

1 **Preliminary Study of Linear Viscoelasticity Limits of Cold Recycled**  
2 **Mixtures determined in Simple Performance Tester (SPT)**

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11           **Abstract**

12           The publication presents methodology developed for determination of linear  
13 viscoelasticity limits for cold recycled mixtures with cement and bituminous emulsion  
14 using Simple Performance Tester (SPT). Methodology was verified on reference  
15 materials (PCV and steel dummy specimens, cement concrete and asphalt concrete) to  
16 comply with elasticity and viscoelasticity theory. The developed methodology enabled  
17 determination of linear viscoelasticity limits for the tested cold recycled mixtures for base  
18 course. Tests were conducted for controlled strain ranging from 10 up to 110  $\mu$ strain.  
19 Linear viscoelasticity limits were determined based on stiffness moduli and phase angles.  
20 The combination of binding agents and test temperature had the greatest influence on the  
21 obtained values.

22           **Keywords:** linear viscoelasticity; cold recycled mixtures; cement; bituminous  
23 emulsion

24

## 25 **1. Introduction**

### 26 1.1. Background

27 Constant increase in road traffic and aging of road sections result in deterioration of the  
28 existing bituminous road pavements, which should be reconstructed using the most  
29 environmentally friendly and low-emission technologies available. Common processes that  
30 allow one to obtain a pavement with high bearing capacity include cold recycling, in which  
31 material is produced and compacted at ambient temperature. Cold recycled mixture consists of:  
32 RAP (reclaimed asphalt pavement) material, virgin aggregate, cement and bituminous emulsion  
33 or foamed bitumen. This technology, enabling reuse of any reclaimed pavement material, is  
34 used in many countries, including Poland [1,2,3,4], Germany [5], Czechia [6], Italy [7,8,9],  
35 Serbia [10], USA [11], Canada [12] and China [13]. Depending on the local climatic conditions  
36 and materials used, the mixtures differ in binding agents – cement and bituminous emulsion,  
37 cement and foamed bitumen or just one of the listed binders. The amount of the used binders is  
38 determined based on local climatic conditions and requirements stated for the prepared  
39 mixtures. In colder countries [1], where resistance to water and frost action is a serious issue,  
40 the amount of cement increases, while in warmer ones [7, 10] cement is used only to accelerate  
41 the breakage of bituminous emulsion and provide minimum mechanical properties of the  
42 mixture during further construction works. This results in a very wide range of the used  
43 quantities of binding agents: cement content ranges from 0.5% to 6%, with typical values  
44 around 2%, while the content of bituminous emulsion or foamed bitumen ranges from 2% to  
45 7%, with typical values around 3-4%. Consequently, different mixture recipes vary greatly in  
46 the obtained mechanical properties, which also change with time. This also causes considerable



47 problems in terms of proper determination of mechanical and rheological properties of cold  
48 recycled mixtures.

49 As cold recycled mixtures have only been extensively researched for the last ten years,  
50 there are still no common standards for the tests. Since cold recycled mixtures are partly similar  
51 to typical asphalt concretes, appropriately adjusted asphalt concrete test procedures are used for  
52 their mechanical characterization [14, 15]. Adjustments are usually introduced based on the  
53 experience of the specific researcher [14,15]. Typical tests used for determination of  
54 mechanical properties include indirect tensile tests (modulus, strength and fatigue) [7, 16, 26,  
55 28] and cyclic compression or tension/compression tests (modulus and phase angle) [12, 14,  
56 15], which were originally designed for asphalt mixtures. Compression tests (strength) that  
57 were designed for cement-bound materials are also used.

58 Researchers usually assume that cold recycled mixtures fit the model of thermo-  
59 rheologically simple linear viscoelastic material [14, 15], due to the strong influence of bitumen  
60 present in the bituminous emulsion and RAP material. Previous international practice generally  
61 confirms this assumption [15]. The modulus of the mixture changes with test temperature and  
62 time of loading. It is possible to develop stiffness modulus and phase angle master curves for  
63 the whole range of loading times and test temperatures [14]. Nevertheless, due to the influence  
64 of cement, the differences between the highest and lowest values of both properties are not as  
65 high as in the case of typical asphalt concretes [14]. This leads to question whether the criteria  
66 typically assumed for linear viscoelasticity limits of asphalt concretes can be directly applied  
67 to cold recycled mixtures containing Portland cement. Generally, researchers either use the  
68 same criteria as for asphalt concretes or lower the values of strain/deformation/stress applied  
69 during tests [14, 15]. However, the question of actual linear viscoelasticity limits of cold  
70 recycled mixtures and the factors that affect them (such as: age of the specimen, composition



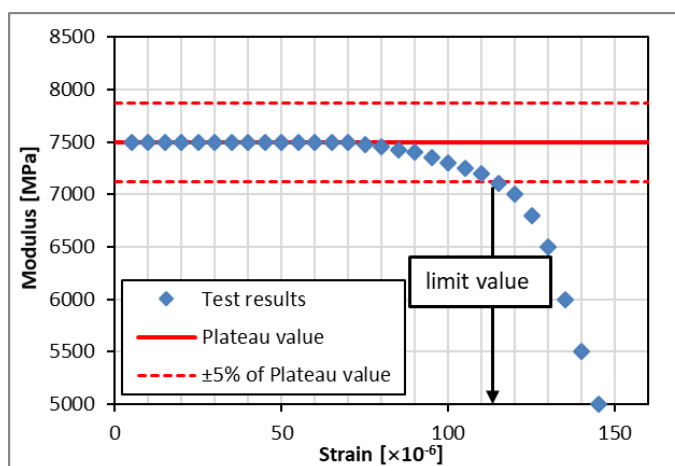
71 of the mixture, test temperature, frequency/time of loading, preparation and compaction of the  
72 specimen) still remains open. Establishing correct viscoelasticity limits is required for  
73 preparation of unified standard specifications for material testing and, subsequently, for correct  
74 modelling of cold recycled mixtures in FEM or other methods. It is also required for proper  
75 comparison of the results obtained by different researchers.

## 76 1.2. Linear viscoelasticity limits in bituminous materials

77 Under typical traffic conditions (typical axle loads, typical traffic speed), all materials  
78 with bituminous compounds usually display linear behaviour [17, 18, 19]. In pavement analyses  
79 it is usually assumed that their rheological properties (especially moduli and phase angles) at  
80 the specific analysed temperature and for typical load conditions are constant regardless of the  
81 applied stresses, strains or deformations. However, this assumption is correct only for a specific  
82 small range of applied loads, which is referred to as linear viscoelasticity limit (LVE limit) and  
83 strongly depends on the tested material, test temperature and test setup. In the case of asphalt  
84 mixtures the range of LVE limit is relatively wide; usually it covers the typical values of  
85 vehicle-induced strains or stresses that may occur in a pavement. In the case of cyclic  
86 compression test, the LVE limit for temperatures ranging from 4°C to 45°C usually falls within  
87 the range of 20  $\mu$ strain to 115  $\mu$ strain [23]. Some discrepancies may be noted at higher  
88 temperatures for certain bitumen types (especially softer, with lower ring and ball temperature).  
89 Such behaviour of the material enables researchers to assume constant values of mechanical  
90 properties in pavement design and analysis. Additionally, when material fulfils the  
91 requirements for linear viscoelasticity, it is possible to compare its properties determined in  
92 various research efforts conducted at different laboratories. Therefore, it is of great importance  
93 to evaluate whether the limits are similar in the case of cold recycled mixtures.



94 The range of linear viscoelasticity limits for bituminous materials has been extensively  
95 tested since the 1960s [18, 19, 20]. Usually the ranges of permissible strains (in controlled strain  
96 mode) or permissible stresses (in controlled stress mode) are presented in various research  
97 works as the linear viscoelasticity limit. Currently, linear viscoelasticity limits or means of their  
98 determination for asphalt mixtures are established and included in the standard specifications  
99 for laboratory tests (for example, in the amplitude sweep test in the DSR device). It is generally  
100 assumed that a material is treated as linear viscoelastic until its modulus deviates more than 5%  
101 from the initial modulus value (as presented in Fig. 1, after Airey et al. [18]). The deviation of  
102 5% of the modulus value is currently assumed as the LVE limit. While it was observed during  
103 complex modulus testing that the phase angle increased when specimens started to show non-  
104 linear behaviour, no established limits have been presented yet. In this study criteria similar to  
105 those applied to the moduli were assumed to determine viscoelasticity limits in the case of phase  
106 angles. Usually the LVE limit is determined solely on the basis of stiffness moduli. Phase angles  
107 are taken into consideration in the case of material modelling [31, 32], but are not used as means  
108 to determine the LVE limits.



109 **Fig. 1.** Determination of linear viscoelasticity limits for asphalt mixture in strain-controlled mode, after  
110 Airey et al. [18]  
111

112 1.3. Objectives

113 The main objective of the study is to determine whether the Simple Performance Tester  
114 (SPT) apparatus (IPC Global) can be used for evaluation of the viscoelastic behaviour of cold  
115 recycled mixtures. Second objective of the study is to determine linear viscoelasticity limits for  
116 cold recycled mixtures and analyse the impact of mixture composition (the amounts of binding  
117 agents used) on those limits. For this purpose, 9 different cold recycled mixtures (of two types)  
118 were tested; their dynamic moduli and phase angles were determined. The study consisted of  
119 two main parts: a) adoption of the test methodology and its verification on various materials,  
120 and b) analysis of the influence of mixture composition on the determined values of linear  
121 viscoelasticity limits. Linear viscoelasticity limits were determined using the criteria  
122 established for other asphalt materials, after Airey et al. [18].

## 123 2. Materials and methods

### 124 2.1. Materials

125 Preliminary evaluation was also performed on different types of materials (steel and  
126 PCV dummy specimens, asphalt concrete, cement concrete). At the preliminary stage, typical  
127 road pavement mixtures, representative of each group, were tested. In the case of steel and  
128 PCV, dummy calibration specimens were used. In the case of asphalt concrete, a mixture of  
129 gradation of 0/32 mm containing 35/50 penetration bitumen was used. In the case of cement  
130 concrete, a typical road pavement C35/40 class mixture was used. The mixtures were designed  
131 according to the Polish requirements [29, 30].

132 The main part of the laboratory experiments was conducted for two types of cold  
133 recycled mixtures. Stage 1 (A and B) was conducted on mixture designed for binder courses  
134 and Stage 2 was conducted on mixtures designed for base courses. All mixtures were designed  
135 according to the Polish recommendations and local experience [1, 21], with appropriate  
136 adjustment for the first mixture (lower maximum gradation). Portland cement CEM I 32.5R

137 and slow-setting cationic asphaltic emulsion C 60 B10 ZM/R (with neat 70/100 residual  
 138 bitumen) were used as binding agents. Mixtures were prepared in a laboratory mixer according  
 139 to the EN 12697-35 standard. Specimens were compacted in a gyratory compactor according  
 140 to the EN 12697-31 standard. The limiting compaction ratio was set as 99% of the maximum  
 141 dry density determined in the modified Proctor test. The specimens were compacted to the  
 142 height of 170 mm and the diameter of 150 mm and later cut to the target specimen height of  
 143 150 mm and diameter of 100 mm. The base course mixture specimens were previously used in  
 144 long-term tests [14, 22]. In each case the age of the specimen was over a year, so the impact of  
 145 the processes associated with curing of the materials was minimised. Basic information  
 146 regarding composition of cold recycled mixtures used in the study is presented in Table 1.

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**Table 1.** Properties of cold recycled mixtures.

Property	Stage of the study Mixture designation (b/c ratio)	
	First stage C3E7 (1.52)	Second stage C2E2 (0.65), C2E4 (1.30), C2E6 (1.95) C4E2 (0.33), C4E6 (0.98) C6E2 (0.22), C6E4 (0.43), C6E6 (0.65)
Mixture composition		
Virgin aggregate 0/16 or 0/31.5 <sup>a)</sup> (% by mass)	23.3	18
Virgin aggregate 0/2 (% by mass)	9.3	10, 8, 6 <sup>b)</sup> (depending on the cement content)
RAP aggregate (% by mass)	57.5	70
Bitumen emulsion content (% by mass)	7	2, 4, 6
Cement content (% by mass)	3	2, 4, 6

Remarks:

1) Mixture designations are as follows: C – quantity of cement in the mixture [%], E – quantity of emulsion in the mixture [%], b/c ratio – residual bitumen to cement ratio

2) Detailed information regarding the tested mixtures can be found in previous studies [14, 22]

a) 0/16 in the case of C3E7 mixture and 0/31.5 in the case of C2E2, C2E4, C2E6, C4E2, C4E6, C6E2, C6E4 and C6E6 mixtures

b) depending on the cement content; total quantity of cement and virgin aggregate 0/2: 12 % (by mass)

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150 2.2. Methods



### 151 2.2.1. Cyclic compression test

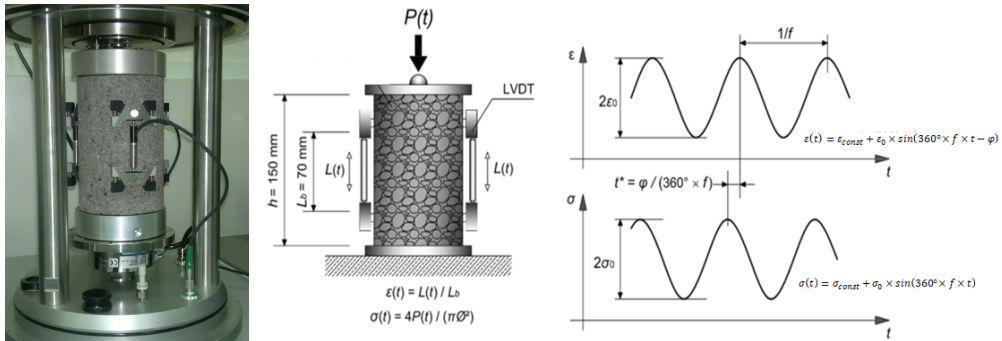
152 Stiffness moduli and phase angles for all mixtures were determined in the cyclic  
153 compression test according to the AASHTO TP79 standard [23]. Tests were performed using  
154 Simple Performance Tester (IPC Global, Australia). The tests were conducted at two  
155 temperatures depending on the stage of the experiment: first stage was conducted at 10°C to  
156 avoid excessive deformation of the specimen; the second stage was conducted at 20°C. Prior to  
157 testing, each specimen was conditioned overnight at the temperature of the test. Dynamic  
158 moduli and phase angles were determined for 9 frequencies: 25, 20, 10, 5, 2, 1, 0.5, 0.2 and 0.1  
159 Hz.

160 The performed study encompassed three major stages. Preliminary stage consisted in  
161 performance of the SPT test on known elastic and viscoelastic materials to verify the used test  
162 equipment. Stage 1 aimed to confirm that the observed behaviour of cold recycled mixtures is  
163 caused by nonlinearity of the tested mixtures (and not by other phenomena, such as material  
164 fatigue) and to determine whether the applied methodology can be utilised for determination of  
165 linear viscoelasticity limits for cold recycled mixtures. Stage 2 was the main research, which  
166 aimed to determine mixture properties that have influence on linear viscoelasticity limits of  
167 cold recycled mixtures. To achieve these goals, the following conditions were applied at  
168 respective stages of research:

- 169 • Preliminary Stage – testing on known materials (cement concrete, steel and PCV  
170 – elastic materials; asphalt concrete AC 22P – viscoelastic material) to verify  
171 whether the Simple Performance Tester can be used to determine the  
172 viscoelasticity and its limits and whether it can correctly differentiate between  
173 elastic and viscoelastic behaviour of materials. 15 consecutive test series were  
174 performed with varied controlled strain: ranging from the level of 10-20  $\mu$ strain

- 175 up to 150-160  $\mu$ strain, with the constant increment of 10  $\mu$ strain in consecutive  
176 tests.
- 177 • Stage 1A – determination of the impact of consecutive tests on specimen (the  
178 impact of specimen fatigue on obtained results). 16 consecutive tests – first 6  
179 tests were conducted for controlled strain value in the range of 50-60  $\mu$ strain,  
180 the following 10 tests were conducted for controlled strain value in the range of  
181 90-100  $\mu$ strain.
  - 182 • Stage 1B – adopting the methodology for determination of linear viscoelasticity  
183 limits and verification vs. other elastic and viscoelastic materials. 15 consecutive  
184 tests were performed with varied controlled strain values: ranging from the level  
185 of 10-20  $\mu$ strain, up to 150-160  $\mu$ strain, with the constant increment of 10  
186  $\mu$ strain in consecutive tests.
  - 187 • Stage 2 – determination of the influence of mixture composition on linear  
188 viscoelasticity limits. 10 consecutive tests were performed with varied  
189 controlled strain value: ranging from the level of 10-20  $\mu$ strain up to 100-110  
190  $\mu$ strain, with the constant increment of 10  $\mu$ strain in consecutive tests.

191 For the main part of the conducted research (Stages 1 and 2), the typical test setup and  
192 procedure was as follows: mounting a preconditioned specimen in the test chamber, reaching  
193 the designated test temperature, first test (9 frequencies), 10 minutes rest, second test (9  
194 frequencies), 10 minutes rest, next test (9 frequencies) etc., until the final test conditions were  
195 reached (either the maximum controlled strain value or the specified number of test repetitions).  
196 The test setup is presented in Fig. 2. In the first stage two different specimens were used, (one  
197 in Stage 1A and one in Stage 1B). In the second stage a single specimen for each mixture  
198 composition was used.



199 **Fig. 2.** Simple Performance Tester – test setup: Specimen ready for testing (left) scheme of the test in  
 200 Simple Performance Tester (centre) and plot that visualises the shift between stress and strain (right).  
 201  
 202  
 203

204 **3. Results and discussion**

205 All the obtained results were determined using cyclic compression test mode, as  
 206 described in the preceding section. Using a different test load mode, such as tension-  
 207 compression, bending or shear, can give different results. Cyclic compression test mode was  
 208 chosen due to its widespread usage and the simplest preparation of specimen and performance  
 209 of the test.

210 **3.1. Verification of the results determined in the Simple Performance Tester for known**  
 211 **elastic and viscoelastic materials – Preliminary stage**

212 Procedure planned for testing of cold recycled mixtures was first validated on two  
 213 groups of known materials – elastic and viscoelastic – to determine whether the obtained results  
 214 are correct and correspond to the basic theoretical models. Tested specimens are presented in  
 215 Fig. 3.

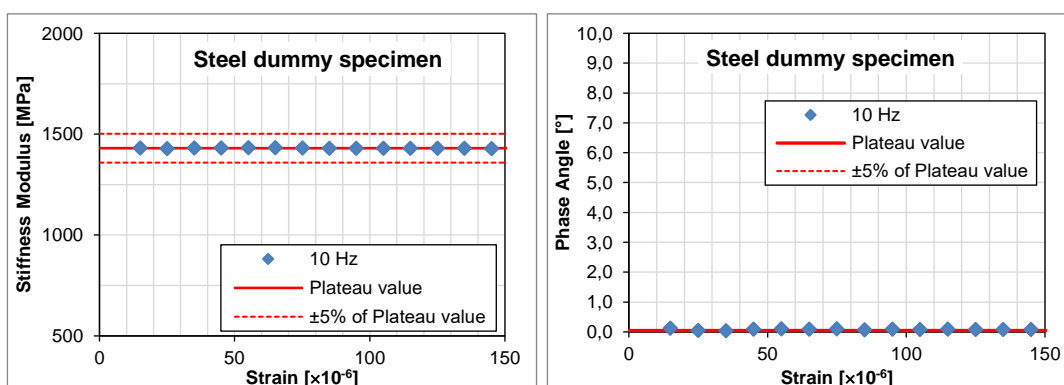


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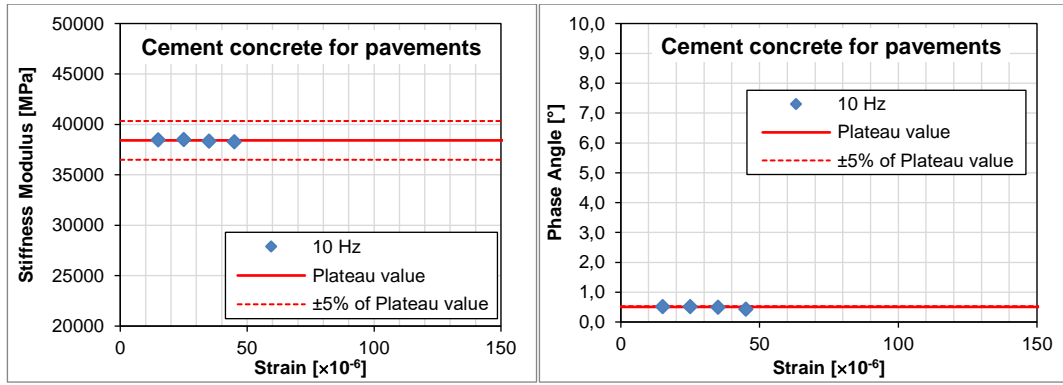
**Fig. 3.** Specimens used for verification of the test procedure (from left): steel dummy specimen, cement concrete, PCV and asphalt concrete.

219 Each specimen was subjected to 15 consecutive tests. The applied strain ranged from  
220 10-20  $\mu$ strain to 150-160  $\mu$ strain. The tested materials were elastic – steel dummy specimen  
221 used for calibration of the SPT device, cement concrete of C35/40 class and PCV (results  
222 presented in Fig. 4) – and viscoelastic – asphalt concrete of class AC 22P with 35/50 neat  
223 bitumen for asphalt base course (results presented in Fig. 5). In the case of cement concrete, the  
224 test was ended at strain range of 40-50  $\mu$ strain due to very high strength of the material; the  
225 SPT equipment could not perform test at higher strains.

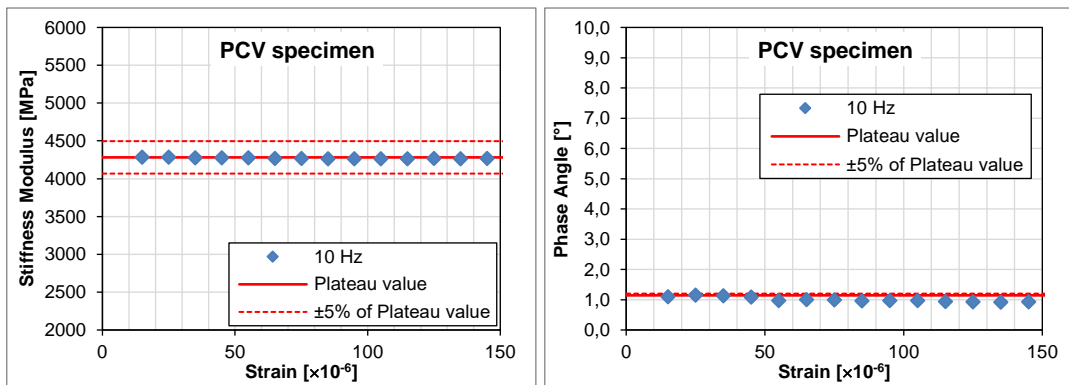
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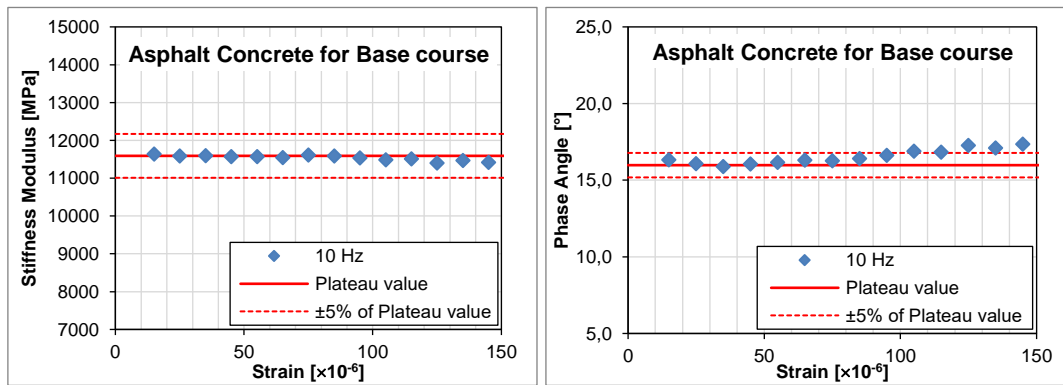


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**Fig. 4.** Verification of linear behaviour of elastic materials: steel dummy specimen, cement concrete and PCV,  $T = 20^{\circ}\text{C}$ ,  $f = 10\text{ Hz}$ .

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**Fig. 5.** Verification of linear behaviour of viscoelastic materials: asphalt concrete for base course,  $T = 20^{\circ}\text{C}$ ,  $f = 10\text{ Hz}$ .

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For elastic specimens the obtained results correspond to the general theory – the stiffness modulus does not change with a change in load and the reaction of the material is immediate (phase angle equal to  $0^{\circ}$ ). Such results were obtained for all the tested elastic materials. Some discrepancies are visible in the case of phase angles. For the steel dummy specimen and cement concrete the results are  $<1^{\circ}$ , which is in agreement with previous studies. In the case of the PCV specimen, the phase angle of  $\sim 1^{\circ}$  suggests that the material is not ideally

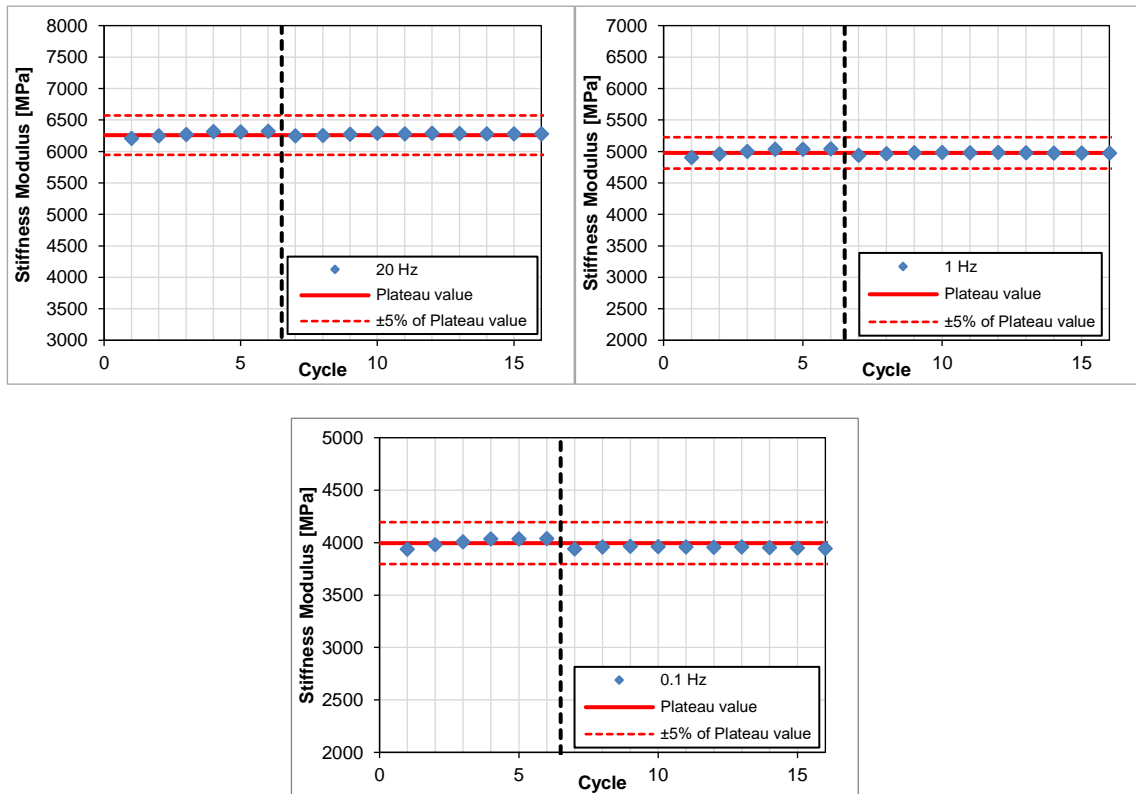
240 elastic, but still fits the general theory of immediate response to the subjected load. In the case  
241 of viscoelastic material (asphalt concrete), the obtained verification test results are also in  
242 agreement with the general theory. Stiffness modulus maintains constant value for small strains,  
243 while further, for higher strains, the modulus starts to decrease, as visible for strains of 120  
244  $\mu$ strain and greater. In the case of phase angle, a steady increase in its value is visible almost  
245 across the entire range of tested strains (for 30  $\mu$ strain and greater). Therefore, the conducted  
246 tests confirmed compliance with the theory.

### 247 3.2.Verification of the methodology for determination of linear viscoelasticity limits of 248 cold recycled mixtures – Stage 1

249 Previous research [16, 25, 26, 27, 28] proved that cold recycled mixtures are similar to  
250 asphalt mixtures in terms of fatigue behaviour. Therefore, it was important to determine first  
251 whether the observed behaviour is fatigue of the tested mixture or rather a change due to  
252 nonlinear viscoelastic behaviour. For this purpose, one specimen of the C3E7 mixture was  
253 subjected to two series of loading: first to six low-strain (50-60  $\mu$ strain) tests and next to ten  
254 medium-strain (90-100  $\mu$ strains) tests. Each full test in the SPT equipment consists of 180 load  
255 cycles of variable loading time (from 0.1 Hz up to 25 Hz). Taking the performed sixteen tests,  
256 specimen was subjected to a total of 2880 load cycles. Behaviour of the specimen was similar  
257 across all load frequencies, : after a steady increase in the modulus, the constant value was  
258 obtained – higher for low strains and slightly lower for medium strains. The difference between  
259 the highest and the lowest modulus plateau value was within 0.5%. Behaviour of phase angle  
260 was different. In the first cycles with low strains, phase angles slightly decreased before  
261 reaching a constant value. When higher strains were applied in the following cycles, the  
262 measured phase angles were already at their constant value, which was greater than that  
263 measured for low strains. The difference between the highest and the lowest plateau value

264 ranged from 0.3% to 1.4%. The values of moduli and phase angles obtained for selected  
 265 frequencies are presented in Figs 6 and 7. No influence of mixture fatigue on the rheological  
 266 parameters was observed during the consecutive tests. The vertical dashed line in the figures  
 267 represents the change between the different levels of controlled strain applied to the specimen  
 268 (6 tests at low strain and 10 tests at medium strain).

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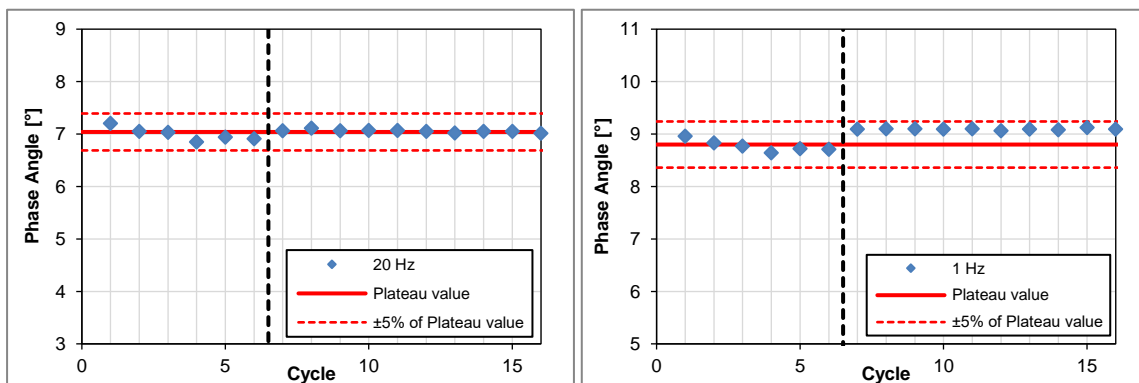
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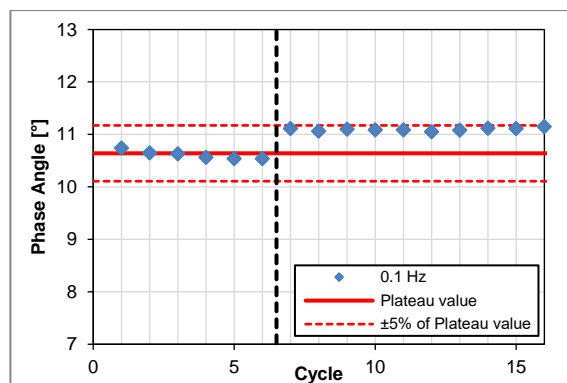
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**Fig. 6.** Stage 1A test results – stiffness modulus,  $T = 10^{\circ}\text{C}$ , test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen

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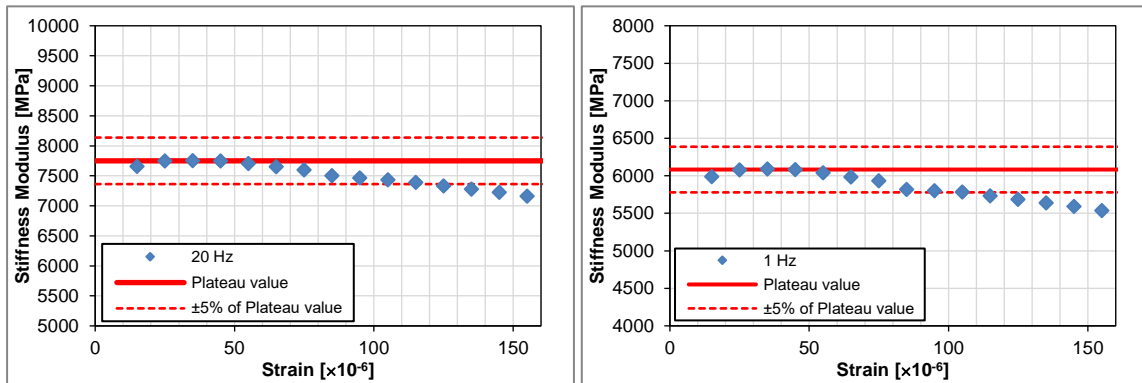
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275 **Fig. 7.** Stage 1A test results – phase angles,  $T = 10^{\circ}\text{C}$ , test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7  
276 specimen

277 The aim of the next step was to determine whether the different (gradually increasing)  
278 strains applied to the specimen influence the values of rheological properties of cold recycled  
279 mixtures similarly to the case of asphalt mixtures (presented in Fig. 1). For this purpose, 15  
280 consecutive tests were performed on a single specimen. The applied strain ranged from 10-20  
281  $\mu\text{strain}$  to 150-160  $\mu\text{strain}$ . The tests were divided into two days, with one long rest period.  
282 Strains from 10 up to 80  $\mu\text{strain}$  were tested on the first day, while strains greater than 80  $\mu\text{strain}$   
283 were tested on the second day. While this fact did not significantly affect the obtained values  
284 of stiffness modulus (only a small deviation from the line), it resulted in a considerable  
285 difference in the case of the phase angles (visible in Fig. 9). Nevertheless, for the purpose of  
286 this stage of the research, the obtained results of rheological parameters were sufficient. Cold  
287 recycled mixtures displayed behaviour similar to asphalt mixtures – the obtained values of  
288 stiffness modulus began to decrease after reaching a specific strain limit; in the case of phase  
289 angle the obtained values began to increase. Example results are presented in Figs 8 and 9. One  
290 difference was observed in comparison to asphalt mixtures – the “length” of the plateau was  
291 different for phase angles and for stiffness values. It is also visible that linear viscoelasticity  
292 limits (5% of difference) are different for stiffness moduli and phase angles, even despite the  
293 fact that some phase angle values have shifted. The visible change in phase angles could have  
294 also resulted from a change in the structure of the recycled mixture and beginning of non-linear  
295 creep or strain hardening due to creep. During this stage of the research, it was confirmed that

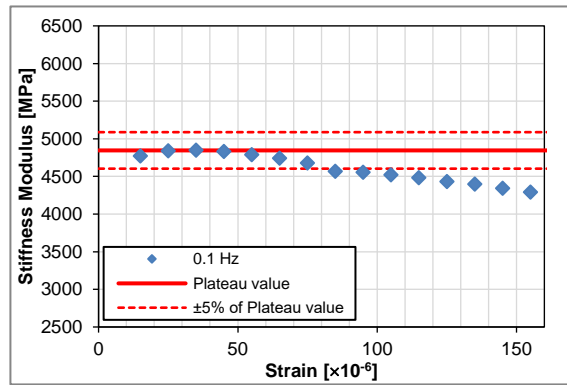


296 it is possible to apply the methodology used in the case of asphalt mixtures to cold recycled  
 297 mixtures.

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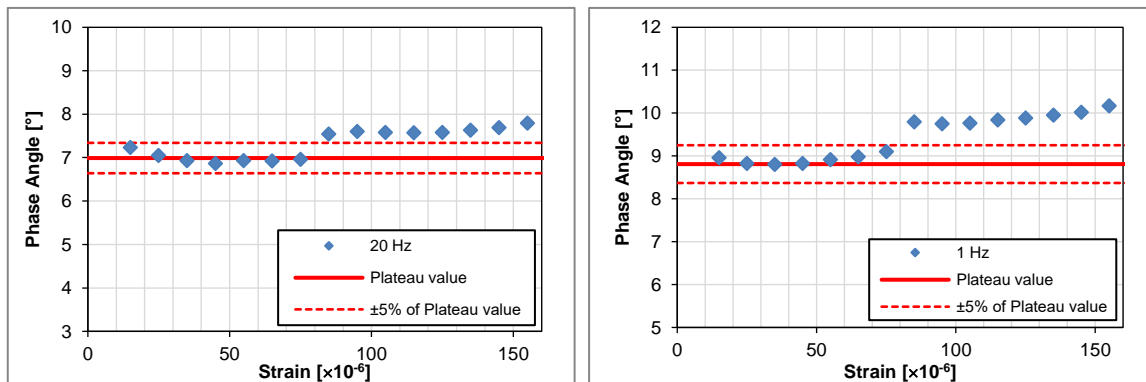
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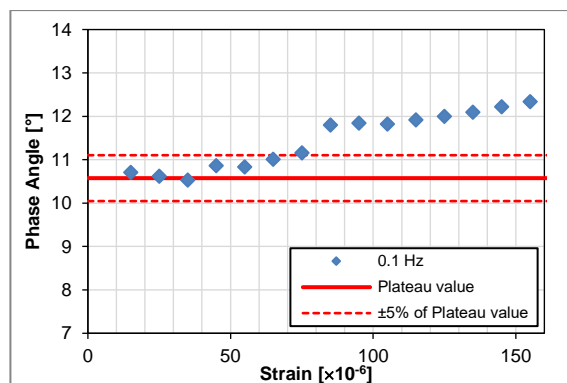


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**Fig. 8.** Stage 1B test results – stiffness modulus,  $T = 10^{\circ}\text{C}$ , test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen

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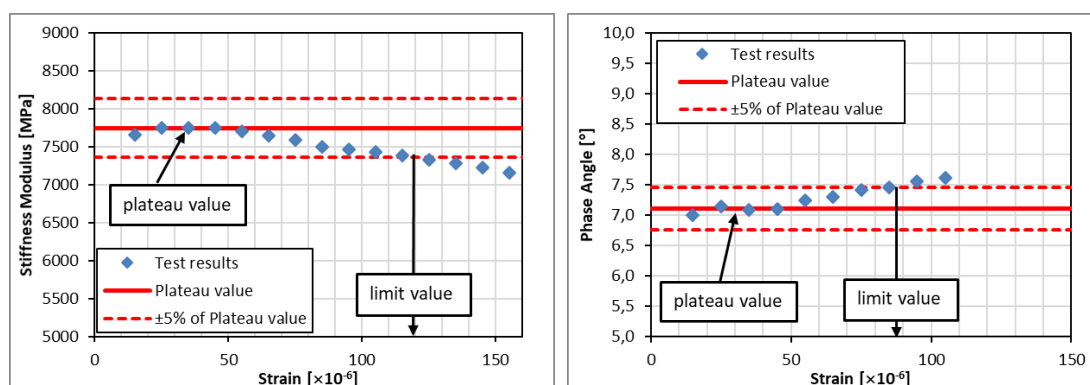




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**Fig. 9.** Stage 1B test results – phase angles,  $T = 10^{\circ}\text{C}$ , test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen

306 The final methodology assumed in further research for determination of linear  
307 viscoelasticity limits is presented in Fig. 10. It was determined that in the following stage the  
308 specimen should be tested in the range of strains from 10-20  $\mu\text{strain}$  up to 100-110  $\mu\text{strain}$ . The  
309 plateau value for each specimen was assumed based on the results obtained for the range of  
310 controlled strain between 20 and 40  $\mu\text{strain}$ . If the values of the tested property were within the  
311 range of  $\pm 5\%$  of the plateau value for all test conditions, the limit value was determined to be  
312  $>110 \mu\text{strain}$ . Specimens that displayed such values will be tested again in further studies.

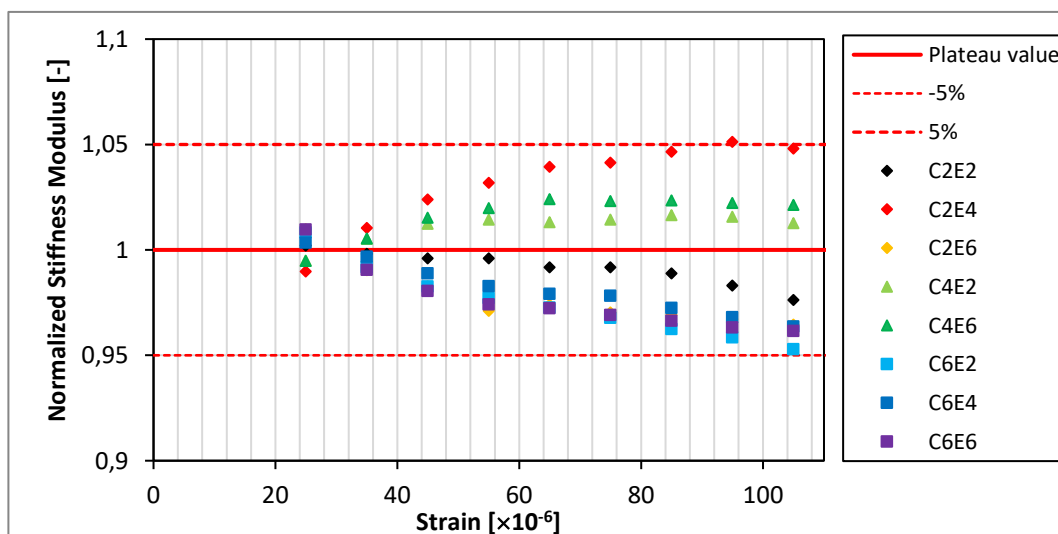


313  
314 **Fig. 10.** Determination of linear viscoelasticity limits: on the basis of dynamic modulus (left); on the basis  
315 of phase angle (right).

316 3.3. Determination of linear viscoelasticity limits for different combinations of binding  
317 agents and temperatures – Stage 2

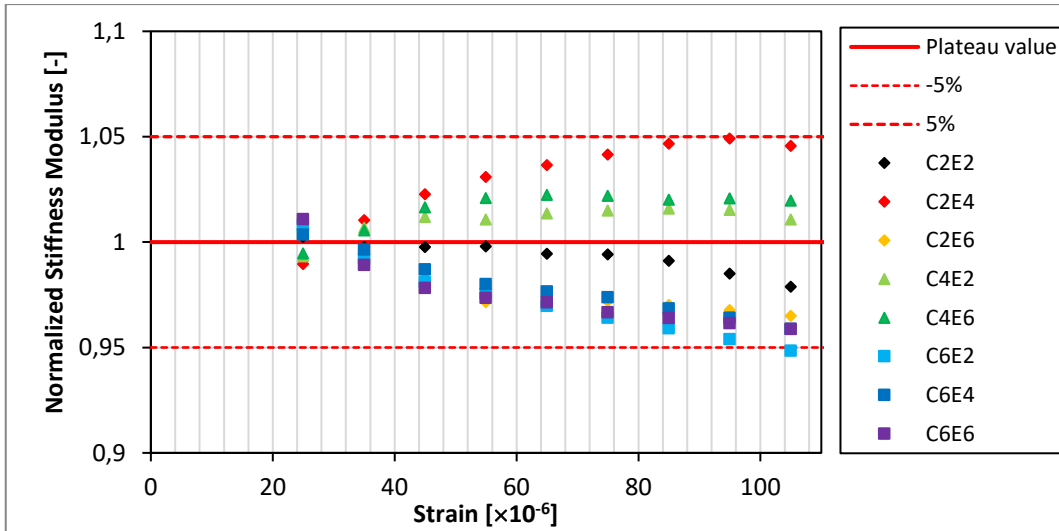
318 Stiffness moduli and phase angles determined during the main (second) stage of the  
319 study are presented in Figs 11, 12 and 13 (normalised stiffness moduli) and Figs 14, 15 and 16

320 (normalised phase angles). Results for three frequencies (20 Hz, 10 Hz, 1 Hz) were presented  
 321 for all the tested mixtures. Frequencies were selected to present mixture behaviour across a  
 322 wide range of loading conditions. However, certain mixtures did not display clear linear  
 323 viscoelasticity limits for the selected loading conditions (range of applied strains). Some of  
 324 them presented constant plateau value, without any signs of decrease, up to strain value of 100  
 325  $\mu$ strain. It is especially apparent in the case of mixtures with higher content of bituminous  
 326 emulsion and lower content of cement. A possible cause of such behaviour is strain hardening  
 327 due to creep of specimens with high quantity of bitumen (in emulsion and/or RAP). This aspect  
 328 calls for further investigation with more bitumen-dominated specimens. Different behaviour is  
 329 visible in mixtures which contained 6% of cement. In every mixture from this group, a decrease  
 330 in stiffness modulus with an increase in strain is visible from the beginning. This behaviour  
 331 changes slightly when the quantity of bituminous emulsion increases. Two stages of the  
 332 phenomenon are visible – after the initial relatively rapid decrease in value (up to around 50  
 333  $\mu$ strain), the rate of decrease is reduced. In contrast, only one type of behaviour is visible in the  
 334 case of phase angles – after a short plateau (up to 50  $\mu$ strains), the value of phase angle starts  
 335 to increase at a constant rate.



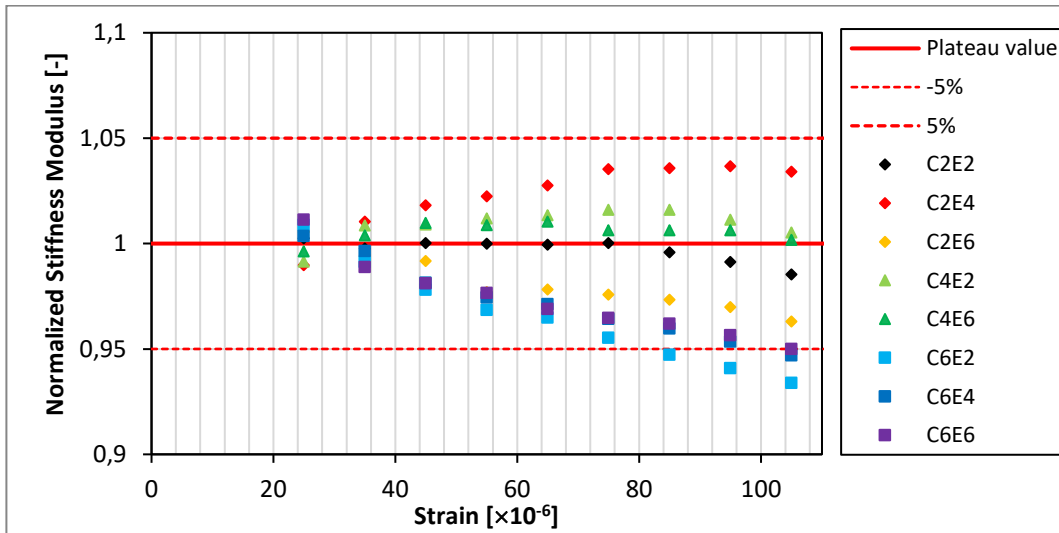
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 337 **Fig. 11.** Stage 2 test results – stiffness modulus,  $f = 20$  Hz,  $T = 20^\circ\text{C}$   
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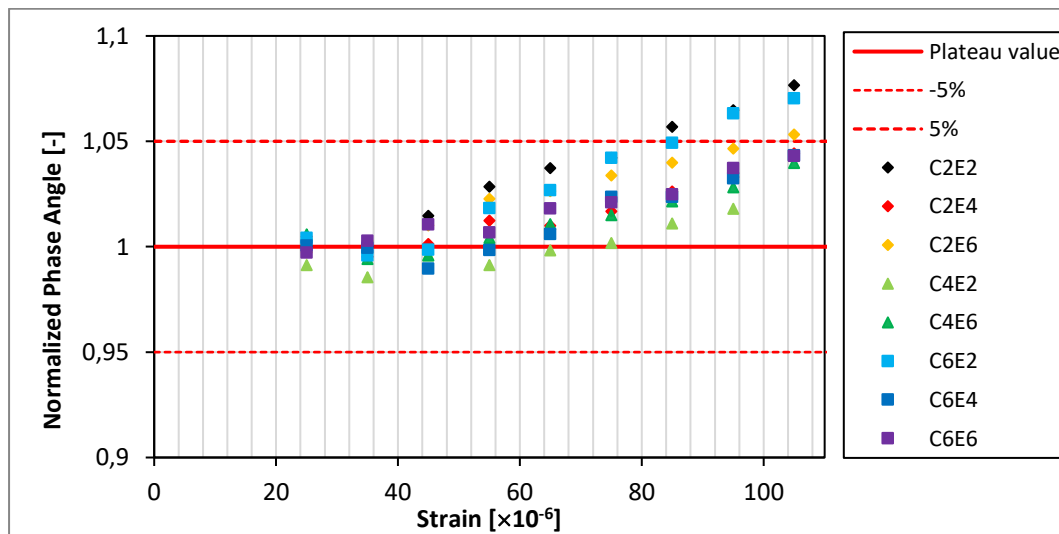
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Fig. 12. Stage 2 test results – stiffness modulus,  $f = 10$  Hz,  $T = 20^\circ\text{C}$



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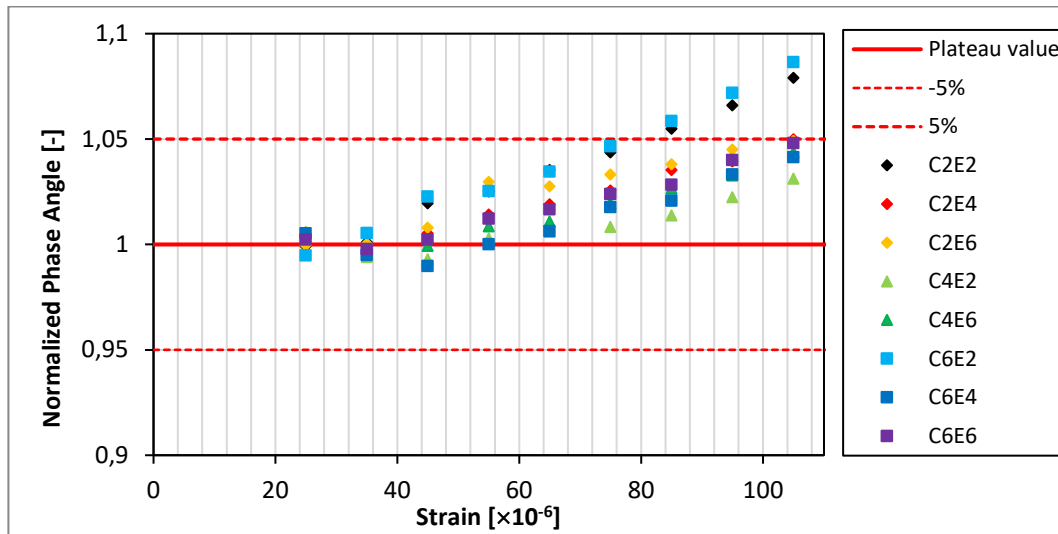
Fig. 13. Stage 2 test results – stiffness modulus,  $f = 1$  Hz,  $T = 20^\circ\text{C}$



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Fig. 14. Stage 2 test results – phase angle,  $f = 20$  Hz,  $T = 20^\circ\text{C}$



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Fig. 15. Stage 2 test results – phase angle,  $f = 10$  Hz,  $T = 20^\circ\text{C}$

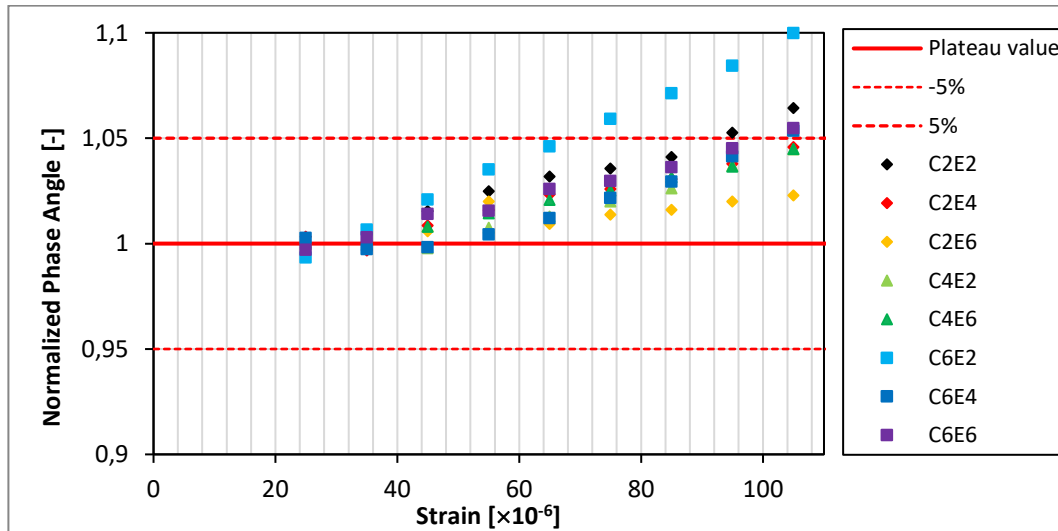


Fig. 16. Stage 2 test results – phase angle,  $f = 1$  Hz,  $T = 20^\circ\text{C}$

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357 Linear viscoelasticity limits were determined for each frequency and mixture  
358 composition on the basis of stiffness moduli and phase angles, using methodology presented in  
359 section 2.2.2. Limits were determined for 8 different cold recycled mixtures, which differed  
360 only in the quantities of binding agents used. The remaining properties and the age of the  
361 specimens were the same. In contrast to Stage 1 of the research, linear viscoelasticity limits  
362 were reached only for several specimens, as visible in Figs 11 to 16. The influence of strain  
363 hardening due to creep of the mixture is visible in some of the tested specimens. It is observable

364 as a slowing increase in stiffness modulus with consecutive strain increases (cf. Figs 11-13,  
 365 specimens C4E2 and C4E6). Different behaviour of specimens tested in Stage 2 in comparison  
 366 to Stage 1B proves that the test temperature also has impact on the values of linear  
 367 viscoelasticity limits. The determined linear viscoelasticity limits are presented in Table 2. The  
 368 lowest values of the determined linear viscoelasticity limits were highlighted in grey. This value  
 369 was assumed as the recommended maximum strain in the SPT test of cold recycled mixtures,  
 370 as it was the maximum value for which all the tested specimens (regardless of their composition  
 371 and test temperature) remained in the LVE limit assumed as deviation of +5% of the initial  
 372 stiffness/phase angle value.

373 **Table 2.** Stage 2 – linear viscoelasticity limits (stiffness modulus, phase angle), C3E7 ( $T = 10^{\circ}\text{C}$ ), other  
 374 specimens ( $T = 20^{\circ}\text{C}$ )

Mixture designation	Linear viscoelasticity limits ( $\mu\text{strain}$ )								
	Test frequency [Hz]								
	25	20	10	5	2	1	0.5	0.2	0.1
Stage 1B									
C3E7 ( $E^*$ )	>110	>110	>110	>110	105	105	95	75	75
C3E7 ( $\varphi$ )	75	75	75	75	75	75	75	75	65
Stage 2 (stiffness modulus $E^*$ )									
C2E2	>110	>110	>110	>110	>110	>110	>110	>110	>110
C2E4	>110	>110	>110	>110	>110	>110	>110	>110	>110
C2E6	>110	>110	>110	>110	>110	>110	>110	>110	>110
C4E2	>110	>110	>110	>110	>110	>110	>110	>110	>110
C4E6	>110	>110	>110	>110	>110	>110	>110	>110	>110
C6E2	>110	>110	95	85	85	75	75	65	65
C6E4	>110	>110	>110	>110	>110	95	85	85	85
C6E6	>110	>110	>110	>110	>110	95	95	85	85
Stage 2 (phase angle $\varphi$ )									
C2E2	85	75	75	75	85	85	95	>110	>110
C2E4	95	>110	95	95	95	>110	>110	>110	>110
C2E6	95	95	95	>110	>110	>110	>110	>110	>110
C4E2	>110	>110	>110	>110	>110	>110	>110	>110	>110
C4E6	>110	>110	>110	>110	>110	>110	>110	>110	>110
C6E2	95	85	75	75	65	65	65	65	65
C6E4	>110	>110	>110	>110	>110	95	95	95	>110
C6E6	>110	>110	>110	95	95	95	95	95	95

375 For mixtures with small and medium quantity of cement, linear viscoelasticity limits  
 376 determined based on the stiffness moduli were not reached, regardless of the used quantity of  
 377 bituminous emulsion. Across all the tested strains, those mixtures remained within their linear  
 378 viscoelasticity limits. Different behaviour was visible in the case of mixtures with higher

379 quantity of cement (which displayed the highest values of stiffness modulus). The obtained  
380 linear viscoelasticity limits decreased with a decrease in value of the applied load frequency  
381 (and with an increase in the time of loading). Nonlinear behaviour was observed earlier for the  
382 mixture with lower quantity of emulsion. It was also the mixture with the lowest  
383 bitumen/cement ratio. It could not be confirmed whether similar behaviour might be observable  
384 for other compositions – it will be the subject of further studies.

385 In the case of the limits determined based on phase angles, the behaviour is more  
386 complex. Factor which could have strong influence in this case are relatively low values of the  
387 analysed property (in comparison to the stiffness moduli). In this case, linear viscoelasticity  
388 limits were not reached only for mixtures with 4% of cement. Limits of mixtures with 6%  
389 cement content displayed behaviour similar to that of limits determined based on stiffness  
390 moduli – the limit decreased with a decrease in test load frequency. Similarly, lower values of  
391 limits were obtained for the mixture with the lowest quantity of bituminous emulsion.  
392 Interestingly, opposite behaviour was observed in the case of mixtures with 2% cement content  
393 – their linear viscoelasticity limits increase with a decrease in test load frequency. However,  
394 similarly to the mixtures with 6% of cement, the lowest limits were obtained for the mixture  
395 with the lowest quantity of bituminous emulsion.

#### 396 **4. Summary and conclusions**

397 Based on the performed tests and analyses, the following conclusions can be drawn:

- 398 1. Tests performed in Simple Performance Tester in cyclic compression test mode  
399 enable determination of viscoelastic behaviour of the tested specimens and  
400 limits of linear viscoelastic behaviour of cold recycled mixtures. Elastic and  
401 viscoelastic properties comply with general theory. The obtained results,

402 especially the viscoelasticity limits, could be different under different test load  
403 mode (for example, tension-compression or bending).

404 2. Cold recycled mixtures present viscoelastic behaviour similar to other materials  
405 with bituminous components. This fact is visible even in the case of specimens  
406 that were stored for more than 1 year in laboratory conditions and presented  
407 behaviour similar to cement-bound materials in terms of the increase in modulus  
408 with time.

409 3. Methodology used for determination of linear viscoelasticity limits for asphalt  
410 materials can be applied successfully also in the case of cold recycled mixtures.

411 4. Cold recycled mixtures display different linear viscoelastic behaviour than  
412 asphalt mixtures based purely on bituminous binders – constant value plateau is  
413 shorter than in the case of pure asphalt mixtures.

414 5. For cold recycled mixtures, limits determined based on stiffness modulus and  
415 based on phase angle have different values for the same specimen.

416 6. Linear viscoelasticity limits depend on mixture composition (especially  
417 quantities of binding agents) and the test temperature:

418 ○ Linear viscoelasticity limits (determined both on the basis of phase angle  
419 and stiffness modulus) for mixtures containing high quantity of cement  
420 decrease with a decrease in the test load frequency

421 ○ Linear viscoelasticity limits (determined based on phase angle) for mixtures  
422 containing low quantity of cement increase with a decrease in the test load  
423 frequency

424 7. Linear viscoelasticity limits increase with a decrease in test temperature.

425 8. The recommended strain value used in the SPT equipment should be lower than  
426 65  $\mu$ strains.



427 Limitations of the conducted study, in conjunction with the planned future works, are  
428 discussed below:

- 429 • Research was performed on limited combinations of specimens and test  
430 conditions – only two similar temperatures, two mixture combinations, narrow  
431 range of the applied strains and only one age of test specimens. Moreover, only  
432 laboratory-prepared and conditioned specimens were tested.
- 433 • Conclusions presented in the paper are valid only for the strain limits considered  
434 in the study (up to 110  $\mu$ strain). Increasing the test strain limit could result in  
435 different behaviour of the material.
- 436 • Further research should be focused on the influence of test temperature on linear  
437 viscoelasticity limit values, especially for temperatures greater than 30°C. Next  
438 stages should encompass analyses of the influence of mixture composition and  
439 base materials used, the age of the specimen and the applied curing and  
440 compacting procedures.

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450 **Authorship contribution statement**

451 Mariusz Jaczewski (M.J.) conceived and designed the experiments, supervised the  
452 research presented in the paper, developed the research methodology, performed the  
453 experiments (Stage 1), supervised the experiments (Stage 2), analysed the data, wrote the paper;  
454 Cezary Szydłowski (C.S.) developed the research methodology, performed the experiments  
455 (Stage 0), analysed the data, wrote the paper; Bohdan Dołżycki (B.D.) analysed the data, wrote  
456 the paper.

457 **Declaration of Competing Interest**

458 The authors declare that they have no known competing financial interests or personal  
459 relationships that could have appeared to influence the work reported in this paper.

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