



Strain-dependent behaviour of cold recycled material mixtures in cyclic compression tests

Mariusz Jaczewski · Andrea Graziani

Received: 12 December 2023 / Accepted: 15 April 2024
© The Author(s) 2024

Abstract The purpose of the study is to evaluate strain-dependent behaviour of Cold Recycled Material (CRM) mixtures using three frameworks typically applied for Hot Mix Asphalt (HMA): linear viscoelastic (LVE) limits; non-linearity directions; changes in rheological model parameters. To this aim, the complex modulus of three CRM mixtures with different bitumen-to-cement ratio (0.2, 0.6 and 1.8) was measured in cyclic compression mode, at increasing level of axial deformation (from 35 to 195 μ strain) and at three temperatures (4, 20 and 40 °C). CRM mixtures showed strong strain dependent behaviour, which does not fully comply with the LVE hypothesis. LVE limit framework is applicable, but strain limits for CRM are different from HMA. Linearity direction framework does not give unique trend, hence it is not applicable in the same way as it was developed for HMA. The most promising framework for further analysis is the change in rheological model parameters, but it requires high number of performed tests.

Keywords Viscoelasticity · Rheological model · Cold recycled mixtures · Cement · Bituminous emulsion · Recycling

1 Introduction

1.1 Background

Cold recycling is currently one of the most environmental friendly and cost-effective techniques for reconstruction of old and heavily deteriorated bituminous pavements [1–3]. Cold recycled material (CRM) mixtures consist mostly of: reclaimed asphalt pavement (RAP) (usually from 60 up to 100%); additional virgin aggregate, used to improve the grading curve, and water, used to improve workability and compactability. CRM mixtures are bound by two differently working binding agents: bituminous emulsion (or foamed bitumen) and Portland cement (or other hydraulic binder).

Due to different environmental issues, specifications for CRM mixtures differ among different countries, especially in terms of amount of binding agents. In countries with warmer climate conditions and mild winters (like Italy [4], Spain [5], Greece [6], South Africa [7] or Brazil [8]), bituminous emulsion is the dominating binding agent. In such cases, Portland cement is used either to enhance the breaking of the emulsion (dosages up to 1.0%) or to improve structural performance (dosages up to 2.0%). In other

M. Jaczewski (✉)
Transportation Engineering Department, Faculty of Civil and Environmental Engineering and EkoTech Center,
Gdansk University of Technology, Narutowicza Street
11/12, 80233 Gdansk, PL, Poland
e-mail: mariusz.jaczewski@pg.edu.pl

A. Graziani
Department of Civil and Building Engineering
and Architecture, Università Politecnica delle Marche,
Ancona, Italy



countries such as Poland [1] or Germany [9] the dosage of Portland cement is higher (up to 4.0%), due to higher mechanical performance required by local specifications. Differences in the composition and mechanical performance of CRM mixtures can be highlighted by using different names (Fig. 1) [4]: bitumen stabilized material (BSM), cement-bitumen treated material (CBTM) or cold recycled asphalt (CRA). Figure 1 also shows the dosages of binding agents required by Polish specifications; the corresponding CRM mixture is normally identified as mineral-cement-emulsion (MCE) mixture.

The presence of two binding agents makes the behaviour of CRM mixture very complex. The bituminous binder leads to time–temperature dependence and to a certain flexibility, while the cementitious binder leads to high strength and stiffness, but also to higher risk of premature brittle failure [10, 11].

Due to their thermo-viscoelastic behaviour, the stiffness of CRM mixtures is often measured using methods and protocols originally developed for hot mix asphalt (HMA) mixtures, such as indirect tensile stiffness modulus [12–18], or complex modulus [19–22] in compression or tension/compression schemes. Usually, it is assumed that the limitations of the methods are similar for both HMA mixtures and CRM mixtures, and therefore the applied protocols are exactly the same. However, recent research showed that this assumption may not be correct if the strain- or stress-dependency of the stiffness is

of concern [23–25]. Specifically, the effect of strain level on CRM mixtures may be different from that of HMA mixtures and, therefore, testing at the same strain level may lead to stiffness values that are not directly comparable. In addition, recent studies performed using the indirect tensile scheme, showed that changes of stiffness due to increasing or decreasing strain levels are not reversible [24, 26]. This implies that, even at low strain levels (less than 100 μ strain), some damage is induced in the specimen during testing.

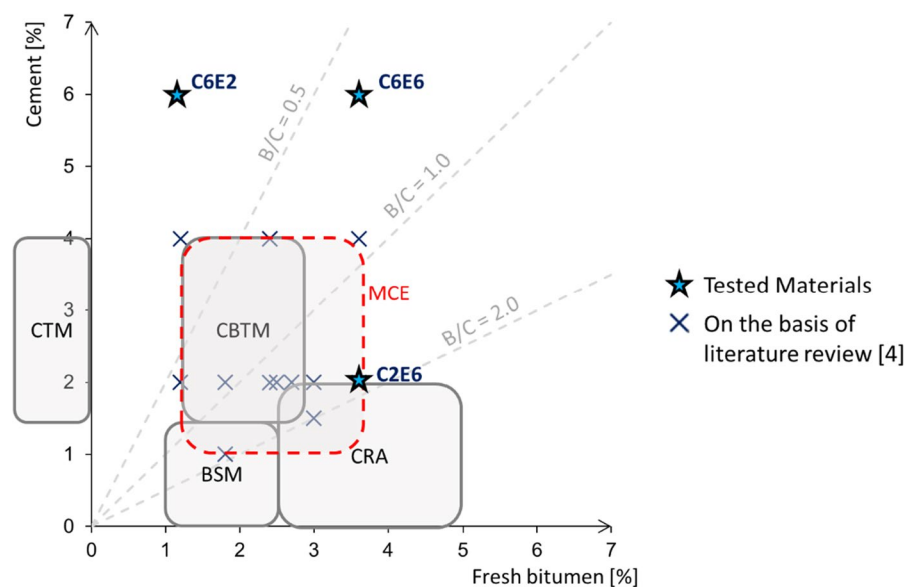
1.2 Methods for evaluating the strain dependant behaviour of HMA mixtures

In the last 20 years, several original approaches were proposed to investigate the strain-dependent behaviour of bitumen, mastic and HMA mixtures ([27–35]).

Normally it is assumed that, when stress/strain is gradually increased, the linearity limit is defined by a 5% reduction in stiffness modulus [27, 36, 37]. While this is relatively easy to verify for both bitumen and mastic (e.g. using the DSR), it is more difficult for mixtures because testing at very low strain levels is challenging. This framework was applied to other materials with trial of using it also for phase angles by Jaczewski et al. [23].

Next common framework used to describe the strain dependent behaviour of bitumen and HMA mixtures is the concept of non-linearity paths in the

Fig. 1 Composition of the mixtures tested in this study and its location among the cold recycled mixtures families, on the basis of Mignini et al. [4]



Black diagram presented by Gauthier et al. [30]. This approach was further developed by Nguyen et al. [31] and Mangiafico et al. [32] that linked the non-linearity directions in the Black and Cole–Cole diagrams to the slopes of stiffness modulus and phase angles variation with increasing strain amplitude.

An additional approach for evaluating the strain dependant behaviour of HMA mixtures is the analysis of changes of the parameters of selected complex modulus rheological models with the change (increase) of applied strain. It is known that complex modulus is strictly defined only in the LVE range. However, its measure at larger strain amplitudes can provide meaningful information and is well documented in the literature [38]. Until now this framework was used to describe the rheological properties of HMA mixtures in the small-strain domain (from 15 to 60 μ strain) [39, 40] and to characterize fatigue related changes of the viscoelastic behaviour of asphalt binders [41].

1.3 Objective

The objective of this study is to evaluate the strain-dependent behaviour of CRM mixtures using the three frameworks described in Sect. 1.2: (a) linear viscoelastic limits; (b) non-linearity directions; (c) changes in the parameters of the linear viscoelastic Huet-Sayegh model. To this aim, the complex modulus of three CRM mixtures with different bitumen-to-cement ratio was measured in cyclic compression mode, at increasing level of axial deformation. Cyclic compression test mode was chosen due to its widespread usage, linked to the relative simplicity of specimen preparation. It is highlighted that using a different loading mode, such as tension–compression, indirect tension or flexure, may lead to different results.

2 Materials and methods

2.1 Materials and mixtures

The laboratory experiments were conducted on three CRM mixtures produced with combinations of binding agents: a) 2% of cement and 6% of emulsion (C2E6), b) 6% of cement and 2% of emulsion (C6E2) and c) 6% of cement and 6% of emulsion (C6E6). The

used binders were Portland cement CEM I 32.5R (EN 197) and slow-setting cationic bituminous emulsion C 60 B10 ZM/R (EN 13808) with neat 70/100 residual bitumen. Mixture C2E6 complies with the Polish requirements for MCE mixtures for base course (Fig. 1) [42]. The two additional mixtures were tested to highlight the impact of cement and emulsion dosages on the stiffness properties. All tested mixtures had the same fixed grading curve, with small differences only on the finest parts, which were exchanged with cement. The base mixture gradation was designed for C2E6 and adjusted for other cement contents. Moreover, similar combinations of binder agents for MCE mixtures were employed in Poland in previous years [1].

Mixtures were prepared in laboratory and compacted in a gyratory compactor (EN 12697–31). The compacted specimens had height of 170 mm and diameter of 150 mm and were cured at 20 °C and 70% RH. Average mass of the specimens was around 3100 g. After 14 days specimens were cut to the target height of 150 mm and diameter of 100 mm. Before the complex modulus tests specimens were cured for total 28 days in laboratory conditions after compaction. Their basic properties are presented in Table 1.

2.2 Cyclic compression test

The complex modulus was determined in the cyclic compression configuration, according to the AASHTO TP79 standard [43] (Fig. 2). The tests were conducted at multiple strain levels (peak-to-peak values from 35 to 195 μ strain), multiple frequencies (from 0.01 to 25 Hz) and at three temperatures (4, 20 and 40 °C). The tests were performed in the Simple Performance Tester equipment (IPC Global) using haversine loading. The tests were performed without lateral confinement. The results were measured by three LVDT sensors with gauge length of 70 mm. In each test frequency the equipment first perform 10 conditioning loads and next it performs additional 10 loads from which the complex modulus and phase angle are determined.

2.3 Experimental plan

While it is assumed that the cyclic compression tests within small strain level are non-destructive test, testing a wide range of target strain levels and three

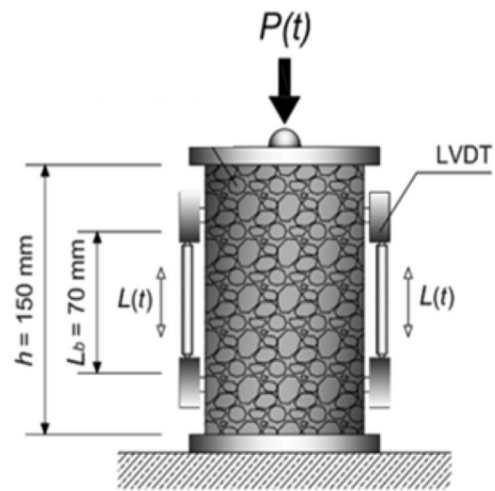
Table 1 Properties of cold recycled mixtures

Property	Mixture designation (b/c ratio)		
	C2E6 (1.8)	C6E2 (0.2)	C6E6 (0.6)
Mixture composition			
Virgin aggregate 0/31.5 (% by mass)	15	15	15
Virgin aggregate 0/2 (% by mass) ^{a)}	13	9	9
RAP aggregate (% by mass)	70	70	70
Bitumen emulsion content (% by mass)	6	2	6
Cement content (% by mass)	2	6	6
Compaction ratio (%) on the basis of modified Proctor test	99	99	99
Optimum fluid content (%) ^{b)}	6	6	6

Remarks: a) depending on the cement content; total quantity of cement and virgin aggregate 0/2 is equal to 15% (by mass)

b) optimum fluid content includes natural humidity of aggregate and RAP, water from emulsion, additional water added to the mixture and half of the bitumen content in emulsion

Fig. 2 Simple Performance Tester – test setup: Specimen ready for testing (left) scheme of the test in Simple Performance Tester (right)



different temperatures required to prepare strict experimental plan. Additionally, previously performed tests [23] suggested to start from the conditions where the material is stiffer (lowest temperature, highest frequency). The experimental plan is presented in Fig. 3 and was performed as follows:

- Prior to testing at each temperature, the specimens (two replicates for each mixture) were conditioned for more than 12 h at that temperature.
- Frequency sweeps (from 25 to 1 Hz) were carried out at each strain level (starting from 35 μ strain), without rest time between consecutive frequencies.
- A rest time of 10 min was allowed between frequency sweeps carried out at different strain levels (e.g. between 35 and 55 μ strain, between 55 and 75 μ strain, and so on).

- At selected strain levels of 45 and 95 μ strain the frequency sweep was extended to lower frequencies (from 25 to 0.01 Hz), those extended tests are shown in grey in Fig. 3.

Selected extended test for 45 and 95 μ strain were performed after the base frequencies sweeps (from 35 up to 195 μ strains) to confirm that there is no damage induced to the specimen. Comparison of the results for 95 μ strain for base and extended sweeps showed almost no differences in the measured moduli (the difference was similar to the consecutive tests performed on the same specimen).

2.4 Rheological modelling

During the analysis of the test data, it was verified that for each strain level the material complied with

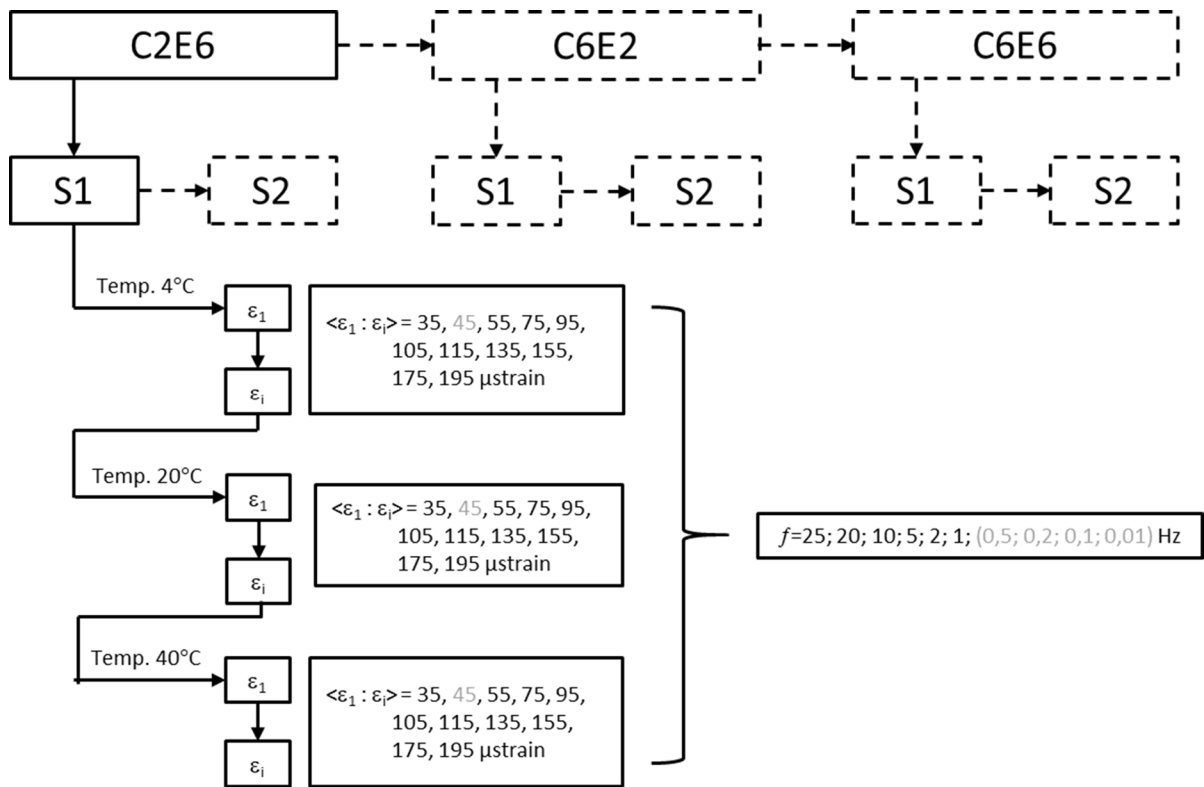


Fig. 3 Scheme of the performed testing sequence, where $\langle \varepsilon_1 : \varepsilon_i \rangle$ describe range of the target strain levels; in grey colour additional extended tests are presented

the time–temperature superposition principle (TTSP). First step for rheological modelling was the development of the master curve for the reference temperature $T_{\text{ref}}=20\text{ }^{\circ}\text{C}$. Shifting of the stiffness modulus data for temperatures of $4\text{ }^{\circ}\text{C}$ and $40\text{ }^{\circ}\text{C}$ was performed using an extended version of the closed-form shifting (CFS) algorithm which is based on the minimisation of the overlapping area between two successive isothermal curves of stiffness modulus [44]. Those shift factors were also applied to the phase angle data. The shift factors were then modelled using the WLF equation [45]:

$$\log \alpha_{\text{Tref}}(T) = \frac{C1(T - T_{\text{ref}})}{C2 + T - T_{\text{ref}}} \quad (1)$$

where $\alpha_{\text{Tref}}(T)$ is the shift factor for data measured at temperature T with respect to the reference temperature, T_{ref} and $C1$, $C2$ are empirical constants determined using least-squares fitting. Rheological modelling of the complex modulus was performed using an

approach developed for CRM mixtures by Graziani et al. [46]. The model describes the complex modulus ($E_{\text{HY}}^*(\omega)$) using the following equation:

$$E_{\text{HY}}^*(\omega) = E_{\text{LVE}}^*(\omega) \cdot \exp(j\varphi_{\text{HY}}) \quad (2)$$

where E_{LVE}^* is a LVE complex modulus model and $\exp(j\varphi_{\text{HY}})$ is a correction (also known as hysteretic dissipation term) that adds a time- and temperature-independent phase angle φ_{HY} to the LVE phase angle φ_{LVE} . In CRM mixtures the hysteretic dissipation may be linked to the presence of cementitious bonds and internal friction caused by an incomplete coating of the aggregate [47, 48]. In the present research the Huet-Sayegh (HS) model [49] was used to simulate the LVE behaviour. The HS model is described by the following equation:

$$E_{\text{LVE}}^* = E_e + \frac{E_g - E_e}{1 + \delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h}} \quad (3)$$

where $\omega = 2\pi f_r$ is the angular frequency, $f_r = f\alpha_{\text{Tref}}(T)$ is the reduced frequency, f is the testing frequency, E_g and E_e are the glassy and equilibrium moduli, h , k , and δ are dimensionless shape parameters and τ is the characteristic time parameter.

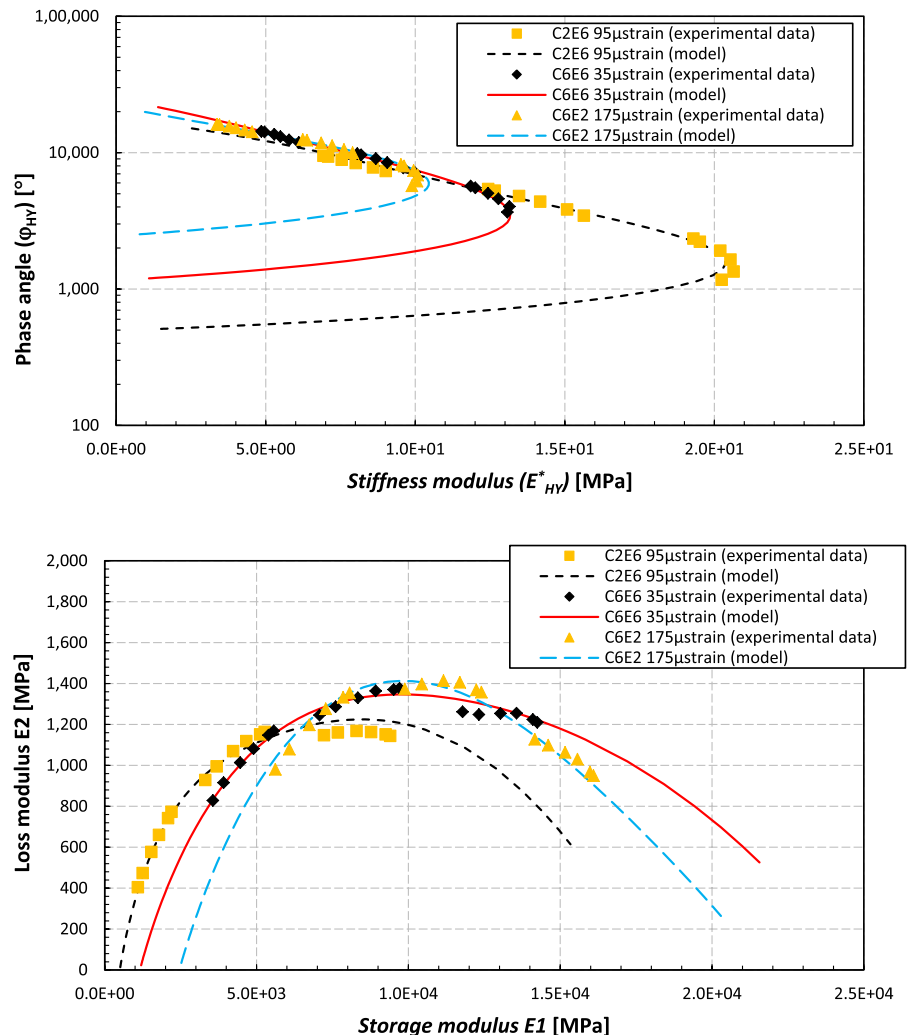
For each tested strain level, the following model fitting procedure was used:

- The CSF algorithm was used to determine the shift factors, for the reference temperature $T_{\text{ref}} = 20^\circ\text{C}$. Afterwards, the C1 and C2 parameters were estimated using non-linear least square fitting.
- The initial values of E_e and E_g were estimated from the trends of the experimental data of the Cole–Cole and Black diagrams, respectively.

- The parameters k , h , δ , $\log \tau$, were estimated using non-linear least square fitting. The error function considered only the residuals of the logarithm of the stiffness modulus.
- The parameter φ_{HY} was estimated using non-linear least square fitting. The error function considered only the residuals of the phase angle.
- The final optimization of all the parameters was achieved by minimizing the distance between the experimental data and the model on the Cole–Cole diagram.

The examples of the rheological modelling of different analysed mixtures and strain levels are presented in Fig. 4.

Fig. 4 Example of the rheological modelling of the test data



3 Results and discussion

3.1 Test results

Selected results of stiffness modulus and phase angle are presented to highlight the behaviour of the three tested mixtures. The full dataset of test results is available as supplementary material [50].

Figure 5 shows the stiffness modulus and phase angle values determined for all six tested specimens using the target strain of $45 \mu\text{strain}$. Only one strain level is presented to highlight the differences between the three mixtures and the typical variability between two replicate specimens of each mixture. All results

show a low scatter between the two replicates and follow typical trends presented in literature [4, 8, 19, 51, 52]. It is interesting to note that the C6E6 specimens showed intermediate values of stiffness modulus and phase angle at all temperatures. This confirms that the time and temperature dependency of CRM mixtures is affected by the relative dosage of the two binders (i.e., the residual bitumen to cement ratio) and, ultimately, by the relative volume of cementitious and bituminous bonds that develop during the curing phase. In the case of the C6E2 ($b/c=0.2$) CRM mixture the cementitious bonds dominate the viscoelastic behaviour of the mixture resulting in higher values of complex modulus and lower values ($< 10^\circ$) of phase

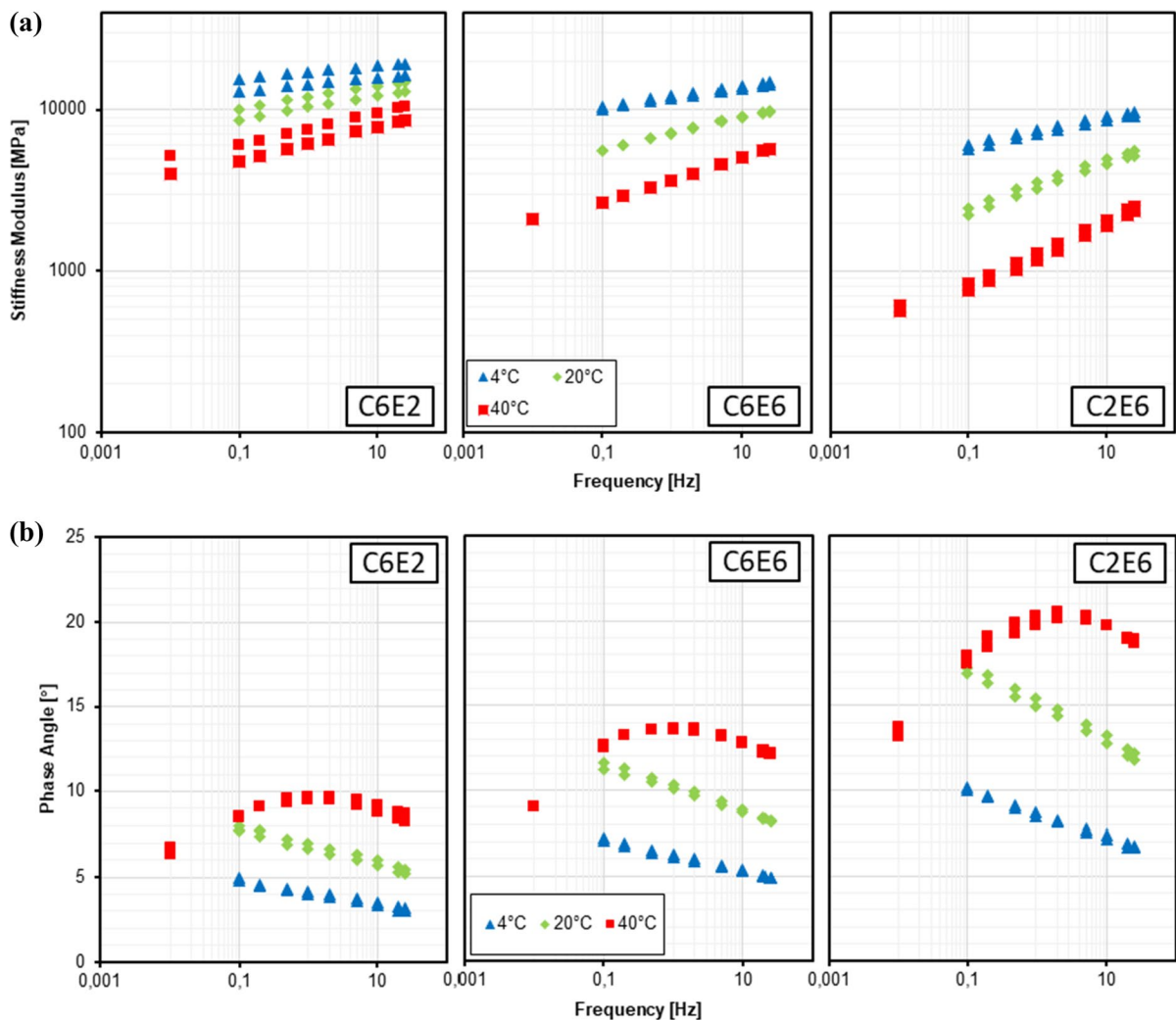


Fig. 5 Results of C2E6, C6E2 and C6E6 at target strain— $45 \mu\text{strain}$ a) Stiffness modulus b) Phase angle

angles, while in the case of C2E6 ($b/c = 1.8$) the bituminous bonds dominates the viscoelastic behaviour of the mixture which results in lower values of complex modulus and higher values (up to 20°) of phase angles. It is also important to note that in the present research several strain levels were applied in sequence at the same temperature, before moving to the next temperature (Fig. 6). Therefore, the data measured at 20 and 40 °C, had been subjected to higher strain levels at the previous testing temperature (5 and 20 °C, respectively).

Figure 6 shows the strain dependency of complex modulus values determined for all six tested specimens at the frequency of 10 Hz. Similar trends

can be observed at other frequencies [50]. The experimental data show that the stiffness modulus decreases with the increase in strain level. The decreasing rate is higher until around 100 μstrain and then it apparently stabilizes. As for phase angle, the behaviour slightly differs for various temperatures. For the temperatures of 4 and 20 °C the increase of phase angle with increasing strain level is with almost constant rate. In the case of 40 °C the behaviour is more similar to that observed for the stiffness modulus (i.e. higher increase rate up to about 100 μstrain). In single cases a decrease of phase angle was also observed, which can indicate damage developing in the specimen. The obtained

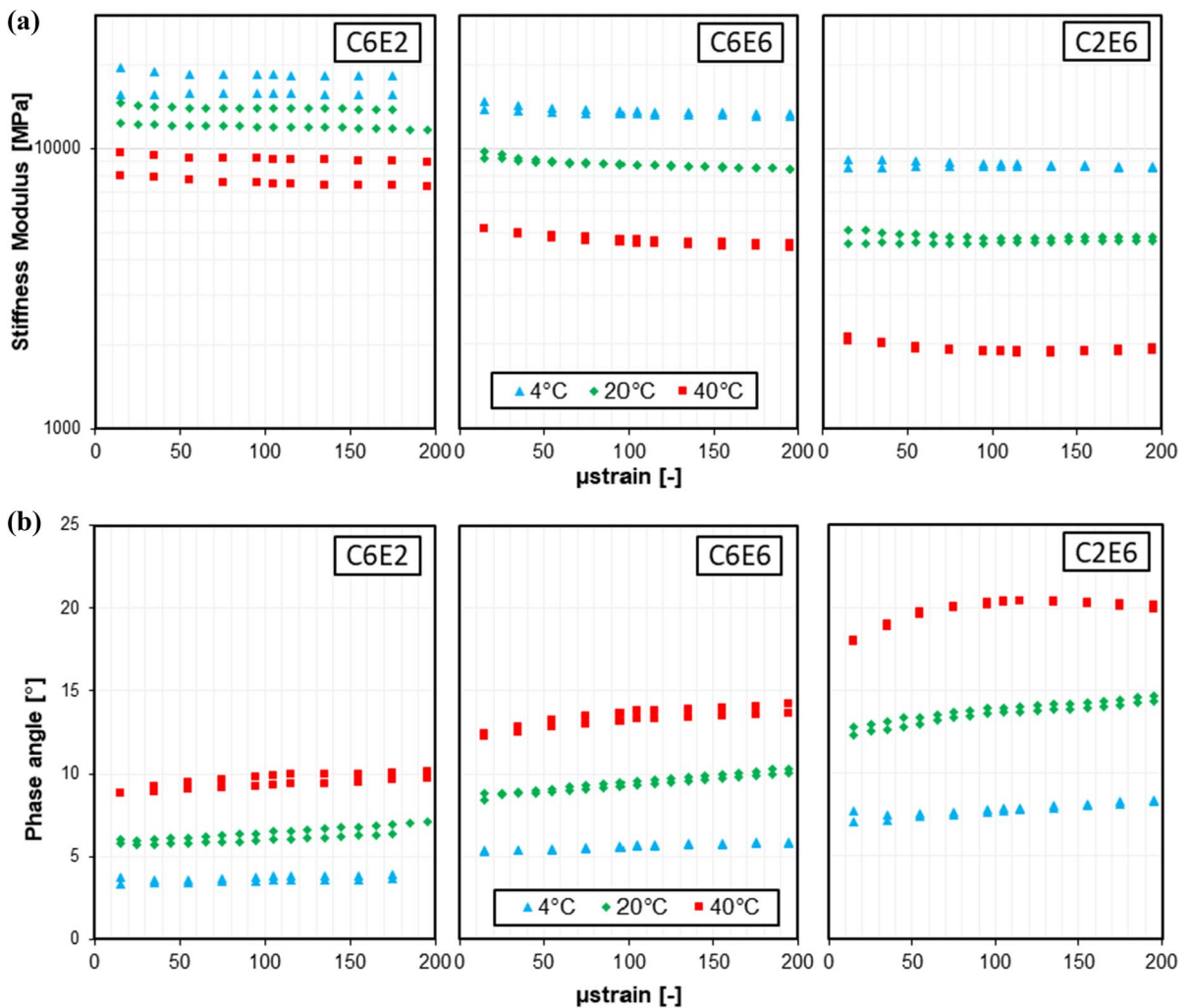


Fig. 6 Relationship between a) the stiffness modulus and target strain level b) the phase angle and target strain level; C2E6, C6E2 and C6E6 mixtures for 28 days after compaction, 10 Hz



results are in compliance with previously obtained [23, 25].

3.2 Frameworks for characterizing the strain-dependant behaviour

3.2.1 The linear viscoelastic limit

The LVE strain limits for three tested mixtures were determined separately, considering a 5% reduction in stiffness modulus, and a 5% increase in phase angle, with respect to the values measured at the lowest strain level (from Fig. 6). The LVE limits are summarized in Fig. 7. The strain limits for the stiffness modulus showed a strong positive linear correlation with the stiffness modulus. In fact, values of the Pearson correlation coefficient varied from 0.86 to 0.96. From

a practical point view this also implies a correlation to the mixture type, with the stiffest mixture (C6E2) showing the highest limits. It is highlighted that 40% of the calculated limits were equal to (or greater than) the maximum strain applied in this investigation (195 μ strain). The strain limits for the phase angle were generally lower than those determined for the stiffness modulus, at same testing temperature and frequency. In fact, 92% of the calculated limits were lower than 120 μ strain. Moreover, the correlation with the phase angle values was not so strong, except for the mixture C2E6 that showed a quite strong negative correlation ($r = -0.81$).

Overall, the determined LVE strain limits confirmed the results of a preliminary study obtained for specimen subjected to very long curing period [23]. In addition, it is possible to state that in cyclic

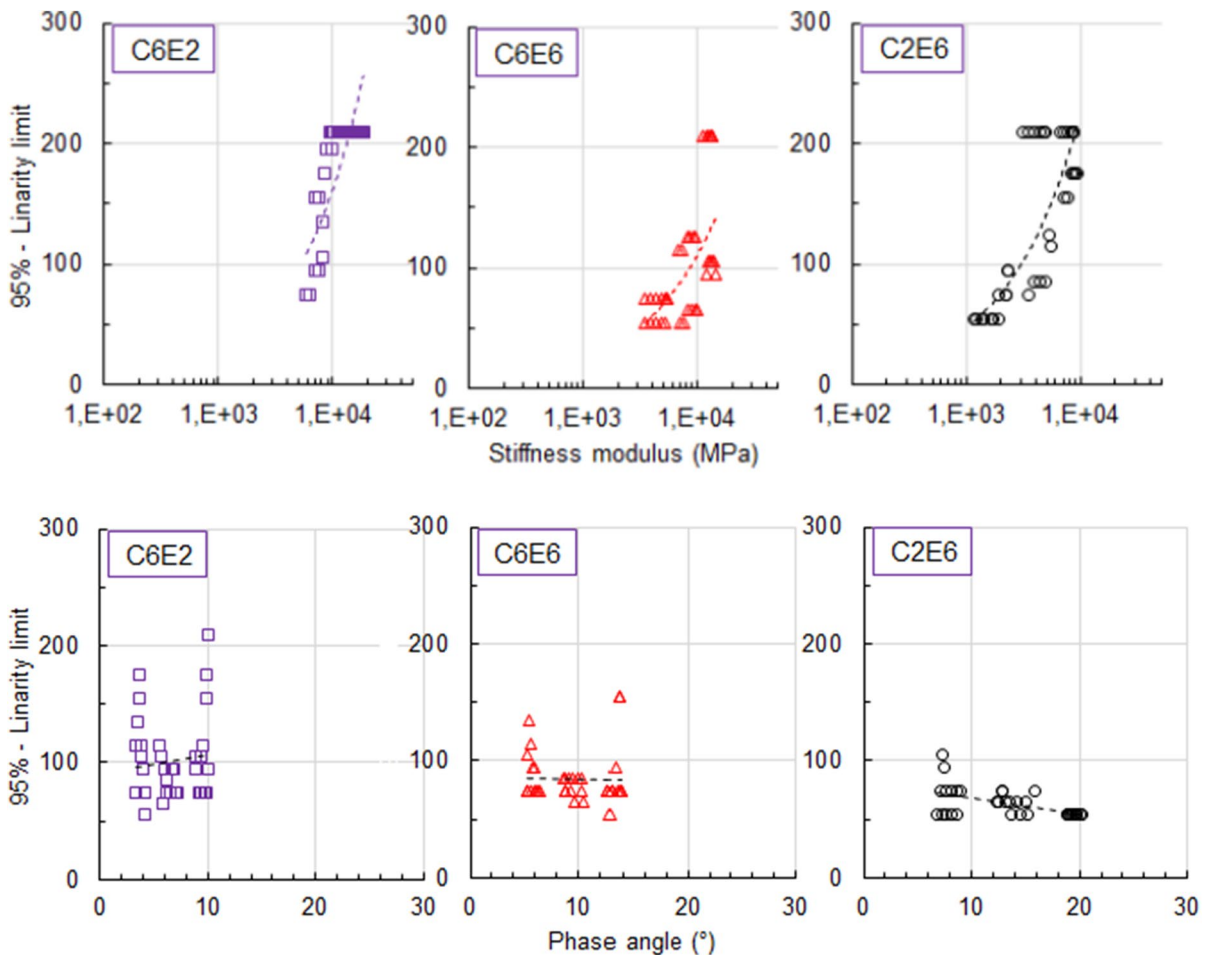


Fig. 7 Summary of LVE-limits [μ strain] for stiffness moduli and phase angles

compression tests, a limiting value of applied strain for which the CRM mixtures are expected to exhibit a linear behaviour is lower than about 50 μ strain (peak-to-peak), as the changes of the measured stiffness moduli and phase angles fits into 5% limit for all tested frequencies and test temperatures. It should be noted that this is trial to applicate the framework determined for HMA, and the behaviour of the CRM mixtures is much more complicated and not always present clear constant value of measured parameters.

3.2.2 Non-linearity direction

The non-linearity directions were determined in the Black diagram considering experimental data for fixed temperature and frequency conditions and using the whole applied strain range – from 35 μ strain up to 195 μ strain. The directions are visually presented as red arrows in Fig. 8 for selected frequencies. Those arrows were obtained using an exponential regression on the data measured at same temperature and frequency.

The direction of change is more or less constant for middle and lower part of the plots which represents results at 4 °C and 20 °C. The direction starts to change with the increase of the temperature to 40 °C and lowering the test frequency. Also, some deviations from the trend are visible in the case of high frequencies for the temperature of 4 °C. The direction of those cases is shifted towards left what is the results of faster decrease of the values of stiffness modulus

with the same rate of change of the phase angles. The probable case of such behaviour could be damage induced to the specimen (in the temperature of 4 °C when the specimen is brittle and in 40 °C when the behaviour of CRM mixture is probably more related to the presence of cement).

Figure 9 shows the slopes of stiffness modulus decrease (pE) and phase angle increase (p ϕ). The slopes were calculated until 100 μ strain, as outlined in Fig. 6. The black solid line represents the unique linear trend obtained by Mangiafico et al. [32] on HMA. For the tested CRM mixtures, the linear trend does not appear. In particular, the data obtained at 40 °C (lowest pE values and highest p ϕ values) deviate from the linear trend – while the changes of the slopes of stiffness moduli are visible the changes of slope of phase angles start to diminish (as presented in Fig. 9). Slopes of phase angles obtained for higher applied strains started to reach value of 0. Results obtained for other set of data with longer curing times [25] also presented diminishing of the slope of the phase angles. It is probably due to cement hydration in the mixture.

3.2.3 Rheological model parameters analysis

Analysis of changes of the parameters of rheological model is the last framework used to evaluate the strain-dependant behaviour of CRM mixtures. For this purpose modified Huet-Sayegh model was used (Eqs. 2 and 3). The analysis was based on two sets

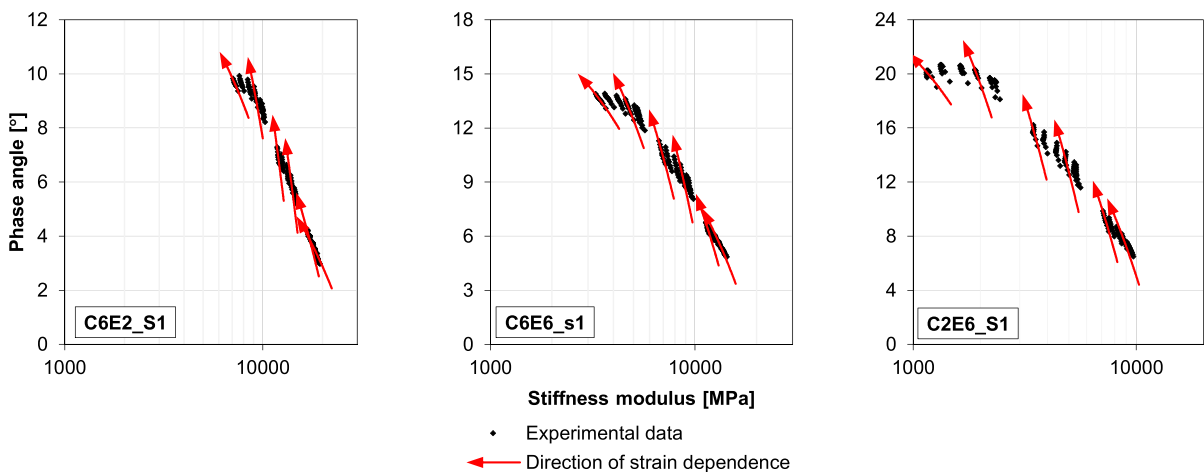


Fig. 8 Application of the non-linearity direction framework for C6E2, C6E6 and C2E6 mixtures for 28 days after compaction



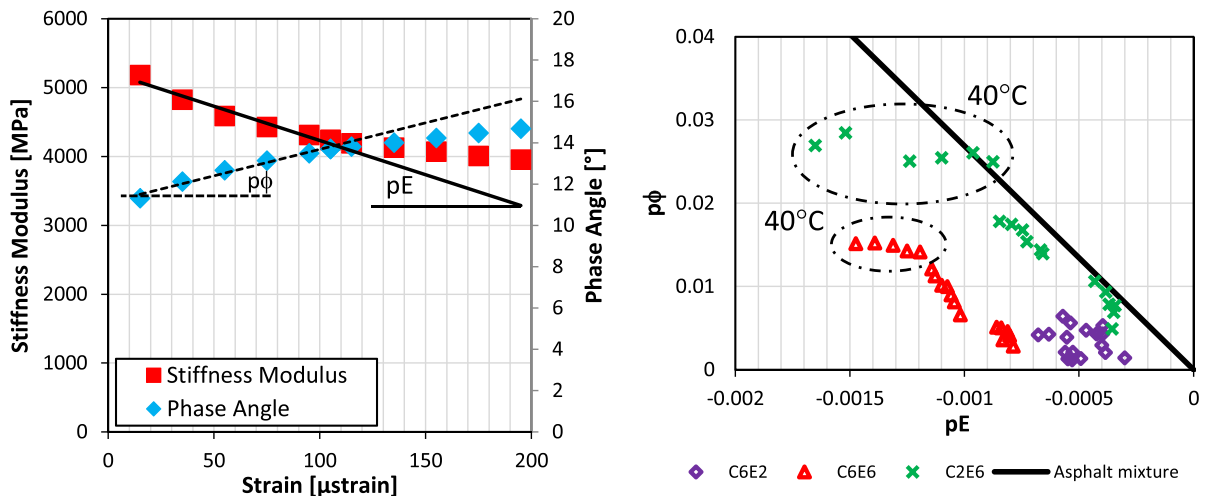


Fig. 9 “Non-linearity direction” framework: (left) Example of calculation of pE and $p\phi$, until $100 \mu\text{strain}$ (right) Comparison of the framework for CRM mixtures and asphalt mixtures (for data from 35 up to $105 \mu\text{strain}$)

of parameters: (a) WLF shift factor model parameters $C1$ and $C2$ and (b) 7 rheological model parameters: E_e , E_g , k , h , δ , $\log \tau$, and ϕ_{HY} . The results for determined rheological model parameters and linear trend for strain dependant behaviour are presented respectively in Figs. 10 (WLF model parameters) and Fig. 11 (HS model parameters). All basic data presented in the figures are given in the supplementary materials [50]. The parameters “a” (slope) and “b” (intercept) of the trend lines are given in the Table 2.

The $C1$ and $C2$ parameters can be considered constant in selected strain range and are not related to the composition of the mixture (Fig. 10). Only

for specimen (C6E2) the value of both parameters decreased with increasing of applied strain.

In the case of HS rheological model parameters, the tested specimen showed evident trends of strain dependence:

- The values of E_g (which describes the glassy modulus) decreased with the increase of applied strain. The decrease had similar slope of change for all tested mixtures regardless of combination of binding agents.
- The values of E_e (which describes the equilibrium modulus) were in the case of this research constant and did not show strain dependence. It

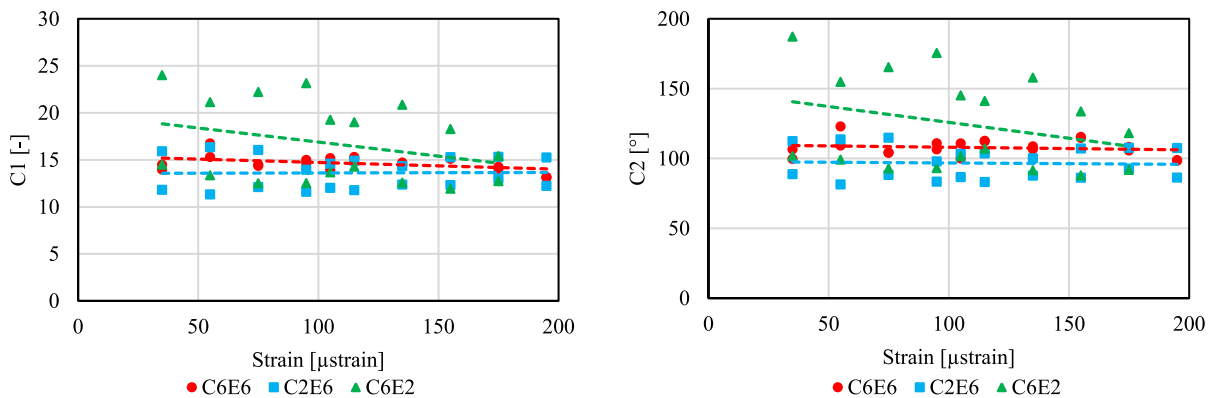


Fig. 10 WLF shift factor model parameters, $T_{ref} = 20 \text{ }^\circ\text{C}$

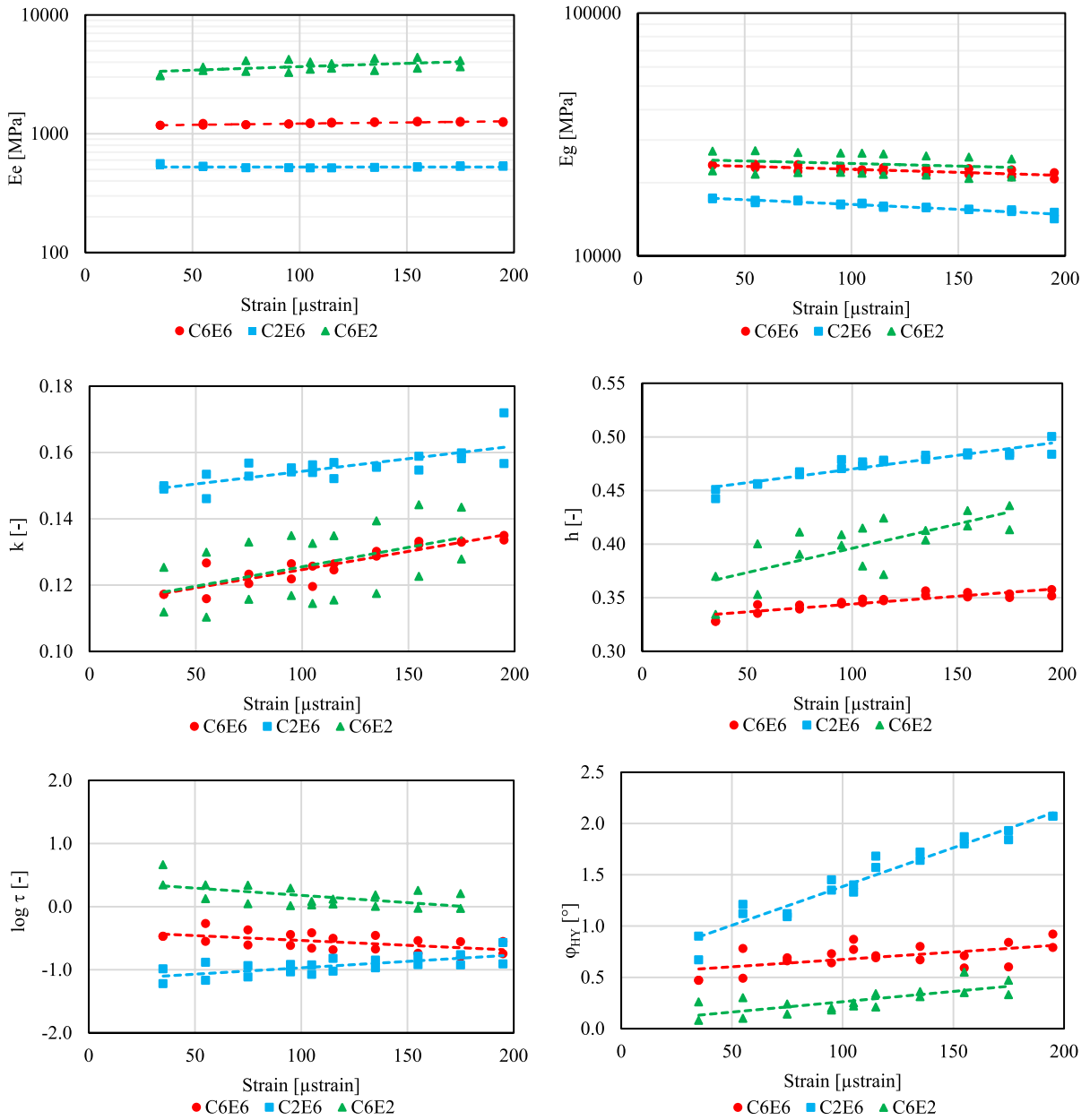


Fig. 11 Selected modified HS rheological model parameters

was expected, that E_g would behave similar to E_e , therefore it should decrease with increasing applied strain [41]. The observed trend could be related to the accumulation of permanent strain due to the selected testing scheme (cyclic compression).

c. The values of k and h (which describe the slope of the Cole–Cole curve at low and high

reduced frequencies, respectively) increased with increased applied strain level. From an analytical point of view, k and h are a fractional order of derivation, ranging from 0 for elastic response to 1 for viscous response [53]. What is interesting, the increase of k and h suggests that the material response is becoming more viscous and less elastic. A similar change was observed by Mignini



Table 2 Parameters of the linear trends for selected rheological model parameters

Rheological model parameters trends	Specimen designation	Specimen designation		
		C2E6	C6E2	C6E6
Ee	a	0,0008	4,8668	0,5689
	b	525,06	3182,8	1159,7
Eg	a	-14,897	-11,691	-13,029
	b	17,773	25,179	24,030
k	a	0,000076	0,00011	0,000117
	b	0,1467	0,1137	0,1138
h	a	0,000254	0,000453	0,000146
	b	0,4446	0,3508	0,3295
log τ	a	0,002	-0,0023	-0,0015
	b	-1,1716	0,4092	-0,3805
C1	a	0,0005	-0,0298	-0,0072
	b	13,56	19,872	15,447
C2	a	-0,0104	-0,2268	-0,0195
	b	97,822	148,58	110,02
φ_{HY}	a	0,0076	0,0014	0,002
	b	0,6299	0,5306	0,0604

et al. [6] when comparing CRM mixtures to HMA mixtures. The possible explanation for this behaviour could be the damage of cementitious bonds in the tested specimen, what should be verified in further research – if this behaviour is reversible and if it depends on the curing time of analysed material.

- d. The $\log \tau$ parameter also showed evident trends that are strongly depended on the mixture composition. For high bitumen-to-cement ratio (C2E6) it showed increase of analysed values with increasing strain. This can be related to a decrease of the crossover frequency and thus to lower the relaxation ability of the mixture. On the other hand, for low bitumen-to-cement ratio (C6E2) it showed decrease of analysed values with increasing strain. This can be related to an increase of the crossover frequency and thus to a higher relaxation ability of the mixture. The explanation of such behaviour requires further analysis.
- e. The value of φ_{HY} showed high dependency on applied strain level and b/c ratio. For all tested mixtures φ_{HY} increased with increasing strain. This confirms that φ_{HY} can be used to represent a dissipation mechanism linked to internal friction

(the higher the strain, the higher the dissipation, the higher the hysteretic phase angle). Similarly, lower slope and initial value characterize the mixtures with lower b/c ratios, confirming a more pronounced cement-like behaviour,

As seen in the analysis the determined trends are generally in compliance with previous results [40] which were obtained from very limited amount of data (3 strain levels lower than $100\mu\text{strain}$). The strain dependent behaviour of CRM mixtures shows clear trends, which can be mathematically modelled. But it should be noted that the study was performed on limited set of materials and test methods to formulate general conclusions about the strain dependent behaviour of CRM mixtures. (Test were performed as compression test for limited amount of frequencies (from 1 to 25 Hz). As analysis shows it could be important especially in higher temperatures. It should be also noted, that while the study was performed for fully cured specimen, the presence of cement changes the properties of the CRM mixtures even for very long times after compaction. Therefore this behaviour should be further validated, especially whether it is a non-linear reversible one or it is related to the micro-damage accumulated developed in the specimen during tests. Nevertheless rheological model framework shows the most promising results for further analysis of strain dependent behaviour of CRM mixtures.

3.2.4 Comparison of the frameworks for evaluating strain dependence

The comparison of potential and limitations of the used frameworks are presented in the Table 3. It should be noted that all of them can be utilized in different aspects of modelling of CRM mixtures. Additionally, it should be noted that those models were used for analysis of linear visco-elastic materials. Recent studies performed in different research groups proved, that CRM mixtures do not show clear linear or non-linear behaviour as it is visible in the case of asphalt mixtures.

4 Conclusions

Study aimed to determine the framework which shows the best performance for analysis and



Table 3 Analysis of used strain dependence frameworks

Property	Framework	Linear viscoelasticity limit	Non linearity direction	Rheological model parameters analysis
Pros	- simple framework which does not need advanced analytical tools - for studies with large amount of tested materials usually shows similar results for all mixtures - verified for other bitumen based materials	- simple framework which does not need advanced analytical tools - with proper data it can allow to distinguish between different phenomena which can appear in the analysed material	- advanced tool for analysis of physically-related parameters of CRM mixtures - framework allows to analyse not only strain dependant behaviour but also other phenomena (such as curing, ageing or damage)	
Cons	- CRM mixtures do not show similar behaviour as bitumen and HMA mixtures - different behaviour in the case of stiffness modulus and phase angles - problematic for compressive test if specimen shows creep behaviour	- the behaviour of CRM mixture changes strongly with temperature (especially for higher temperatures) - only limited set of data (up to 110 μ strain) showed reasonable results - it is difficult to model the properties for higher strain values	- requires advanced analytical tools for analysis and experience of the operator for fitting data - requires higher amount of data in comparison to the other two frameworks	
Possible application	Determination of the test assumptions for standardized material tests	Distinguish between different phenomena which appear in materials	Modelling of the strain dependant properties of CRM mixtures	

modelling of cold recycled material (CRM) mixtures. Three different frameworks used in literature were used and compared. The following conclusions can be stated on the basis of preformed research:

1. CRM mixtures showed strain dependent behaviour, which does not fully comply with LVE hypothesis most often assumed for such mixtures. Due to small reduction in the value of stiffness modulus, behaviour presented by CRM mixture is approximated as linear. This behaviour is similar as present in HMA mixtures.
2. All presented frameworks can be used with limitations to describe the behaviour of CRM mixtures, but for different applications.
3. LVE limit approach is applicable, but LVE limits for CRM are different from HMA. The approach can be applied to stiffness modulus, but not to phase angle. Moreover, this approach cannot be used to characterize "non-linearity"
4. Linearity direction ($pE/p\phi$), does not give unique trend, hence it is not applicable in the same way as it was developed for HMA. Moreover, it is applicable only until 100 μ strain, because above this value the trend is not linear anymore.
5. The most promising framework for further analysis is rheological model parameters framework, but it requires high number of performed tests. Rheological model parameters framework showed following strain dependant trends:
 - o The values of E_g decrease with the increase of applied strain. The decrease has similar slope of change for all tested mixtures regardless of combination of binding agents.
 - o The values of E_c are in case of this research constant and do not show strain dependence.
 - o The values of k and h increased with increased applied strain level.
 - o The $\log\tau$ parameter did not show evident trends, but it is evident that it is strain-dependent, but the direction of trend strongly depended on the mixture composition
 - o The value of ϕ_{HY} showed high dependency on applied strain level and b/c ratio. For all

tested mixtures φ_{HY} increased with increasing strain.

General recommendation is such that regardless of its limitations the rheological model parameters analysis framework shows the most promising results and should be used in further research and verified on bigger database.

Acknowledgements Financial support for these studies from the Gdańsk University of Technology under the DEC-43/2020/IDUB/L.3.3 grant “Linear and non-linear viscoelastic behaviour of cold recycled bitumen-cement composites” – ‘Excellence Initiative – Research University’ program is gratefully acknowledged.

Author contribution Mariusz Jaczewski (M.J.): Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. Andrea Graziani (A.G.): Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declarations

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.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Dołycki B, Jaskała P (2019) Review and evaluation of cold recycling with bitumen emulsion and cement for rehabilitation of old pavements. *J Traffic Transp Eng.* <https://doi.org/10.1016/j.jtte.2019.02.002>
2. Kukielfka J, Sybilski D (2018) Durability of base courses with mineral-cement-emulsion mixes (MCEM). *IOP Conf Ser Mater Sci Eng.* <https://doi.org/10.1088/1757-899X/356/1/012006>
3. Lin J, Hong J, Xiao Y (2017) Dynamic characteristics of 100% cold recycled asphalt mixture using asphalt emulsion and cement. *J Clean Prod* 156:337–344. <https://doi.org/10.1016/j.jclepro.2017.04.065>
4. Mignini C, Cardone F, Graziani A (2022) Complex modulus of cement-bitumen treated materials produced with different reclaimed asphalt gradations. *Mater Struct* 55:169. <https://doi.org/10.1617/s11527-022-02009-4>
5. Recasens RM, Pérez Jiménez FE, Aguilar SC (2000) Mixed recycling with emulsion and cement of asphalt pavements. Design procedure and improvements achieved. *Mater Struct* 33:324–330. <https://doi.org/10.1007/BF02479703>
6. Loizos A, Papavasiliou V (2006) Evaluation of foamed asphalt cold in-place pavement recycling using nondestructive techniques. *J Transp Eng* 132:970–978. [https://doi.org/10.1061/\(ASCE\)0733-947X\(2006\)132:12\(970\)](https://doi.org/10.1061/(ASCE)0733-947X(2006)132:12(970))
7. Dal Ben M, Jenkins KJ (2014) Performance of cold recycling materials with foamed bitumen and increasing percentage of reclaimed asphalt pavement. *Road Mater Pavement Des* 15:348–371. <https://doi.org/10.1080/14680629.2013.872051>
8. Kuchiishi AK, Vasconcelos K, Bariani Bernucci LL (2021) Effect of mixture composition on the mechanical behaviour of cold recycled asphalt mixtures. *Int J Pavement Eng* 22:984–994. <https://doi.org/10.1080/10298436.2019.1655564>
9. Wacker B, Kalantari M, Diekmann M (2020) Cold recycling in Germany—current experiences and future projects, Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements—Mairepav9, pp 813–823 https://doi.org/10.1007/978-3-030-48679-2_76
10. Dołycki B, Jaczewski M, Szydłowski C, Wojciech B, Gajewski M (2023) Analysis of selected mechanical properties of mineral-cement-emulsion mixtures (MCE). *Roads Bridg.—Drog. i Most* 22:41–61. <https://doi.org/10.7409/rabdim.023.003>
11. Mknaci L, Graziani A, Mignini C, Henni AD, Miljković M (2022) Influence of bitumen emulsion on the curing behaviour of standardised cold bitumen emulsion mortars. *Road Mater Pavement Des* 23:99–115. <https://doi.org/10.1080/14680629.2021.2017329>
12. Valentin J, Čížková Z, Suda J, Batista F, Mollenhauer K, Simnofske D (2016) Stiffness characterization of cold recycled mixtures. *Transp Res Procedia* 14:758–767. <https://doi.org/10.1016/j.trpro.2016.05.065>
13. Buczyński P, Iwański M, Mazurek G, Krasowski J, Krasowski M (2020) Effects of portland cement and polymer powder on the properties of cement-bound road base mixtures. *Materials (Basel)* 13:4253. <https://doi.org/10.3390/ma13194253>
14. Pettinari M, Simone A (2015) Effect of crumb rubber gradation on a rubberized cold recycled mixture for road pavements. *Mater Des* 85:598–606. <https://doi.org/10.1016/j.matdes.2015.06.139>
15. Sangiorgi C, Tataranni P, Simone A, Vignali V, Lantieri C, Dondi G (2017) A laboratory and filed evaluation of cold recycled mixture for base layer entirely made

- with reclaimed asphalt pavement. *Constr Build Mater* 138:232–239. <https://doi.org/10.1016/j.conbuildmat.2017.02.004>
16. Graziani A, Godenzoni C, Cardone F, Bocci M (2016) Effect of curing on the physical and mechanical properties of cold-recycled bituminous mixtures. *Mater Des* 95:358–369. <https://doi.org/10.1016/j.matdes.2016.01.094>
 17. Miljković M, Dołżycki B, Jaczewski M, Szydłowski C (2022) Comparative study of the mechanical behaviour of bitumen- and cement-dominated mixtures with reclaimed asphalt, Proceedings of the RILEM international symposium on bituminous materials, RILEM Bookseries 27, pp 413–419. https://doi.org/10.1007/978-3-030-46455-4_52
 18. Orosa P, Orozco G, Carret JC, Carter A, Pérez I, Pasandín AR (2022) Compactability and mechanical properties of cold recycled mixes prepared with different nominal maximum sizes of RAP. *Constr Build Mater* 339:127689. <https://doi.org/10.1016/j.conbuildmat.2022.127689>
 19. Dołżycki B, Jaczewski M, Szydłowski C (2017) The long-term properties of mineral-cement-emulsion mixtures. *Constr Build Mater* 156:799–808. <https://doi.org/10.1016/j.conbuildmat.2017.09.032>
 20. Gandi A, Carter A, Singh D (2017) Rheological behavior of cold recycled asphalt materials with different contents of recycled asphalt pavements. *Innov Infrastruct Solut* 2:1–9. <https://doi.org/10.1007/s41062-017-0094-3>
 21. Grilli V, Virgili A, Graziani A (2023) Evaluation of complex modulus and fatigue properties of cold recycled material mixtures using small-scale specimens. *Road Mater Pavement Des*. <https://doi.org/10.1080/14680629.2023.2194450>
 22. Iwański M, Mazurek G, Buczyński P, Iwański MM (2022) Effects of hydraulic binder composition on the rheological characteristics of recycled mixtures with foamed bitumen for full depth reclamation. *Constr Build Mater* 330:127274. <https://doi.org/10.1016/j.conbuildmat.2022.127274>
 23. Jaczewski M, Szydłowski C, Dołżycki B (2022) Preliminary study of linear viscoelasticity limits of cold recycled mixtures determined in Simple Performance Tester (SPT). *Constr Build Mater* 357:129432. <https://doi.org/10.1016/j.conbuildmat.2022.129432>
 24. Jaczewski M, Szydłowski C, Dołżycki B (2023) Stiffness of cold-recycled mixtures under variable deformation conditions in the IT-CY test. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2023.e02066>
 25. Jaczewski M, Szydłowski C, Dołżycki B (2023) The dependence of linear viscoelasticity limits of cold recycled mixtures on time of curing and compaction method, In: *Mater Today Proc*
 26. Grilli V, Grilli A, Graziani A, Jaczewski M (2024) Effect of strain level on the stiffness of cold recycled bituminous mixtures, In: 8th Int. Conf. Bitum. Mix. Pavements, Thessaloniki, Greece
 27. Airey GD, Rahimzadeh B, Collop AC (2002) Linear viscoelastic limits of bituminous binders. *Assoc Asph Pavement Technol* 71:160–196
 28. Underwood BS, Kim YR (2015) Nonlinear viscoelastic analysis of asphalt cement and asphalt mastics. *Int J Pavement Eng* 16:510–529. <https://doi.org/10.1080/10298436.2014.943133>
 29. Uzan J, Levenberg E (2007) Advanced testing and characterization of asphalt concrete materials in tension. *Int J Geomech* 7:158–165. [https://doi.org/10.1061/\(ASCE\)1532-3641\(2007\)7:2\(158\)](https://doi.org/10.1061/(ASCE)1532-3641(2007)7:2(158))
 30. Gauthier G, Bodin D, Chailleux E, Gallet T (2010) Non linearity in bituminous materials during cyclic tests. *Road Mater Pavement Des* 11:379–410. <https://doi.org/10.1080/14680629.2010.9690339>
 31. Nguyen QT, Di Benedetto H, Sauzéat C (2015) Linear and nonlinear viscoelastic behaviour of bituminous mixtures. *Mater Struct Constr* 48:2339–2351. <https://doi.org/10.1617/s11527-014-0316-5>
 32. Mangiafico S, Babadopulos LFAL, Sauzéat C, Di Benedetto H (2018) Nonlinearity of bituminous mixtures. *Mech Time-Dependent Mater* 22:29–49. <https://doi.org/10.1007/s11043-017-9350-3>
 33. Coulon L, Koval G, Chazallon C, Roux J-N (2021) Modeling of T/C complex stiffness modulus test and non-linearity of asphalt concrete mixes, In: Proceedings of the RILEM International Symposium on Bituminous Materials pp 1343–1350 https://doi.org/10.1007/978-3-030-46455-4_171
 34. Graziani A, Raschia S, Mignini C, Carter A, Perraton D (2020) Use of fine aggregate matrix to analyze the rheological behavior of cold recycled materials. *Mater Struct Constr*. <https://doi.org/10.1617/s11527-020-01515-7>
 35. Zeng M, Bahia HU, Zhai H, Anderson MR, Turner P (2001) Rheological modeling of modified asphalt binders and mixtures. *J Assoc Asph Paving Technol* 70:403–441
 36. Airey GD, Rahimzadeh B, Collop AC (2003) Viscoelastic linearity limits for bituminous materials. *Mater Struct* 36:643–647. <https://doi.org/10.1007/BF02479495>
 37. Di Benedetto H, Olard F, Sauzéat C, Delaporte B (2004) Linear viscoelastic behaviour of bituminous materials: from binders to mixes. *Road Mater Pavement Des* 5:163–202. <https://doi.org/10.1080/14680629.2004.9689992>
 38. Hyun K, Wilhelm M, Klein CO, Cho KS, Nam JG, Ahn KH, Lee SJ, Ewoldt RH, McKinley GH (2011) A review of nonlinear oscillatory shear tests: analysis and application of large amplitude oscillatory shear (LAOS). *Prog Polym Sci* 36:1697–1753. <https://doi.org/10.1016/j.progpolymsci.2011.02.002>
 39. Graziani A, Bocci M, Canestrari F (2014) Complex Poisson's ratio of bituminous mixtures: measurement and modeling. *Mater Struct Constr* 47:1131–1148. <https://doi.org/10.1617/s11527-013-0117-2>
 40. Graziani A, Cardone F, Virgili A, Canestrari F (2019) Linear viscoelastic characterisation of bituminous mixtures using random stress excitations. *Road Mater Pavement Des* 20:S390–S408. <https://doi.org/10.1080/14680629.2019.1587494>
 41. Katbeh J, Masad E, Lakshmi Roja K, Srinivasa A (2023) A framework for the analysis of damage and healing viscoelastic behaviour of asphalt binders. *Constr Build Mater* 374:130908. <https://doi.org/10.1016/j.conbuildmat.2023.130908>
 42. Dołżycki B (2019) Instrukcja projektowania i wbudowania mieszanek mineralno-cementowo-emulsiyjnych (MCE)



43. AASHTO ((2013)) AASHTO TP 79, Standard method of test for determining the dynamic modulus and flow number for asphalt mixtures using the asphalt mixture performance tester (AMPT)
44. Gergesova M, Zupančič B, Saprunov I, Emri I (2011) The closed form t-T-P shifting (CFS) algorithm. *J. Rheol. (N. Y. N. Y)* 55:1–16. <https://doi.org/10.1122/1.3503529>
45. Williams M, Landel RF, Ferry JD (1955) The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids. *J Am Chem Soc* 77:3701–3707
46. Graziani A, Mignini C, Bocci E, Bocci M (2020) Complex modulus testing and rheological modeling of cold-recycled mixtures. *J Test Eval* 48:20180905. <https://doi.org/10.1520/JTE20180905>
47. Ashmawy A, Salgado R, Guha S, Drnevich V (1995) Soil damping and its use in dynamic analyses, In: Third Int. Conf. Recent Adv. Geotech. Earthq. Eng. Soil Dynamics 1-Static Dyn. Eng. Soil Parameters Const. Relations Soils
48. Chen X, Huang Y, Chen C, Lu J, Fan X (2017) Experimental study and analytical modeling on hysteresis behavior of plain concrete in uniaxial cyclic tension. *Int J Fatigue* 96:261–269. <https://doi.org/10.1016/j.ijfatigue.2016.12.002>
49. Olard F, Di Benedetto H (2003) General “2S2P1D” model and relation between the linear viscoelastic behaviours of bituminous binders and mixes. *Road Mater Pavement Des* 4:185–224. <https://doi.org/10.1080/14680629.2003.9689946>
50. Jaczewski M, Szydłowski C, Dołżycki B (2023) Complex modulus of cement bitumen treated material mixture (28 days of curing at 20C), [dataset]. Gdańsk University of Technology, mostwiedzy.pl <https://doi.org/10.34808/7zxz-vw46>
51. Ferrotti G, Grilli A, Mignini C, Graziani A (2020) Comparing the field and laboratory curing behaviour of cold recycled asphalt mixtures for binder courses. *Materials (Basel)* 13:4697. <https://doi.org/10.3390/ma13214697>
52. Buczyński P, Iwański M (2018) Complex modulus change within the linear viscoelastic region of the mineral-cement mixture with foamed bitumen. *Constr Build Mater* 172:52–62. <https://doi.org/10.1016/j.conbuildmat.2018.03.214>
53. Pronk AC (2005) The Huet-Sayegh model: a simple and excellent rheological model for master curves of asphaltic mixes, In: *Asph. Concr.*, American Society of Civil Engineers, Reston, VA pp 73–82. [https://doi.org/10.1061/40825\(185\)8](https://doi.org/10.1061/40825(185)8)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.