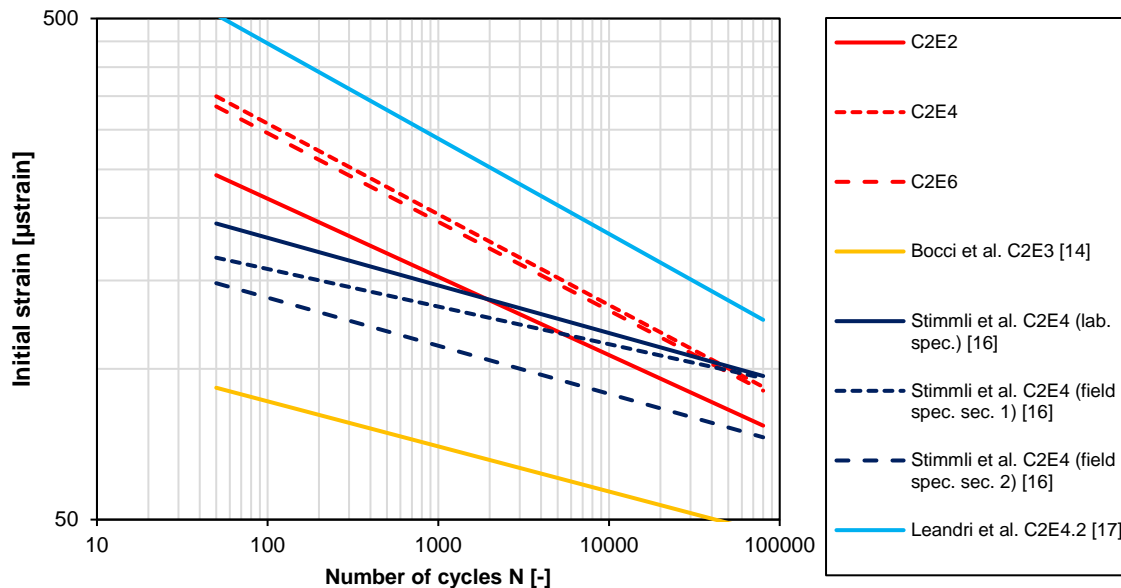
250 As fatigue tests for cold recycled mixtures are relatively uncommon, the test results  
251 obtained in this research were compared with other results given in the literature.  
252 Comparisons are presented in Figures 7 and 8. It should be noted that the test data found in  
253 the literature were usually obtained for specimens tested 28 days after compaction or after an  
254 equivalent period of curing.

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**Fig. 7.** Comparison of the obtained results with other research, on the basis of [15,18], as a relationship between horizontal stress and number of cycles.



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**Fig. 8.** Comparison of the obtained results with other research, on the basis of [14, 16, 17], as a relationship between initial strain and number of cycles

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As shown in Figure 7, when the fatigue life is analyzed as a function of horizontal stress, the results reported in the literature fall into a similar range of values for respective amounts of binding agents. The main difference is the slope of the fatigue curve, which is steeper for results from the literature. Interestingly, if the same fatigue function was chosen for the results of both Buczyński [18] and Yan [15], their results would be parallel to each other. The difference in slope originates mainly from differences in composition of the

270 mixtures, but it could have also been influenced by the chosen curing time, which in case of  
271 Buczyński [18] and Yan [15] equaled 28 days.

272 On the other hand, when the fatigue life is analyzed as a function of initial strain, the  
273 obtained results differ significantly. While the binding agent combinations in the mixtures  
274 presented in the literature are almost the same – the amount of cement equal to 2% and the  
275 amount of emulsion from 3% to 4.2% – the difference in the results for the same curing time  
276 may be even threefold (different value of initial strain for the same fatigue life). Results  
277 obtained in this study suggest that after a longer period of time the fatigue life of cold  
278 recycled mixtures increases, especially in the case of high initial strain values, but it also  
279 becomes more dependent on the initial strain value – the slope of the curve is steeper in  
280 comparison to other results.

281 Nevertheless, in the analysis of the fatigue life as a function of horizontal stresses,  
282 general conclusion from the literature results confirms the findings of the presented research –  
283 an increase in cement content results in an increase in the fatigue life of a cold recycled  
284 mixture. In the case of increase in bituminous emulsion content, in the research conducted by  
285 Buczyński [18] it resulted in a decrease in the fatigue life. It should be noted that this behavior  
286 occurred for a lower amount of cement than in the presented research. Other available results  
287 from the literature are not useful for verification of the obtained trends related to binding  
288 agent combinations, since each test was only focused on a single mixture composition.

#### 289 **4. Summary and conclusions**

290 Based on the test results and the conducted analysis, the following conclusions can be  
291 drawn:

- 292 1. Fatigue behavior of cold recycled mixtures is a very complex aspect which still has  
293 not been sufficiently investigated. The used test protocols and published results are  
294 often noncomparable.
- 295 2. The results obtained for cold recycled mixtures present high variability related to the  
296 mineral composition of the mixtures. This fact should be taken into account when  
297 analyzing the obtained results. The results show specific tendencies rather than direct  
298 relationships. Variability of test results decreased with an increase in the total amount  
299 of binding agents.
- 300 3. When the fatigue life is analyzed as a function of horizontal stress, the following  
301 tendencies are visible:
- 302 a. An increase in cement content for a constant amount of emulsion results in  
303 an increase in the fatigue life. The highest increase in the fatigue life with  
304 cement content is observed for 2% of bituminous emulsion and it gradually  
305 becomes less distinct for higher amounts of emulsion. This kind of  
306 behavior can be connected to the values of stiffness modulus for respective  
307 combinations of binding agents, which increase with an increase in the  
308 amount of cement.
- 309 b. The effect of bituminous binder on fatigue response is strictly related to the  
310 amount of cement within the mixture. For 2% of cement, the fatigue life  
311 increases with an increase in bituminous emulsion content. For 4% of  
312 cement, the fatigue life remains the same regardless of the amount of  
313 bituminous emulsion. For 6% of cement, the fatigue life decreases with an  
314 increase in bituminous emulsion content. Nevertheless, the influence of  
315 bituminous emulsion on the fatigue life is not as evident as in the case of  
316 cement content.

- 317 4. When the fatigue life is analyzed as a function of initial strain, the following  
318 tendencies are visible:
- 319 a. In the case of constant bituminous emulsion content, for a high amount of  
320 emulsion (6%), results for all cement amounts are the same. In the case of  
321 lower amounts of emulsion (2% and 4%), the fatigue properties deteriorate  
322 slightly with the addition of cement.
- 323 b. In the case of constant cement content, for lower amounts of cement (2%  
324 and 4%) increasing of bituminous emulsion content improves fatigue  
325 properties. In the case of a high amount of cement (6%), additional amount  
326 of bituminous emulsion does not significantly change the fatigue properties  
327 of the mixtures.
- 328 5. Comparison with research results presented in the literature confirmed some of the  
329 trends visible in the presented research: an increase in cement content results in an  
330 increase in the fatigue life.
- 331 6. The conducted research and literature study indicate that in the case of coarse  
332 gradation of the mixtures and natural variability of base material, a more reliable test  
333 method should be developed. Additionally, a single universal test protocol should be  
334 established, as each researcher conducts fatigue life tests at different arbitrarily set test  
335 conditions, which makes it difficult to compare and analyze the obtained results.

### 336 **Acknowledgments**

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340 Road Innovations”.

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