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

Mariusz Jaczewski, Cezary Szydlowski, Bohdan Dolzycki

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

Gdansk University of Technology, Faculty of Civil and Environmental Engineering and EkoTech Center
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 methodology developed for determination of linear viscoelasticity limits for cold recycled mixtures with cement and bituminous emulsion using Simple Performance Tester (SPT). Methodology was verified on reference materials (PCV and steel dummy specimens, cement concrete and asphalt concrete) to comply with elasticity and viscoelasticity theory. The developed methodology enabled determination of linear viscoelasticity limits for the tested cold recycled mixtures for base course. Tests were conducted for controlled strain ranging from 10 up to 110 μstrain. Linear viscoelasticity limits were determined based on stiffness moduli and phase angles. The combination of binding agents and test temperature had the greatest influence on the obtained values.

Keywords: linear viscoelasticity; cold recycled mixtures; cement; bituminous emulsion

1. Introduction

1.1. Background

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

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

Researchers usually assume that cold recycled mixtures fit the model of thermo-rheologically simple linear viscoelastic material [14, 15], due to the strong influence of bitumen present in the bituminous emulsion and RAP material. Previous international practice generally confirms this assumption [15]. The modulus of the mixture changes with test temperature and time of loading. It is possible to develop stiffness modulus and phase angle master curves for the whole range of loading times and test temperatures [14]. Nevertheless, due to the influence of cement, the differences between the highest and lowest values of both properties are not as high as in the case of typical asphalt concretes [14]. This leads to question whether the criteria typically assumed for linear viscoelasticity limits of asphalt concretes can be directly applied to cold recycled mixtures containing Portland cement. Generally, researchers either use the same criteria as for asphalt concretes or lower the values of strain/deformation/stress applied during tests [14, 15]. However, the question of actual linear viscoelasticity limits of cold recycled mixtures and the factors that affect them (such as: age of the specimen, composition of the mixture, test temperature, frequency/time of loading, preparation and compaction of the specimen) still remains open. Establishing correct viscoelasticity limits is required for preparation of unified standard specifications for material testing and, subsequently, for correct modelling of cold recycled mixtures in FEM or other methods. It is also required for proper comparison of the results obtained by different researchers.

1.2. Linear viscoelasticity limits in bituminous materials

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

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

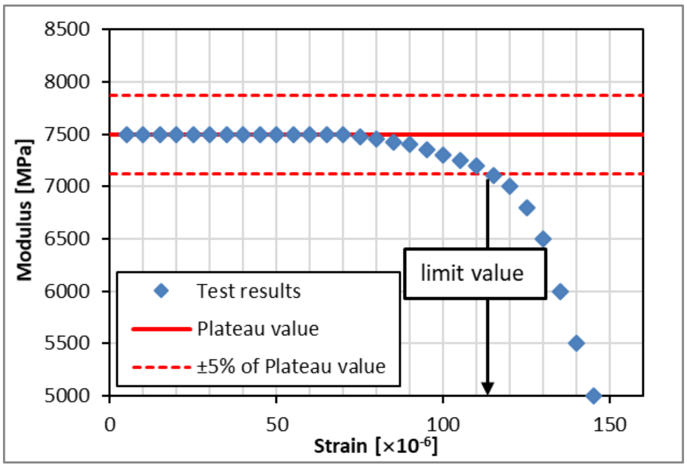


Fig. 1. Determination of linear viscoelasticity limits for asphalt mixture in strain-controlled mode, after Airey et al. [18]

1.3. Objectives

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

2. Materials and methods

2.1. Materials

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

The main part of the laboratory experiments was conducted for two types of cold recycled mixtures. Stage 1 (A and B) was conducted on mixture designed for binder courses and Stage 2 was conducted on mixtures designed for base courses. All mixtures were designed according to the Polish recommendations and local experience [1, 21], with appropriate adjustment for the first mixture (lower maximum gradation). Portland cement CEM I 32.5R and slow-setting cationic asphaltic emulsion C 60 B10 ZM/R (with neat 70/100 residual bitumen) were used as binding agents. Mixtures were prepared in a laboratory mixer according to the EN 12697-35 standard. Specimens were compacted in a gyratory compactor according to the EN 12697-31 standard. The limiting compaction ratio was set as 99% of the maximum dry density determined in the modified Proctor test. The specimens were compacted to the height of 170 mm and the diameter of 150 mm and later cut to the target specimen height of 150 mm and diameter of 100 mm. The base course mixture specimens were previously used in long-term tests [14, 22]. In each case the age of the specimen was over a year, so the impact of the processes associated with curing of the materials was minimised. Basic information regarding composition of cold recycled mixtures used in the study is presented in Table 1.

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 a) (% by mass)	23.3	18
Virgin aggregate 0/2 (% by mass)	9.3	10, 8, 6 b) (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)

2.2. Methods

2.2.1. Cyclic compression test

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

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

- Preliminary Stage – testing on known materials (cement concrete, steel and PCV – elastic materials; asphalt concrete AC 22P – viscoelastic material) to verify whether the Simple Performance Tester can be used to determine the viscoelasticity and its limits and whether it can correctly differentiate between elastic and viscoelastic behaviour of materials. 15 consecutive test series were performed with varied controlled strain: ranging from the level of 10-20 μstrain up to 150-160 µstrain, with the constant increment of 10 µstrain in consecutive tests.

- Stage 1A – determination of the impact of consecutive tests on specimen (the impact of specimen fatigue on obtained results). 16 consecutive tests – first 6 tests were conducted for controlled strain value in the range of 50-60 µstrain, the following 10 tests were conducted for controlled strain value in the range of 90-100 µstrain.
- Stage 1B – adopting the methodology for determination of linear viscoelasticity limits and verification vs. other elastic and viscoelastic materials. 15 consecutive tests were performed with varied controlled strain values: ranging from the level of 10-20 µstrain, up to 150-160 µstrain, with the constant increment of 10 µstrain in consecutive tests.
- Stage 2 – determination of the influence of mixture composition on linear viscoelasticity limits. 10 consecutive tests were performed with varied controlled strain value: ranging from the level of 10-20 µstrain up to 100-110 µstrain, with the constant increment of 10 µstrain in consecutive tests.

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

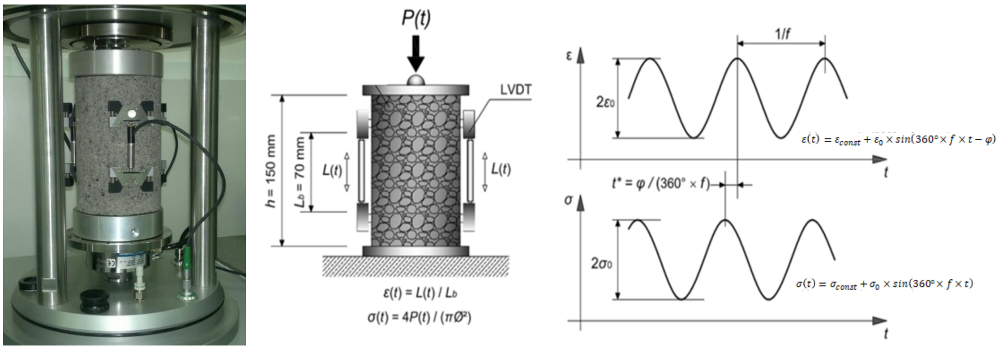


Fig. 2. Simple Performance Tester – test setup: Specimen ready for testing (left) scheme of the test in Simple Performance Tester (centre) and plot that visualises the shift between stress and strain (right).

3. Results and discussion

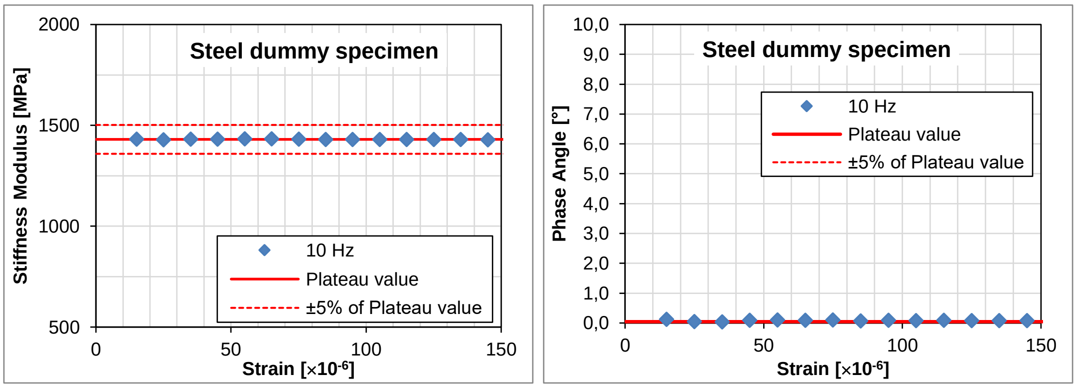
All the obtained results were determined using cyclic compression test mode, as described in the preceding section. Using a different test load mode, such as tension-compression, bending or shear, can give different results. Cyclic compression test mode was chosen due to its widespread usage and the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

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

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

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

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



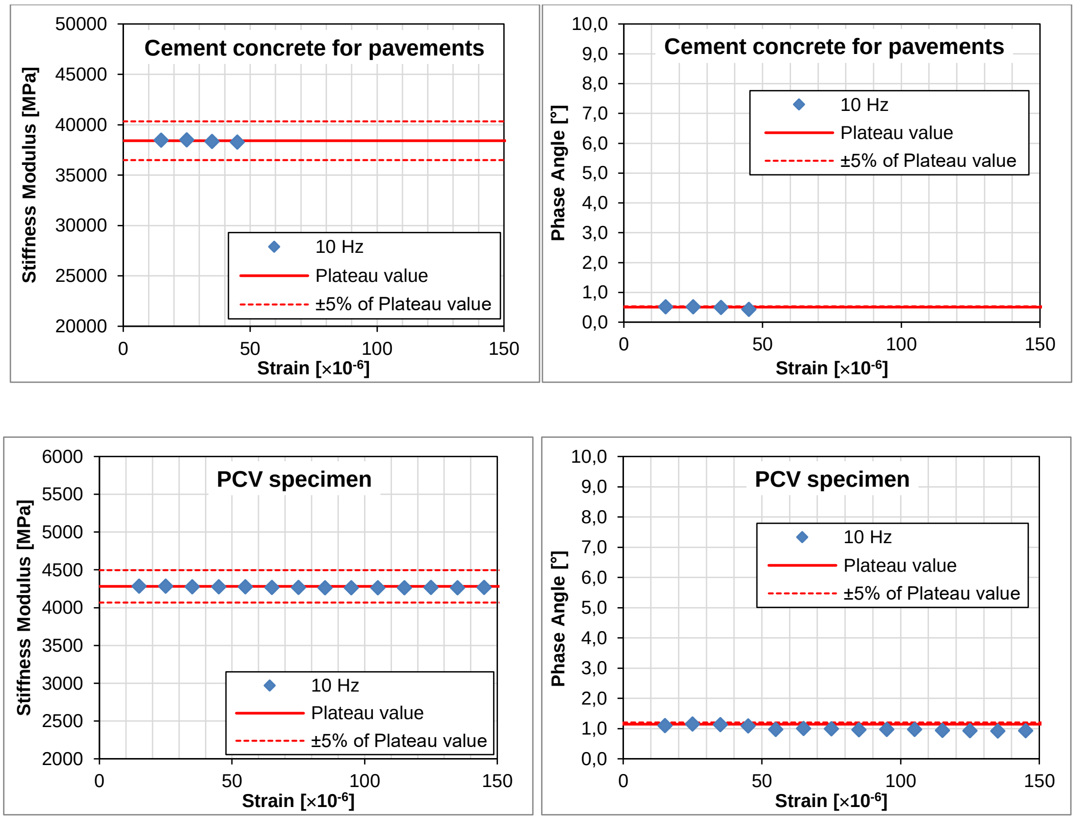


Fig. 4. Verification of linear behaviour of elastic materials: steel dummy specimen, cement concrete and PCV, *T* = 20°C, *f* = 10 Hz.

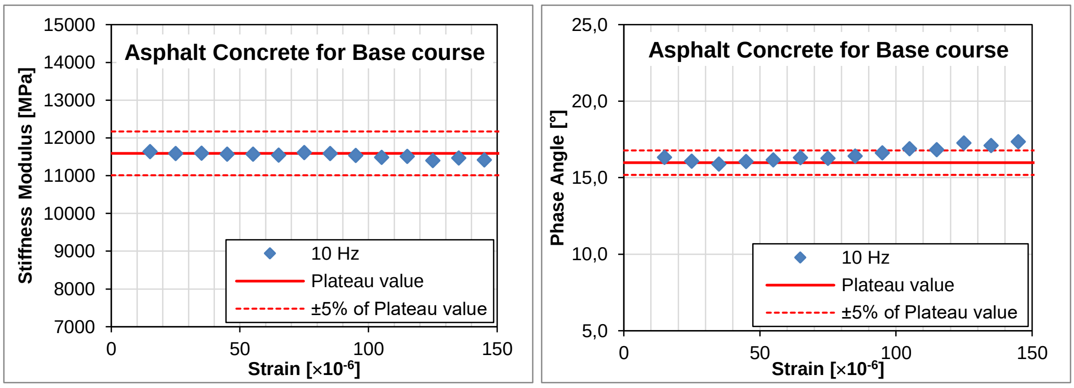


Fig. 5. Verification of linear behaviour of viscoelastic materials: asphalt concrete for base course, *T* = 20°C, *f* = 10 Hz.

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°). 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°, which is in agreement with previous studies. In the case of the PCV specimen, the phase angle of ~1° suggests that the material is not ideally elastic, but still fits the general theory of immediate response to the subjected load. In the case of viscoelastic material (asphalt concrete), the obtained verification test results are also in agreement with the general theory. Stiffness modulus maintains constant value for small strains, while further, for higher strains, the modulus starts to decrease, as visible for strains of 120 μstrain and greater. In the case of phase angle, a steady increase in its value is visible almost across the entire range of tested strains (for 30 μstrain and greater). Therefore, the conducted tests confirmed compliance with the theory.

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

Previous research [16, 25, 26, 27, 28] proved that cold recycled mixtures are similar to asphalt mixtures in terms of fatigue behaviour. Therefore, it was important to determine first whether the observed behaviour is fatigue of the tested mixture or rather a change due to nonlinear viscoelastic behaviour. For this purpose, one specimen of the C3E7 mixture was subjected to two series of loading: first to six low-strain (50-60 μstrain) tests and next to ten medium-strain (90-100 μstrains) tests. Each full test in the SPT equipment consists of 180 load cycles of variable loading time (from 0.1 Hz up to 25 Hz). Taking the performed sixteen tests, specimen was subjected to a total of 2880 load cycles. Behaviour of the specimen was similar across all load frequencies, : after a steady increase in the modulus, the constant value was obtained – higher for low strains and slightly lower for medium strains. The difference between the highest and the lowest modulus plateau value was within 0.5%. Behaviour of phase angle was different. In the first cycles with low strains, phase angles slightly decreased before reaching a constant value. When higher strains were applied in the following cycles, the measured phase angles were already at their constant value, which was greater than that measured for low strains. The difference between the highest and the lowest plateau value ranged from 0.3% to 1.4%. The values of moduli and phase angles obtained for selected frequencies are presented in Figs 6 and 7. No influence of mixture fatigue on the rheological parameters was observed during the consecutive tests. The vertical dashed line in the figures represents the change between the different levels of controlled strain applied to the specimen (6 tests at low strain and 10 tests at medium strain).

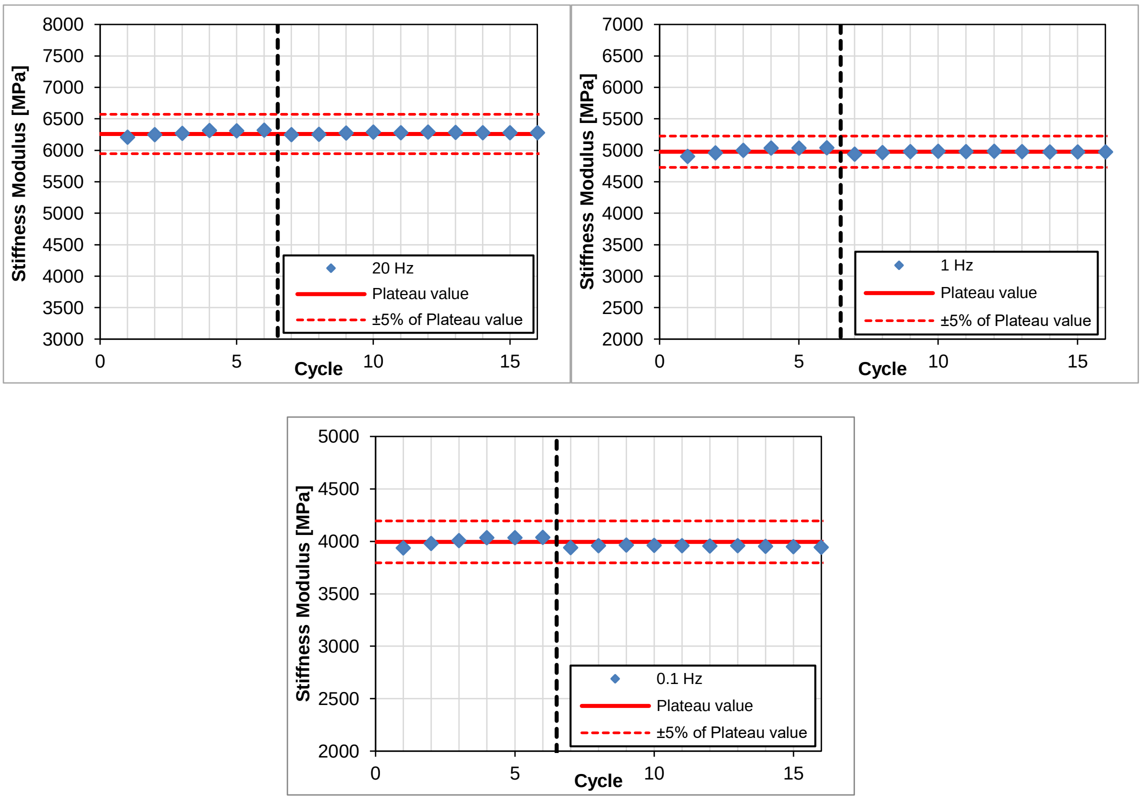
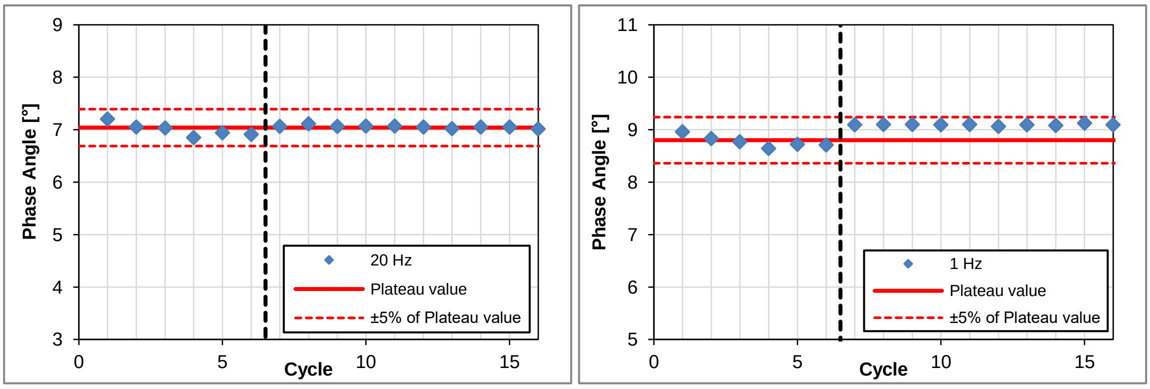


Fig. 6. Stage 1A test results – stiffness modulus, T = 10°C, test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen



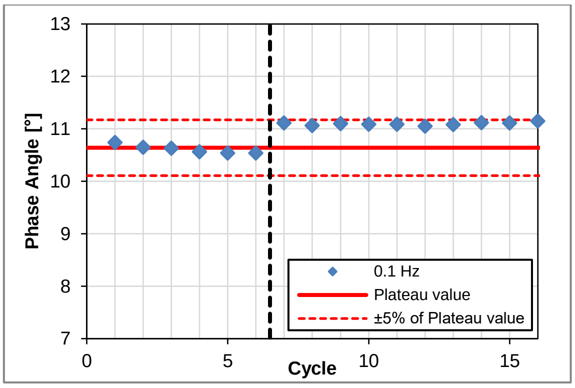


Fig. 7. Stage 1A test results – phase angles, T = 10°C, test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen

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

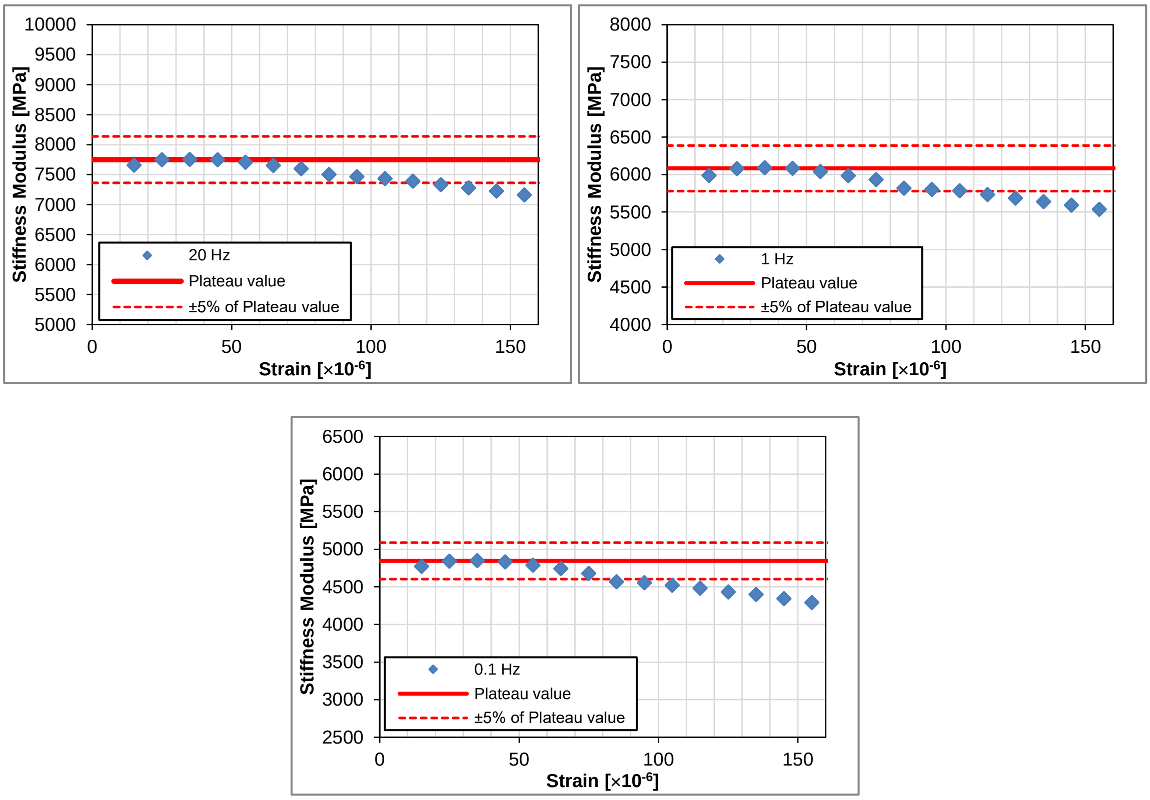
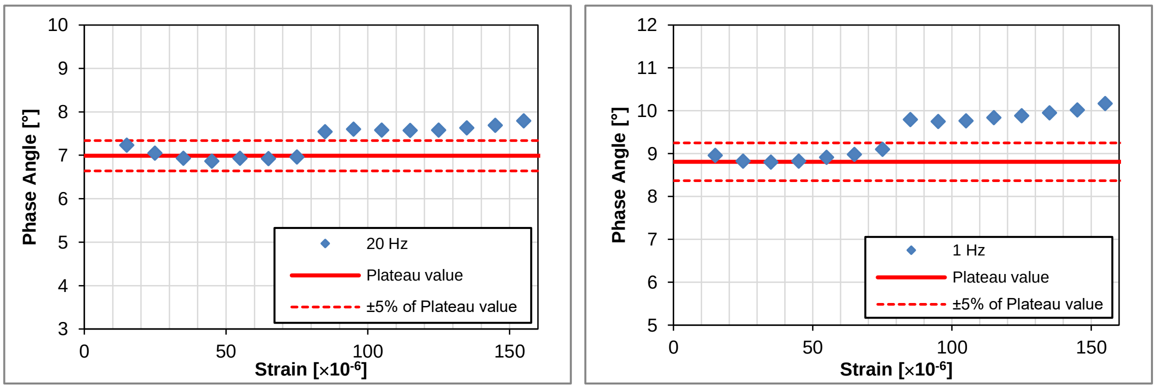


Fig. 8. Stage 1B test results – stiffness modulus, T = 10°C, test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen



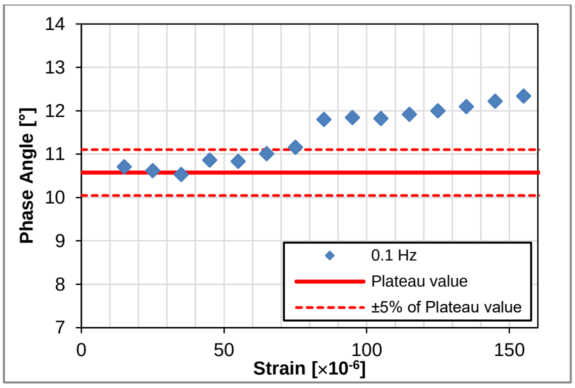


Fig. 9. Stage 1B test results – phase angles, T = 10°C, test frequencies: 20 Hz, 1 Hz, 0.1 Hz, C3E7 specimen

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

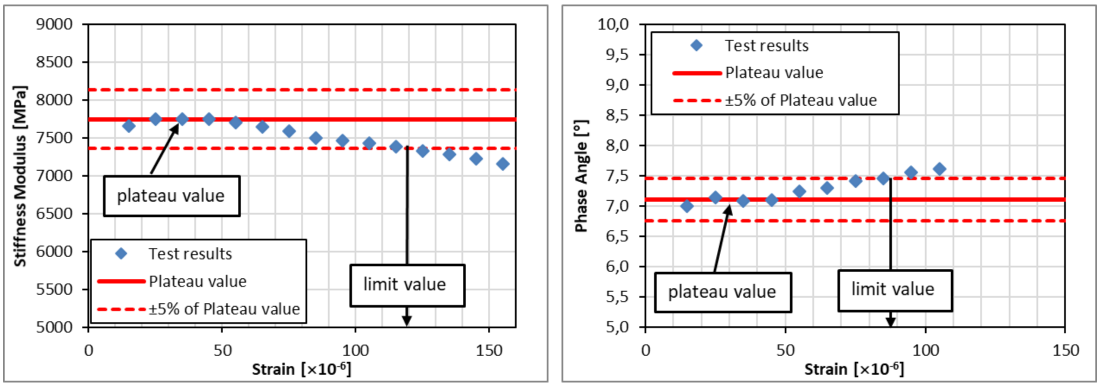


Fig. 10. Determination of linear viscoelasticity limits: on the basis of dynamic modulus (left); on the basis of phase angle (right).

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

Stiffness moduli and phase angles determined during the main (second) stage of the study are presented in Figs 11, 12 and 13 (normalised stiffness moduli) and Figs 14, 15 and 16 (normalised phase angles). Results for three frequencies (20 Hz, 10 Hz, 1 Hz) were presented for all the tested mixtures. Frequencies were selected to present mixture behaviour across a wide range of loading conditions. However, certain mixtures did not display clear linear viscoelasticity limits for the selected loading conditions (range of applied strains). Some of them presented constant plateau value, without any signs of decrease, up to strain value of 100 µstrain. It is especially apparent in the case of mixtures with higher content of bituminous emulsion and lower content of cement. A possible cause of such behaviour is strain hardening due to creep of specimens with high quantity of bitumen (in emulsion and/or RAP). This aspect calls for further investigation with more bitumen-dominated specimens. Different behaviour is visible in mixtures which contained 6% of cement. In every mixture from this group, a decrease in stiffness modulus with an increase in strain is visible from the beginning. This behaviour changes slightly when the quantity of bituminous emulsion increases. Two stages of the phenomenon are visible – after the initial relatively rapid decrease in value (up to around 50 µstrain), the rate of decrease is reduced. In contrast, only one type of behaviour is visible in the case of phase angles – after a short plateau (up to 50 µstrains), the value of phase angle starts to increase at a constant rate.

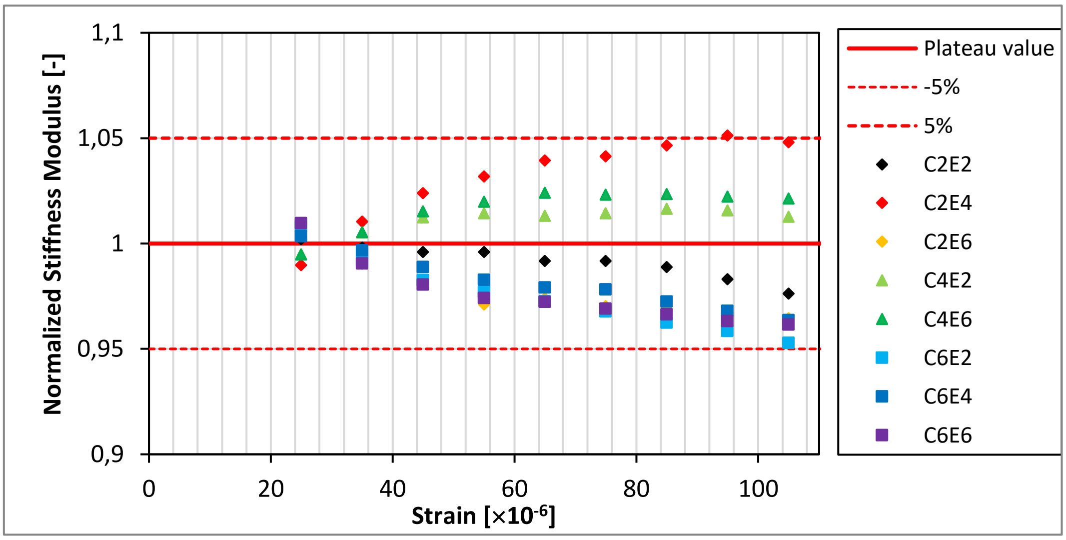


Fig. 11. Stage 2 test results – stiffness modulus, *f* = 20 Hz, *T* = 20°C

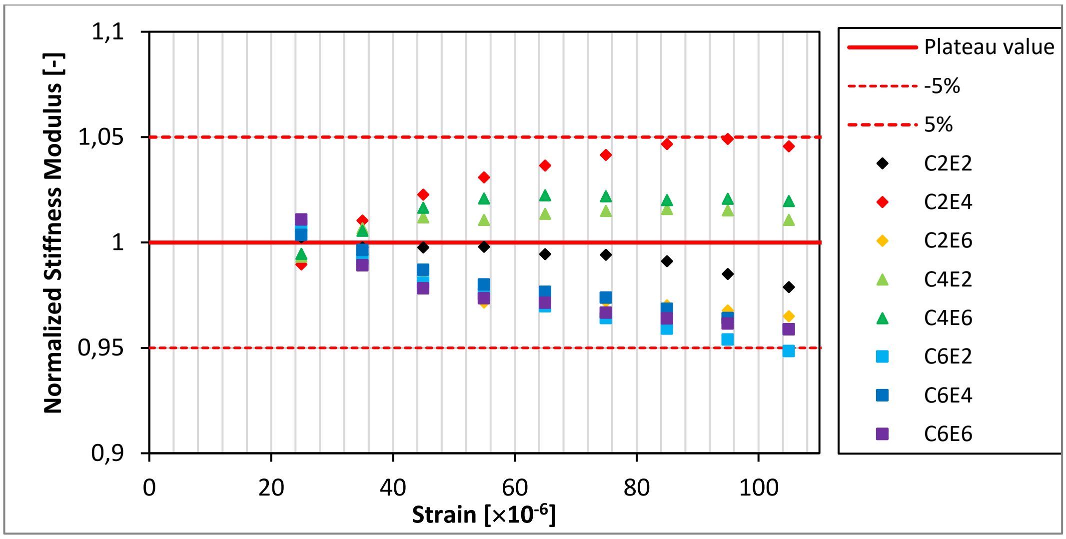


Fig. 12. Stage 2 test results – stiffness modulus, *f* = 10 Hz, *T* = 20°C

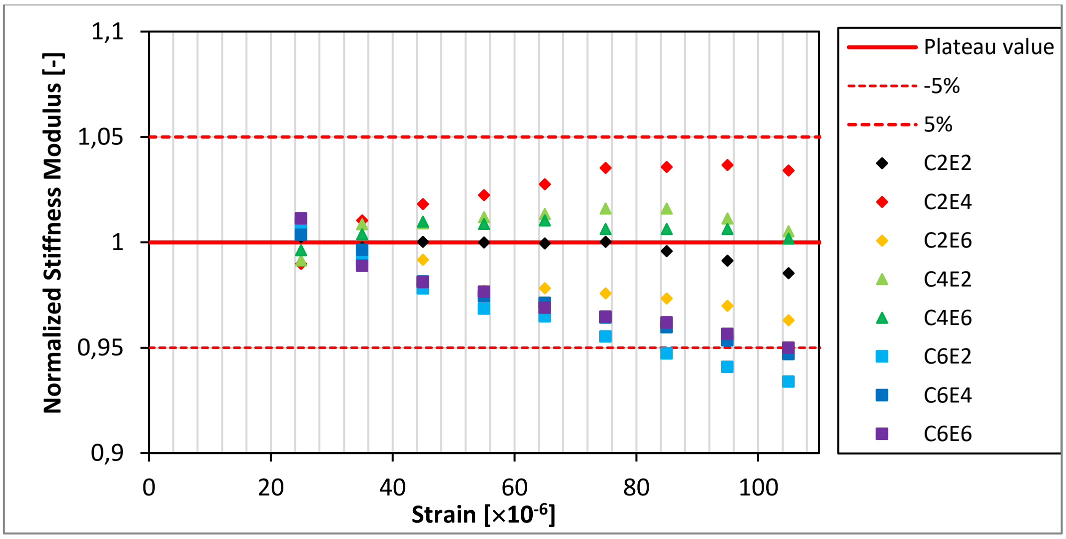


Fig. 13. Stage 2 test results – stiffness modulus, *f* = 1 Hz, *T* = 20°C

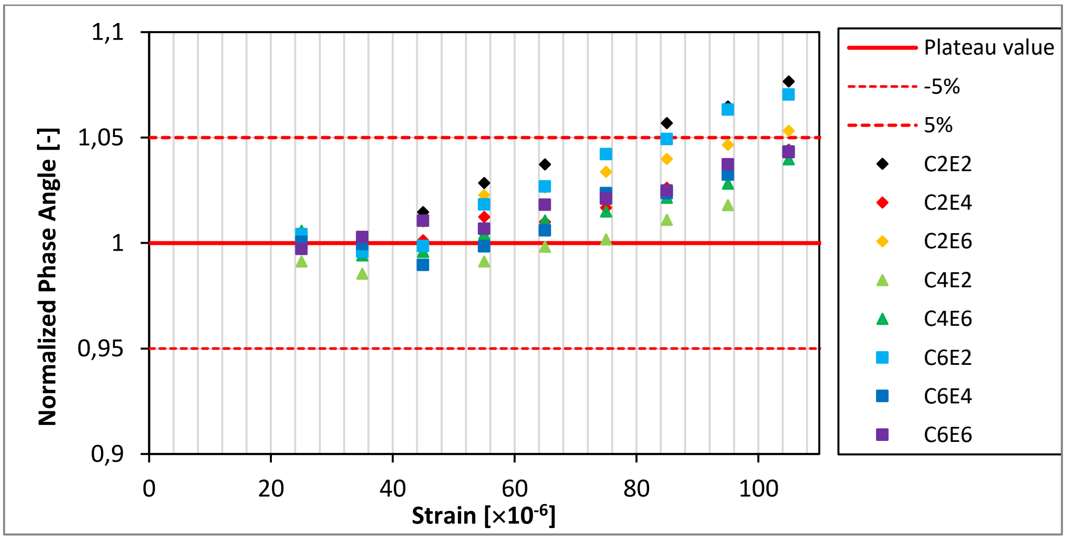


Fig. 14. Stage 2 test results – phase angle, f = 20 Hz, T = 20°C

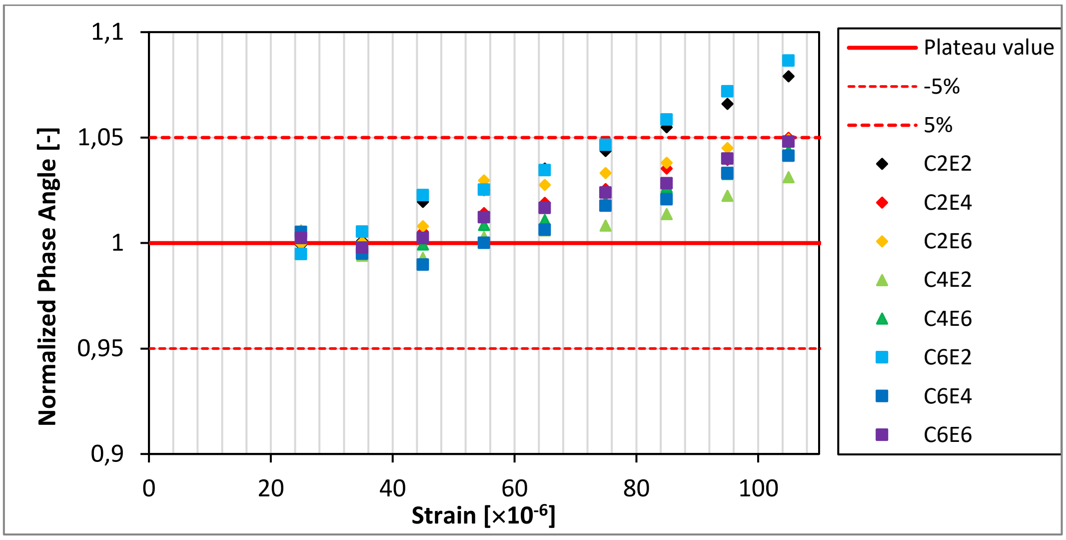


Fig. 15. Stage 2 test results – phase angle, f = 10 Hz, T = 20°C

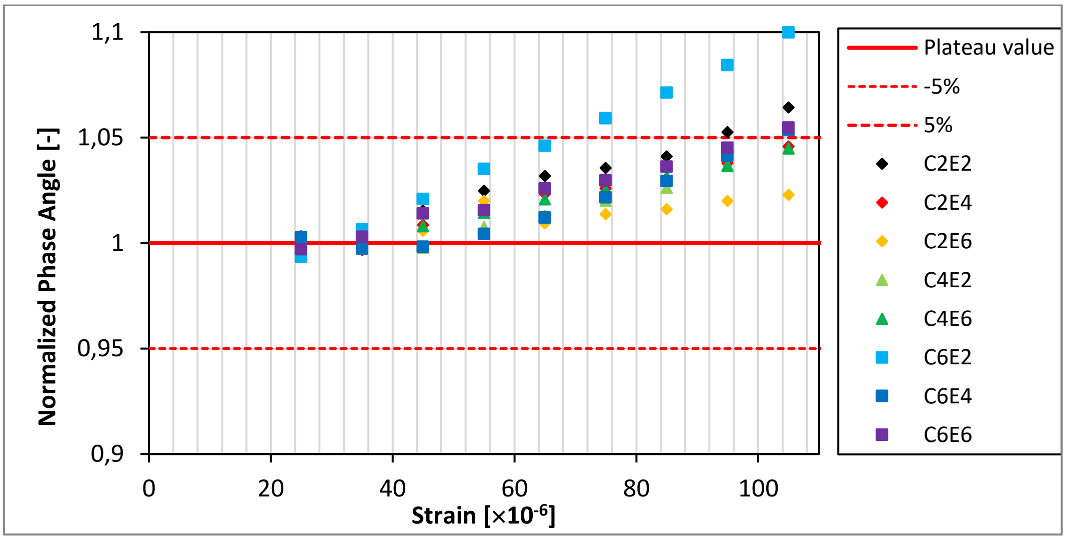


Fig. 16. Stage 2 test results – phase angle, f = 1 Hz, T = 20°C

Linear viscoelasticity limits were determined for each frequency and mixture composition on the basis of stiffness moduli and phase angles, using methodology presented in section 2.2.2. Limits were determined for 8 different cold recycled mixtures, which differed only in the quantities of binding agents used. The remaining properties and the age of the specimens were the same. In contrast to Stage 1 of the research, linear viscoelasticity limits were reached only for several specimens, as visible in Figs 11 to 16. The influence of strain hardening due to creep of the mixture is visible in some of the tested specimens. It is observable as a slowing increase in stiffness modulus with consecutive strain increases (cf. Figs 11-13, specimens C4E2 and C4E6). Different behaviour of specimens tested in Stage 2 in comparison to Stage 1B proves that the test temperature also has impact on the values of linear viscoelasticity limits. The determined linear viscoelasticity limits are presented in Table 2. The lowest values of the determined linear viscoelasticity limits were highlighted in grey. This value was assumed as the recommended maximum strain in the SPT test of cold recycled mixtures, as it was the maximum value for which all the tested specimens (regardless of their composition and test temperature) remained in the LVE limit assumed as deviation of +5% of the initial stiffness/phase angle value.

Table 2. Stage 2 – linear viscoelasticity limits (stiffness modulus, phase angle), C3E7 (*T* = 10°C), other specimens (*T* = 20°C)

Mixture designation	**Linear viscoelasticity limits (μstrain)**								
	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 (φ)	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 φ)									
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

For mixtures with small and medium quantity of cement, linear viscoelasticity limits determined based on the stiffness moduli were not reached, regardless of the used quantity of bituminous emulsion. Across all the tested strains, those mixtures remained within their linear viscoelasticity limits. Different behaviour was visible in the case of mixtures with higher quantity of cement (which displayed the highest values of stiffness modulus). The obtained linear viscoelasticity limits decreased with a decrease in value of the applied load frequency (and with an increase in the time of loading). Nonlinear behaviour was observed earlier for the mixture with lower quantity of emulsion. It was also the mixture with the lowest bitumen/cement ratio. It could not be confirmed whether similar behaviour might be observable for other compositions – it will be the subject of further studies.

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

4. Summary and conclusions

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

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

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

2. Cold recycled mixtures present viscoelastic behaviour similar to other materials with bituminous components. This fact is visible even in the case of specimens that were stored for more than 1 year in laboratory conditions and presented behaviour similar to cement-bound materials in terms of the increase in modulus with time.
3. Methodology used for determination of linear viscoelasticity limits for asphalt materials can be applied successfully also in the case of cold recycled mixtures.
4. Cold recycled mixtures display different linear viscoelastic behaviour than asphalt mixtures based purely on bituminous binders – constant value plateau is shorter than in the case of pure asphalt mixtures.
5. For cold recycled mixtures, limits determined based on stiffness modulus and based on phase angle have different values for the same specimen.
6. Linear viscoelasticity limits depend on mixture composition (especially quantities of binding agents) and the test temperature:
    - Linear viscoelasticity limits (determined both on the basis of phase angle and stiffness modulus) for mixtures containing high quantity of cement decrease with a decrease in the test load frequency
    - Linear viscoelasticity limits (determined based on phase angle) for mixtures containing low quantity of cement increase with a decrease in the test load frequency
7. Linear viscoelasticity limits increase with a decrease in test temperature.
8. The recommended strain value used in the SPT equipment should be lower than 65 μstrains.

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

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

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Authorship contribution statement

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

Declaration of Competing Interest

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

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