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

Bohdan Dolzycki, Cezary Szydlowski, Mariusz Jaczewski

Highway and Transportation Engineering Department, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland

Gdansk University of Technology, Faculty of Civil and Environmental Engineering
Narutowicza Street 11/12
Gdansk, PL 80-233
tel.:+48 58 347 27 82
e-mail: mariusz.jaczewski@pg.edu.pl

Abstract

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

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

1. Introduction

1.1. Background

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

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

1.2. Fatigue behavior of cold recycled mixtures

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

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

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

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	$y = 130.32x^{-0.09}$ $\varepsilon_6 = 33.1$ µstrain a = 0.111	ITFT	Test temperature 20°C Test mode: not specified Axis: ε [µstrain] – N
Yan et al. [15]	cement 1.5% emulsion 3.5% gradation 0/26 100% RA	$y = 2E\text{-}10x^{-3.5233}$	ITFT	Test temperature 20°C Test mode: controlled stress Axis: log ε [-] – 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: ε [µstrain] – 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 ε [µstrain] – log N
Buczyński [18]	cement 3.0% emulsion 3.0 / 5.0% gradation 0/31.5 RA amount not stated	<u>250kPa</u> $y = 55.950e^{2E\text{-}06x}$ (5% emulsion) $y = 37.858e^{2E\text{-}06x}$ (3% emulsion) <u>375 kPa</u> $y = 89.007e^{0.0002x}$ (5% emulsion) $y = 50.591e^{1E\text{-}05x}$ (3% emulsion)	ITFT	Test temperature 20°C Test mode: controlled stress Axis: log ε [µstrain] – 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	$N_F = 4x10^{16} \cdot \sigma^{-4.785}$ (3% cement) log N - σ $y = 1E+26x^{-9.8310}$ (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 μstr – 88 200 cycles 250 μstr – 560 000 cycles 200 μstr – 172 000 cycles 140 μstr – 2 400 000 cycles 120 μstr – 1 700 000 cycles	4PB	Test temperature: 5°C Test mode: controlled strain Test frequency, 10 Hz

1.3. Aims and scope

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

2. Materials and methods

2.1. Materials and preparation

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

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

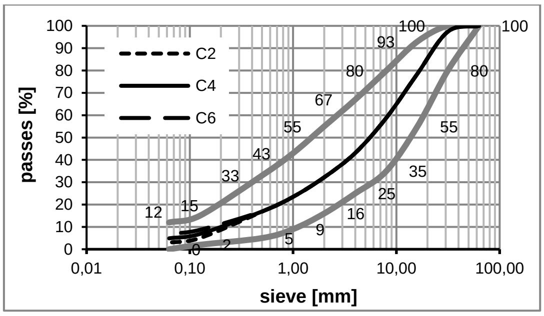


Fig. 1. Grading curve of mineral mixtures.

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

	Cold Recycled Mixture							
Mixture designation	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^3]	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

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

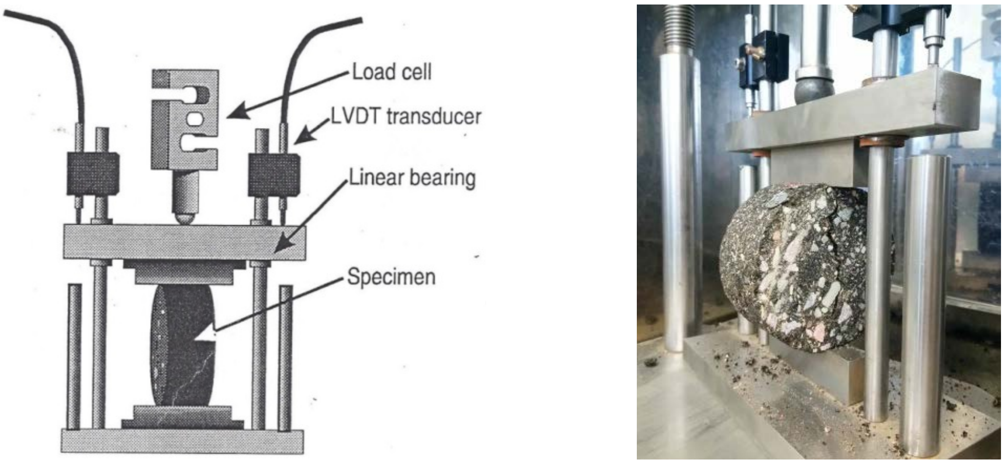
Before fatigue testing, specimens were used for long-term modulus testing [28,29]. Since the earlier tests were nondestructive, the same material – already after over 4 years of curing – was used for fatigue testing, in order to gather valuable data on performance of mixtures with various combinations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

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

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

2.2. Methods

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



(a) (b)

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

3. Results and discussion

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

$$\sigma = a \cdot N^{b} \tag{1}$$

where σ is the applied horizontal stress (MPa), *N* is the fatigue life (number of loading cycles), *a* and *b* are regression parameters;

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

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

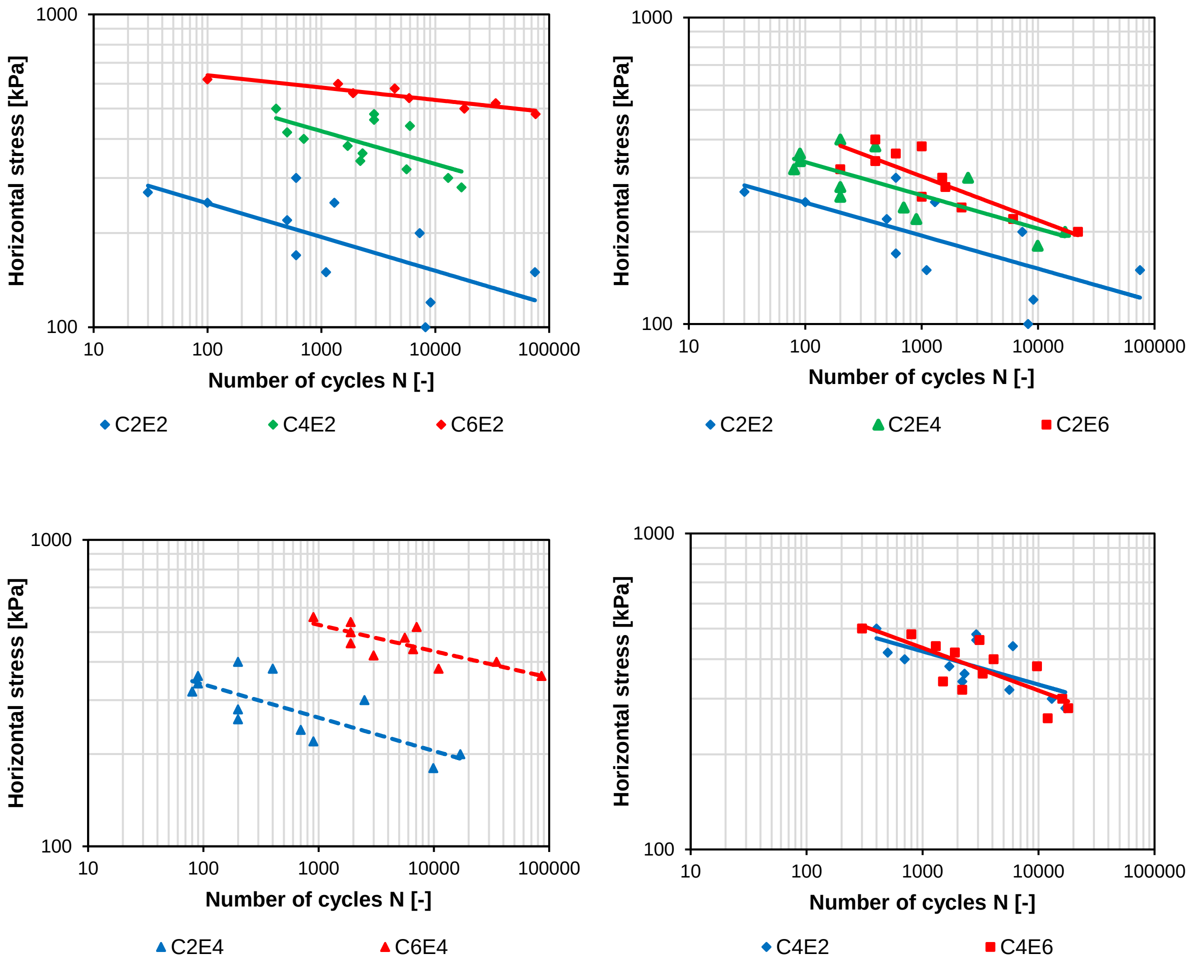
Table 3. Detailed tests results

Mixture designation	Sample no.	Bulk density [Mg/m^3]	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

Table 4. Indirect Tensile Fatigue Test results

	Cold Recycled Mixture							
Mixture designation	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 max, MPa	 100 300	 180 400	 200 400	 280 500	 260 500	 480 620	 360 560	 340 600
Regression parameters for equation (1) a b	 409.01 -0.108	 577.02 -0.109	 814.40 -0.143	 873.66 -0.105	 1103.40 -0.135	 766.10 -0.039	 956.84 -0.086	 1160.40 -0.114
Regression parameters for equation (2) a b	 448.10 -0.156	 709.99 -0.181	 667.11 -0.177	 360.25 -0.146	 395.02 -0.124	 197.47 -0.046	 312.17 -0.101	 425.80 -0.124



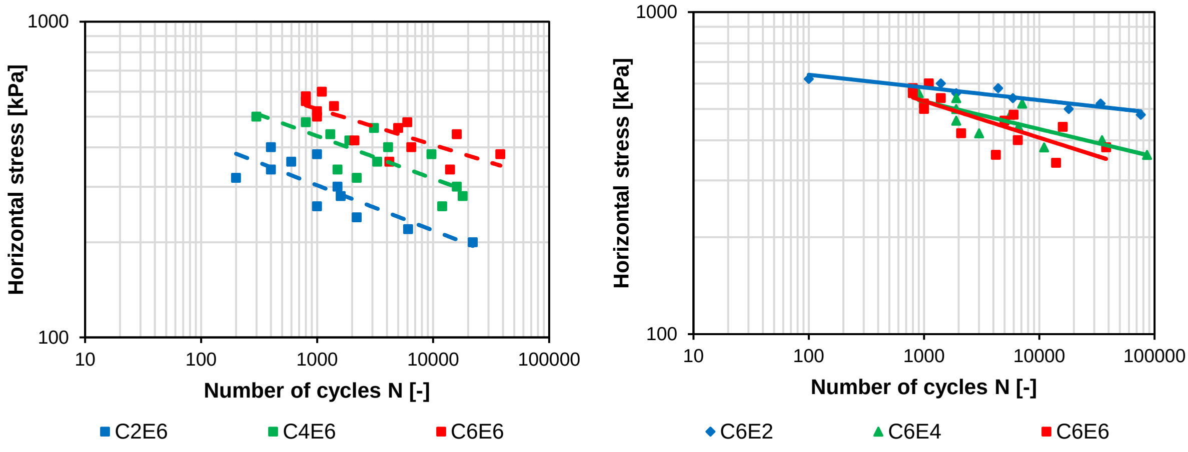


Fig. 5. Summary of the Indirect Tensile Fatigue Test for all the tested mixtures as a relationship between horizontal stresses and number of fatigue cycles.

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).

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

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

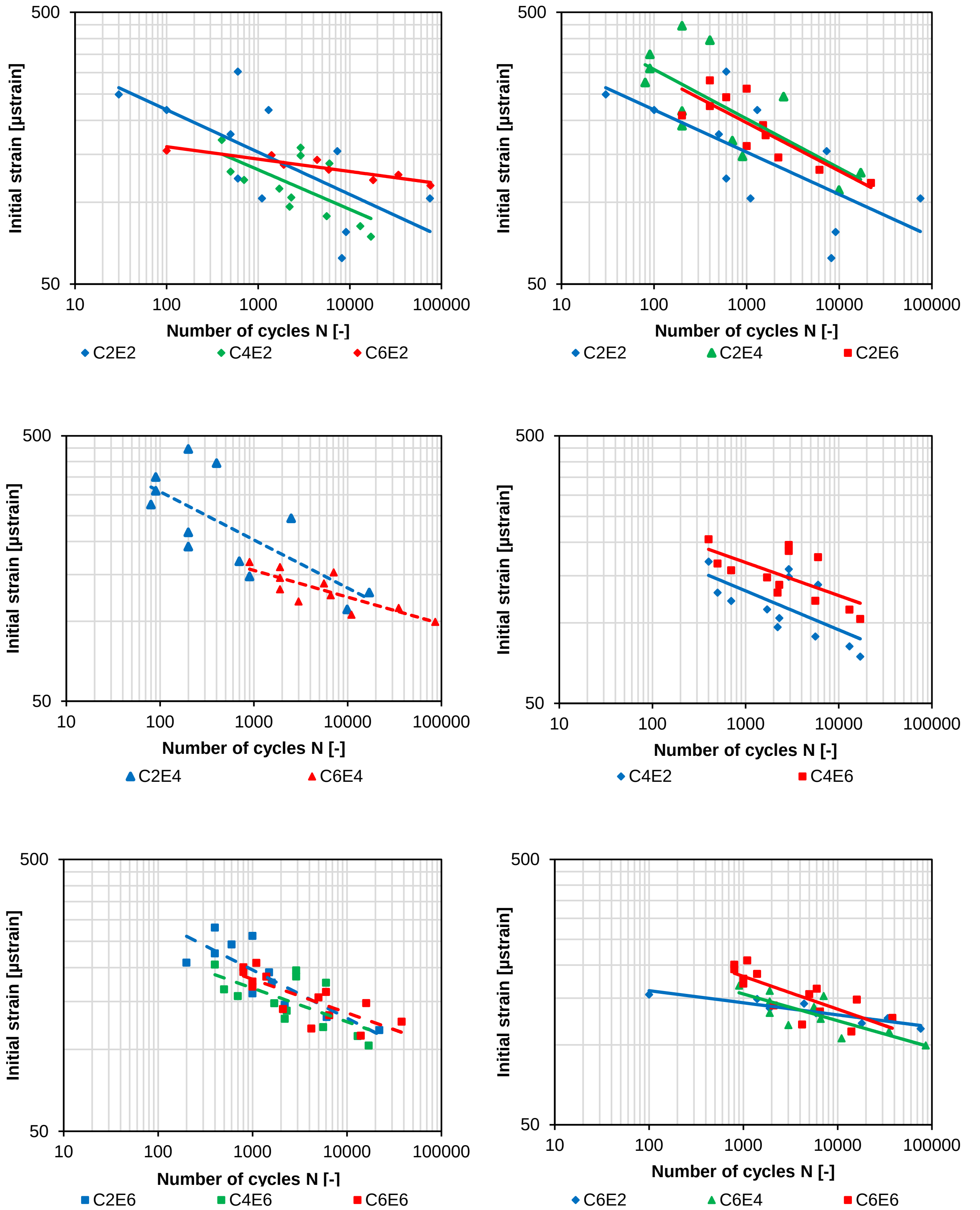


Fig. 6. Summary of the Indirect Tensile Fatigue Test for all the tested mixtures as a relationship between initial strain and number of cycles.

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

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

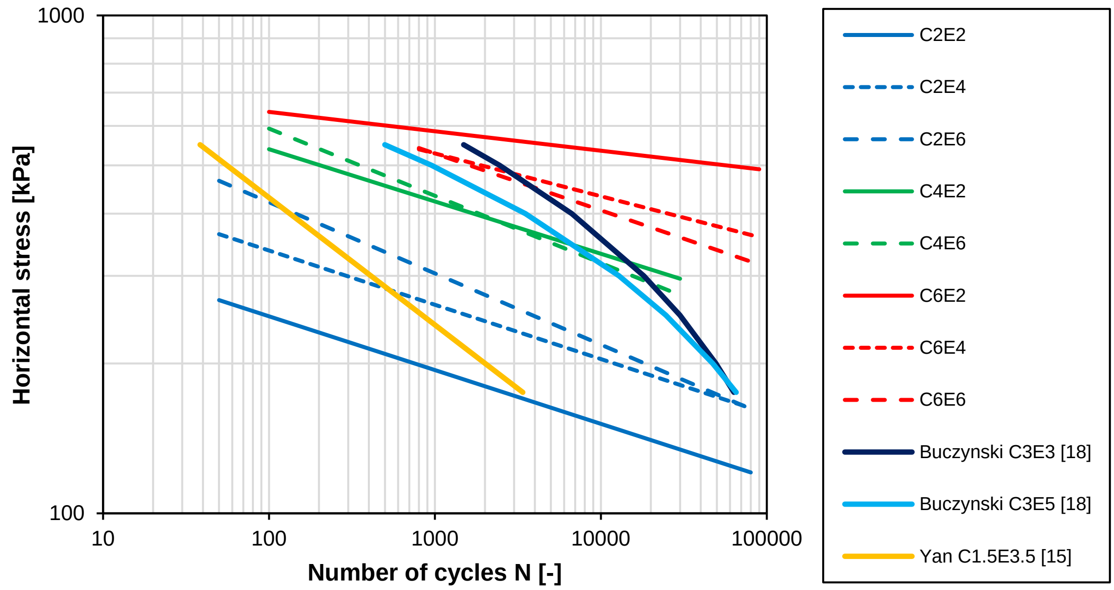


Fig. 7. Comparison of the obtained results with other research, on the basis of [15,18], as a relationship between horizontal stress and number of cycles.

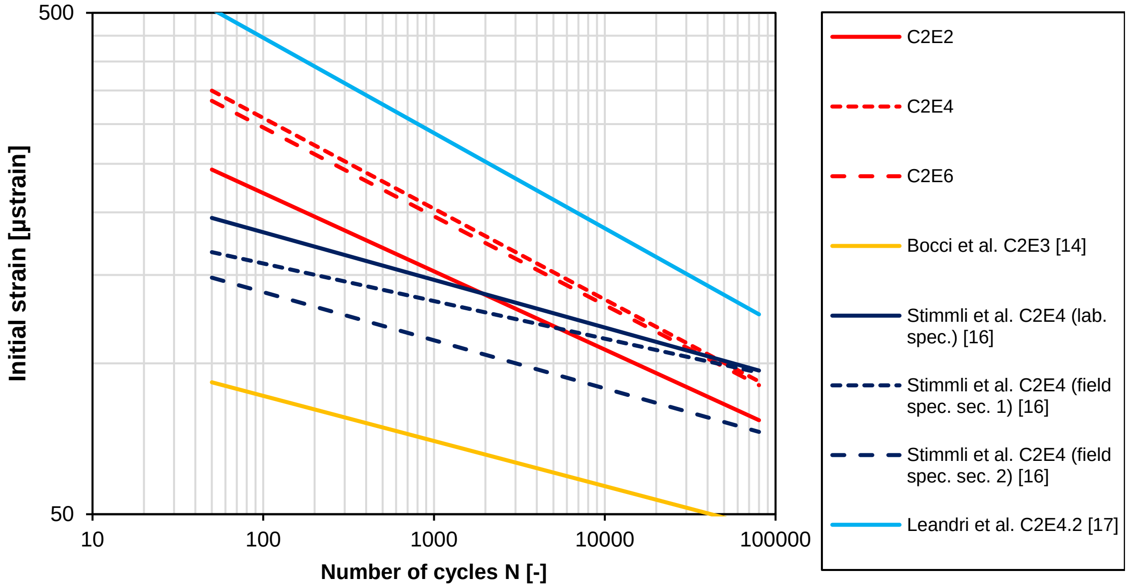


Fig. 8. Comparison of the obtained results with other research, on the basis of [14, 16, 17], as a relationship between initial strain and number of cycles

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

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

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

4. Summary and conclusions

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

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

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

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