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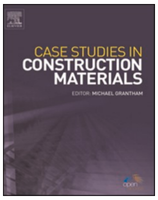

Short communication

Stiffness of cold-recycled mixtures under variable deformation conditions in the IT-CY test

Mariusz Jaczewski [*], Cezary Szydłowski, Bohdan Dołżycki

Gdańsk University of Technology, Faculty of Civil and Environmental Engineering and EkoTech Center Narutowicza Street 11/12 Gdańsk, PL 80-233, Poland

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ABSTRACT

Stiffness modulus belongs to the most important properties describing the cold-recycled mixtures (CRM) in terms of their usability in road pavement structures. Previous research proved that this property is strongly dependent on the scheme and conditions of the test (temperature and time of loading) and the time that has passed since the compaction of the specimen or pavement layer. It is a result of the influence of two different types of bonds – hydraulic bonds from cement and bituminous bonds from bituminous emulsion or foamed bitumen. Research presented in this paper showed that the target horizontal deformation values selected during the stiffness modulus test have a strong impact on the obtained results as well. In this paper the popular Indirect Tensile Stiffness Modulus (ITSM) test on cylindrical specimen (IT-CY scheme) was used to show the dependence of the stiffness modulus values on the selected target horizontal deformation level. Research was conducted on four different CRM mixtures and three reference materials. The research proved that even for a narrow deformation range the CRMs do not present linear viscoelastic behavior and display very high effort of material even for typical test conditions. In consequence, they are very prone to failure. Research also proved that CRM mixtures present different rheological behavior than cement concrete or asphalt concrete, and more attention should be given to establishing proper test conditions. Based on the research, it was determined that the recommended target horizontal deformation in IT-CY test of CRM should be reduced to 3 μm.

1. Introduction

1.1. Background

Cold recycled mixtures (CRM) produced using bituminous emulsion and cement belong to the two main cold recycling technologies used commonly in Poland [1,2]. By improving the grading curve of recycled asphalt pavement (RAP) and adding binding agents (cement or other hydraulic binder and bituminous emulsion or foamed bitumen) it is possible to obtain base layer with high bearing capacity. However, since two different binders with different mechanical and rheological properties are added, the final CRM displays relatively complex properties, which are dependent on many factors. Numerous research works [3–8] proved that CRM presents dual behavior. Due to the addition of bitumen, CRM exhibits viscoelastic behavior with dependence of stiffness modulus on temperature

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[*] Corresponding author
E-mail address: mariusz.jaczewski@pg.edu.pl (M. Jaczewski).

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and time of loading; due to the addition of hydraulic binder, after compaction it exhibits an increase in stiffness modulus in time, with pattern identical to that observed for typical cement concrete. The high similarity of CRM to hot mix asphalt (HMA) results in usage of identical or similar test methods, without changes to the parameters of the test. However, it should be noted that addition of cement significantly alters the overall behavior of the mixture – it becomes more brittle, with lower value of indirect tensile strength in comparison to classical HMA. Additionally, the material becomes more elastic with time, and its stiffness modulus becomes less temperature-dependent, due to the hydraulic bonds, which develop in the mixture as cement hydration progresses. In this aspect CRMs are similar to other cement-treated materials [4].

One of the commonly used test methods for assessing the stiffness modulus of CRM and typical HMA mixtures is the indirect tensile modulus test (IT-CY according to the EN 12697-26 standard). The typical conditions of the test are similar for both types of mixes. The only difference is the test temperature stated by respective requirements. As stated in the Polish regulations for designing of CRM [9], stiffness modulus is used for validation of the design of mixture composition. The test should be conducted in IT-CY mode using the following settings: rise-time of 124 ± 4 ms, cycle time of 3 s, target horizontal deformation of 5 μm, 10 conditioning cycles, 5 test cycles. In the EN 12697-26 standard it is stated that the amplitude of the load shall be such that no damage will be generated during the test. The strain level of 50×10^{-6} m/m should not be exceeded to prevent fatigue damage in the case of most HMA mixtures at the temperature of 10 °C. Therefore, in the case of cylindrical specimens with the diameter of 100 mm, horizontal deformation of 5 μm should not be exceeded. The maximum horizontal deformation changes recommended for other test temperatures are presented in Fig. 1. At the test temperature of 10 °C, the peak load value should be adjusted to achieve the target peak transient horizontal deformation of 0.005 % of the specimen diameter.

The Polish guidelines [9] specify the test temperature of CRM as +5 °C and Poisson ratio as 0.3. Specimens should be tested 7 and 28 days after compaction. These are typical test periods for cement-bound mixtures. In the case of HMA it is stated that prior to testing the specimens shall be stored on a flat surface at a temperature no greater than 20 °C for a period of 14–42 days from the time of their compaction. It is also stated that storage time influences the mechanical properties of the specimen. Phenomena which affect the mechanical properties in the case of HMA – steric hardening and aging of the bitumen – have marginal effect in the case of CRM. Other countries (e.g. Czechia or Italy) also adapt their test conditions for CRM based on the requirements for asphalt concretes [10,11]. In the case of HMA, the EN 12697-26 standard states that the recommended range of test temperatures should cover the extremes of the actual full-scale climatic conditions. For determination of the stiffness modulus without determining a master curve, tests at one equivalent temperature are most commonly used. In Polish climatic conditions, the equivalent temperature is +13 °C [12].

Recent research conducted by Jaczewski et al. [13] and Dołżycki et al. [14] showed that the values of stiffness modulus and phase angles determined in cyclic compression test for CRM are strongly dependent on the target strain value. Moreover, contrary to the common assumptions, CRM does not present clear linear viscoelastic performance similar to bitumen or HMA. Every change in the target strain adopted in the test causes a change in the determined stiffness modulus and phase angle. Due to such behavior, the settings of the cyclic compression test performed on CRM were changed [15]. The new suggested values of typical target strains were reduced from the range of 75–125 μstrain (as for HMA) to the range of 30–50 μstrain.

Introduction of such changes to one of the common stiffness modulus tests gives rise to doubts regarding settings used in an even more popular test method – the IT-CY test, which is the basic test performed during CRM design in many countries. Nevertheless, currently there are no broadly accepted test conditions for CRM testing. Typical values assumed in the literature in the case of tests on cylindrical specimens with 100 mm diameter are in the range of 2 μm to 7 μm [16–21]; sometimes the values vary even in a single country. It is visible that in the recent research works [15,16] the target deformation level in the test was changed to lower values.

Another important issue is the need to validate whether the conditions, especially the stress levels necessary to achieve the target horizontal deformation in the test, do not exceed the reasonable strength level of the material. There are no commonly accepted levels of stress (expressed in relation to mixture strength) for which it can be declared that the mixture will remain in linear viscoelastic state and no damage will appear on the specimen during the test. This level can be assumed on the basis of the creep tests, such as the Tensile Creep Test described in the EN 12697-46 standard. For the temperature of + 5 °C, the applied initial deformation should be chosen so

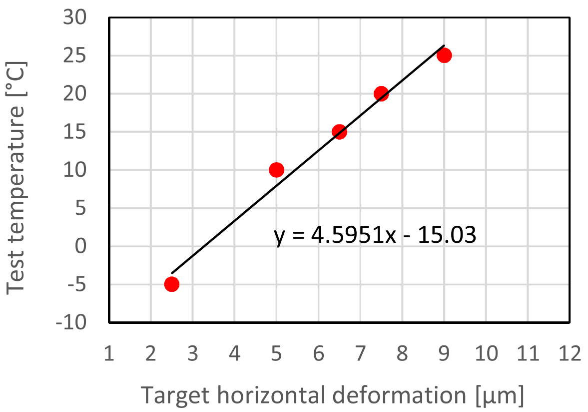


Fig. 1. Relation between target horizontal deformation and test temperature, as recommended in EN 12697-26.

that it will cause stress corresponding to 10 % of the tensile strength. For lower temperatures and more elastic state of the HMA the recommended percentage of tensile strength is higher, and achieves values of 50 %. As for IT-CY test, there are no such recommendations.

1.2. Objectives

The main purpose of the paper is to analyze the changes in stiffness modulus of CRM tested in the IT-CY test depending on the applied target horizontal deformation. CRM mixtures display highly non-linear behavior and, as determined based on the literature review, currently there are no standardized regulations regarding CRM testing in stiffness-related tests (as compared to HMA). Especially, there is a lack of recommendations which would take into consideration the varied bitumen/cement (b/c) ratio, which strongly influences the rheological behavior of the CRM mixtures (either more elastic or viscoelastic behavior). Additionally, the obtained values will be evaluated to verify whether they fit into the linear viscoelastic range, taking into consideration the change in stiffness modulus values and the level of stress in relation to the indirect tensile strength value.

It should be mentioned that the established limit is not universal, as the differences between the CRM mixture compositions used in different countries are considerable, resulting from practical experience gained during the use of such material in the field. In some countries the mixtures have higher content of cement due to harsh frost/thaw conditions, and in other countries cement is used as a filler or as a material for acceleration of emulsion breakage. The limits established in this study are valid only for the mixes tested and conditions in which they were tested. Similarly, if foamed bitumen had been used as one of the binding agents, the results could have been different.

2. Materials and methods

2.1. Materials

The research was conducted on 4 CRM and 3 reference materials. The reference materials included two typical elastic materials (cement concrete and steel calibration ring) and one typical linear viscoelastic material (HMA). To comprehensively analyze the variations in CRM behavior, different combinations of binding agents were evaluated. CRM and cement concrete were compacted (to 98 % compaction ratio) using gyratory compactor as cylindrical specimens of the height of 150 mm and diameter of 100 mm. Each cylindrical specimen was further cut into 3 specimens of the height of 46–47 mm. The HMA specimen was compacted using Marshall compactor with 75 blows for each side to the target height of 63 ± 2 mm. The basic properties of CRM are presented in Table 1 (obtained from the recipe of the tested mixtures). The basic properties of other materials are presented in Table 2. All the tested materials are also presented in Fig. 2. The CRM mixtures were designed according to the Polish requirements [9]. The C4E6 mixture (4 % of Portland cement and 6 % of bituminous emulsion) was selected as the base mixture for the test, due to high homogeneity of the obtained results. Later the tests were conducted on three supplementary mixtures with different combinations of binding agents. All the CRM mixtures tested in this study were assumed to be fully cured (to avoid an increase in stiffness or strength due to hydration of the cement). For the purpose of achieving linearity, test specimens were compacted one year before the tests and stored in controlled laboratory conditions (temperature of approx. 20 °C and humidity of 60–80 %).

Table 1
Properties of cold recycled mixtures.

Property	**Mixture designation (b/c ratio)**			
	C4E6 (0.9) **Base mixture**	**C4E2 (0.3)** **Supplementary**	**C6E2 (0.2)** **Supplementary**	**C6E4 (0.4)** **Supplementary**
Mixture composition				
Virgin aggregate 0/31.5 (% by mass)	18	18	18	18
Virgin aggregate 0/2 (% by mass)	8	8	6	6
RAP aggregate (% by mass)	70	70	70	70
Optimum moisture content (% by mass)	7.0	7.0	7.1	7.1
Water addition (% by mass)	2.8	5.6	5.7	4.3
Bitumen emulsion content C60B10 (% by mass)	6	2	2	4
Cement content CEM I 32.5R (% by mass)	4	4	6	6
Mixture properties (recipe stage)				
Proctor density (Mg/m^3)	2.138	2.138	2.140	2.140
Voids in Marshall specimen (2 × 75 blows) (%)	15.8	13.9	12.8	13.4
Stiffness Modulus (IT-CY, 5 °C, 28 days) (MPa)	6140	8615	Not tested	Not tested
Strength (ITS, 5 °C, 28 days) (MPa)	1.08	1.18	Not tested	Not tested

Table 2
Properties of reference mixtures.

Material	Property	Value
Cement Concrete C8/10 acc. to EN 206	Gradation	0/16
	Cement Content (%)	6.5
	Type of cement	CEM II/B-V 32.5R
	Consistency	S1
	W/C ratio	0.73
	Air content (%)	2
	Tensile strength, 7 days (MPa)	9.6
	Tensile strength, 28 days (MPa)	16.9
Asphalt Concrete AC 22P 35/50 acc. to WT-2 [22], EN 13108-1	Gradation	0/22
	Binder Content (%)	3.9
	Type of binder	35/50
	Air voids content (%)	4.5

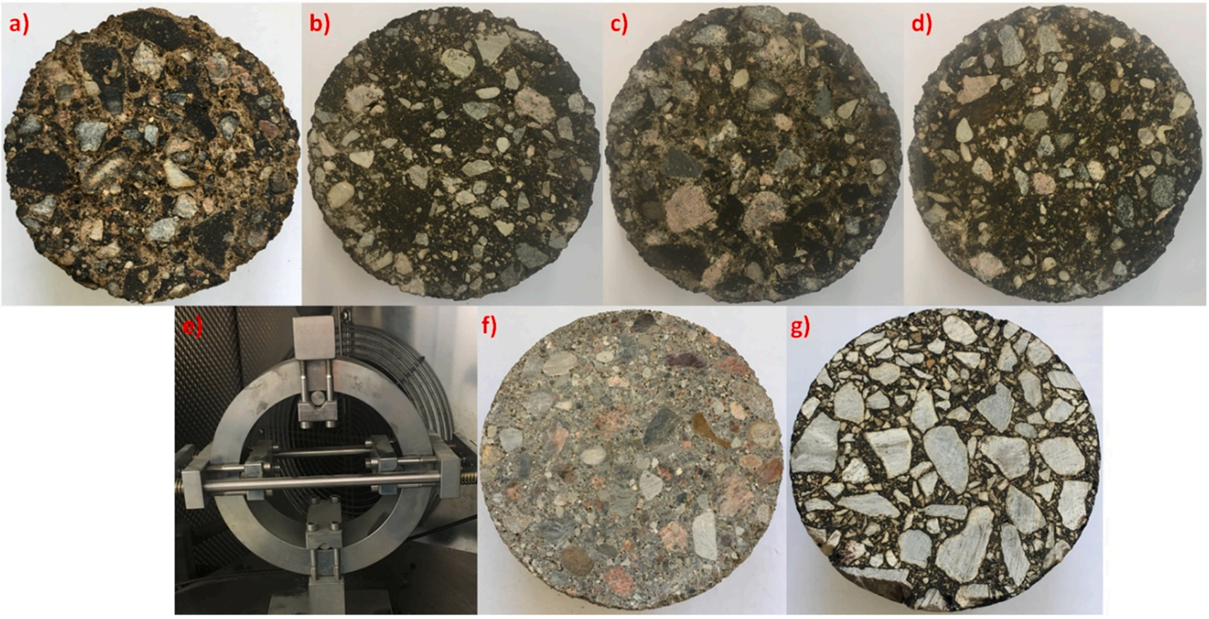


Fig. 2. Specimen used in research: (a) CRM C4E2, (b) CRM C4E6, (c) CRM C6E2, (d) CRM C6E4, (e) steel calibration ring, (f) cement concrete C8/10, (g) asphalt concrete AC 22 P 35/50.

3. Methods

3.1. Indirect tensile stiffness modulus test (IT-CY)

The Indirect Tensile Stiffness Modulus tests in IT-CY scheme were conducted on the basis of the EN 12697-26 standard, Annex C. The tests were conducted on specimens with the diameter of 100 ± 2 mm and height of 40–47 mm. Test temperature of +5 °C was selected. For the purposes of experiments, to avoid scatter of the obtained results, several changes were introduced to the standardized procedure:

- The test was performed only on one diameter, to avoid the influence of specimen position in the frame;
- Whenever the “single-diameter test” is mentioned herein, it is a test conducted on only one diameter (10 conditioning impulses and 5 test impulses);
- The target horizontal deformation was varied in the range from 2 μm up to the maximum of 15 μm.

Stiffness modulus was determined using formula (1).

$$E = \frac{F \times (\nu + 0.27)}{z \times h} \tag{1}$$

where: E- stiffness modulus [MPa], F – maximum applied vertical load [N], h – specimen height [mm], z – amplitude of resilient horizontal deformation obtained during the load cycle [mm], ν – Poisson's ratio [-].

The research plan consisted of three different testing schemes to determine the relationships between the stiffness modulus and the target horizontal deformation. The schemes were chosen to determine whether the change in stiffness modulus is caused by damage or non-linearity of the material. Tests in the following schemes were performed during research:

1) 16 single-diameter tests with the target horizontal deformation of 5 μm – to evaluate the impact of fatigue on stiffness modulus due to high number of specimen loads;
2) Varied number of single-diameter tests with increasing target horizontal deformation, from 2 μm up to specimen damage, with regular checks of specimen condition (consisting in single-diameter tests with target horizontal deformation of 5 μm) – the basic testing scheme;
3) Varied number of single-diameter tests with increasing target horizontal deformation, from 2–7 μm, with reverse scheme of loading from 7 μm to 2 μm in order to verify if any damage has occurred.
4) Varied number of single-diameter tests with decreasing target horizontal deformation, starting from 5 to 8 μm, with regular checks of specimen condition (consisting in single-diameter tests with target horizontal deformation of 5 μm) – supplementary testing scheme for determining the time of specimen damage due to high load.

If specimen showed physical destruction, the test was stopped. Examples of failed specimens are presented in Fig. 3.

3.1.1. Indirect tensile strength (ITS)

The Indirect Tensile Strength (ITS) tests were conducted on the basis of the EN 12697-23 standard. The tests were conducted on specimens that were first tested in the IT-CY tests. The deformation rate equaled 50 mm/min. Test temperature of +5 °C was selected.

The indirect tensile strength (ITS) was calculated as the maximum value of horizontal stress $\sigma_{horizontal,\max}$ using formula (2).

$$\sigma_{horizontal,\max} = ITS = 2F/\pi hD \tag{2}$$

where: F – maximum vertical load [N], h – specimen height [mm], and D – specimen diameter [mm].

4. Results and discussion

4.1. Indirect tensile stiffness modulus (ITSM, IT-CY test)

As presented in the materials and method section, the first test scheme was performed to check whether specimens were subjected to fatigue due to high number of test cycles. For this purpose, two different specimens of CRM C4E6 were tested. The results are presented in Fig. 4.

Figure presents the results of consecutive single-diameter tests: the results of the five test impulses are marked with dots and the mean value is marked with a line. The vertical force used in the test to obtain the target horizontal deformation is also shown. Such detailed results are presented to show the scatter of the results obtained during stiffness modulus test, and the mean value is presented to evaluate whether the specimen starts to show the effect of damage on measurements made during consecutive tests on the same diameter. The results display very high homogeneity, both in terms of stiffness values (single and mean) and the force values needed to introduce the target horizontal deformation. The observed scatter is the result of natural variability of the tested material. For the 240 consecutive test impulses, both specimens did not show any effects of damage.

Schemes 2) and 3) comprised the main part of the research and were conducted in order to evaluate linear behavior of all the tested materials. To verify the suitability of the test method, three materials of known linear characteristics were tested first: elastic materials – steel calibration ring and cement concrete, and viscoelastic material – asphalt concrete for base course. The diameter of steel calibration ring equaled 150 mm, and in the case of cement and asphalt concretes the diameter equaled 100 mm, similar to CRM test specimens. The results of stiffness modulus for the target horizontal deformation that increased from 2 μm to 12 μm are presented in Fig. 5 (as measured values) and Fig. 6 (as standardized values). The target horizontal deformation of 5 μm, typically used for asphalt

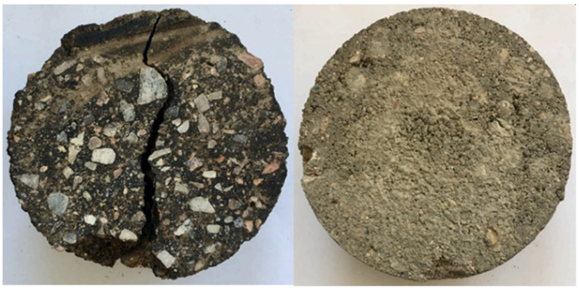


Fig. 3. Specimens after failure in the stiffness modulus test.

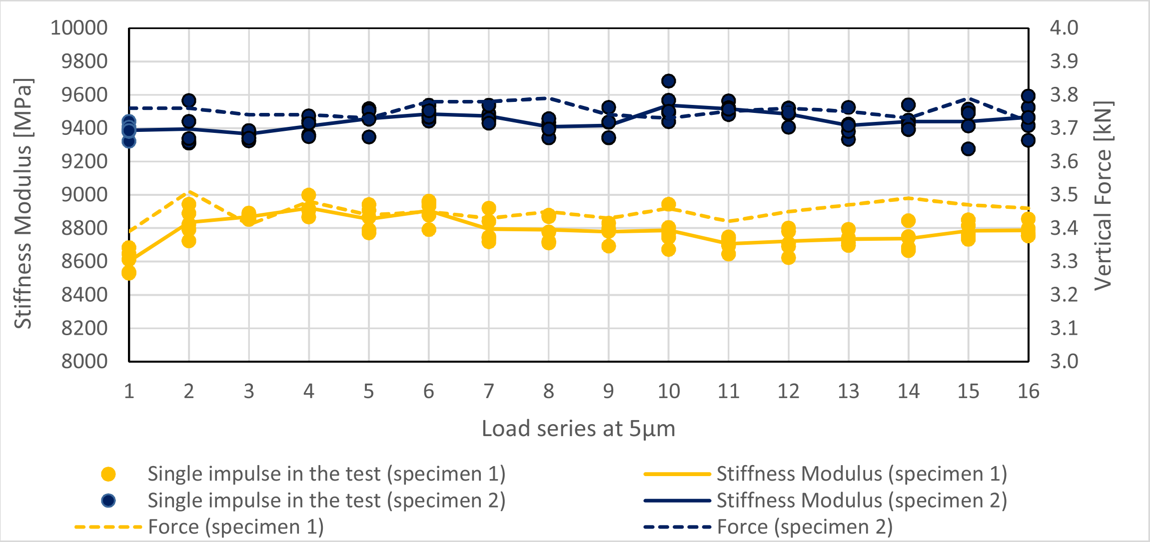


Fig. 4. Results of the load series of two MCE C4E6 specimens with target horizontal deformation of 5 μm.

concrete, was chosen as the standardization level.

In the case of steel calibration ring the determined stiffness values (apart from those for 2 μm) were homogeneous in the entire testing range. The force in the test uniformly increased with increasing target horizontal deformation, while the decrease in stiffness modulus was less than 1 %.

In the case of cement concrete, the changes in stiffness modulus due to the increase in target horizontal deformation were higher, but still remained in the range of ± 7 %. It is slightly outside the 5 % linearity limit assumed for HMA by Airey [23], but the differences resulted from high strength of specimens. Interestingly, moment of damage is clearly visible at the target horizontal deformation of 6–7 μm. It is observable as a rapid decrease in stiffness modulus and disturbance in the linear increase in force with the increase in target horizontal deformation. Such behavior indicates very narrow range of linear elastic behavior and brittle nature of cement concrete. This behavior corresponds very well with the ratio of force vs. strength presented in the earlier paragraph.

In the case of asphalt concrete AC 22 P, linear viscoelastic behavior is clearly visible. The linear behavior is visible for the target horizontal deformations in the range from 3 μm to 6 μm (change of modulus in the range of ± 2.5 % from the initial modulus). For target horizontal deformations greater than 7 μm, the stiffness modulus starts decreasing at a greater rate. At the same time, the rate of the increase in force needed to provide the target horizontal deformation becomes lower.

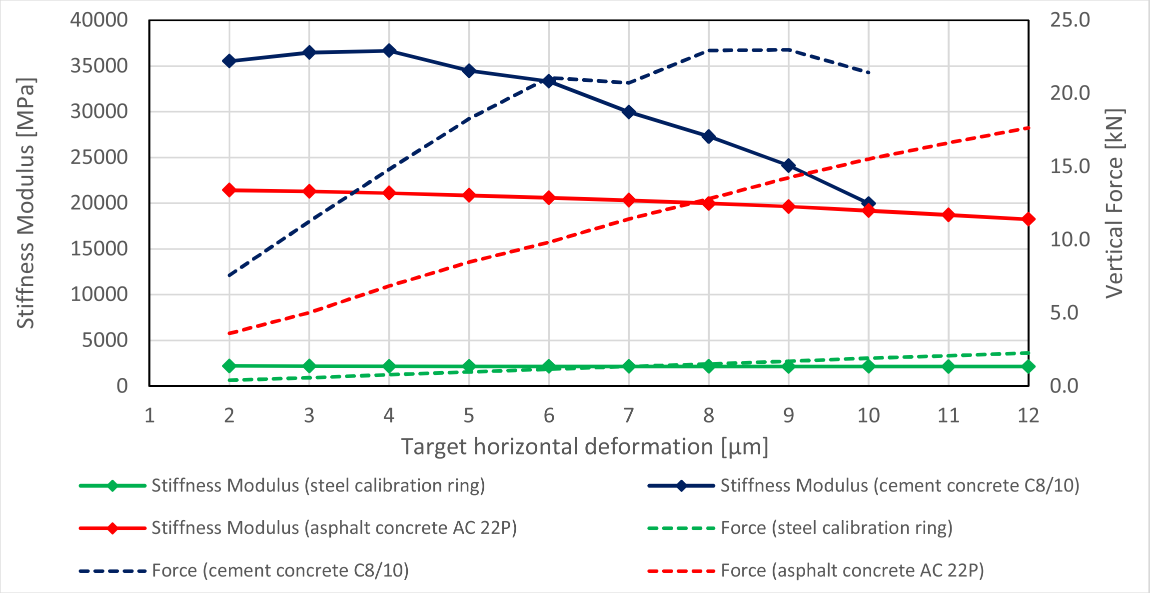


Fig. 5. Results of stiffness modulus test for steel calibration ring, cement concrete C8/10, asphalt concrete AC 22 P.

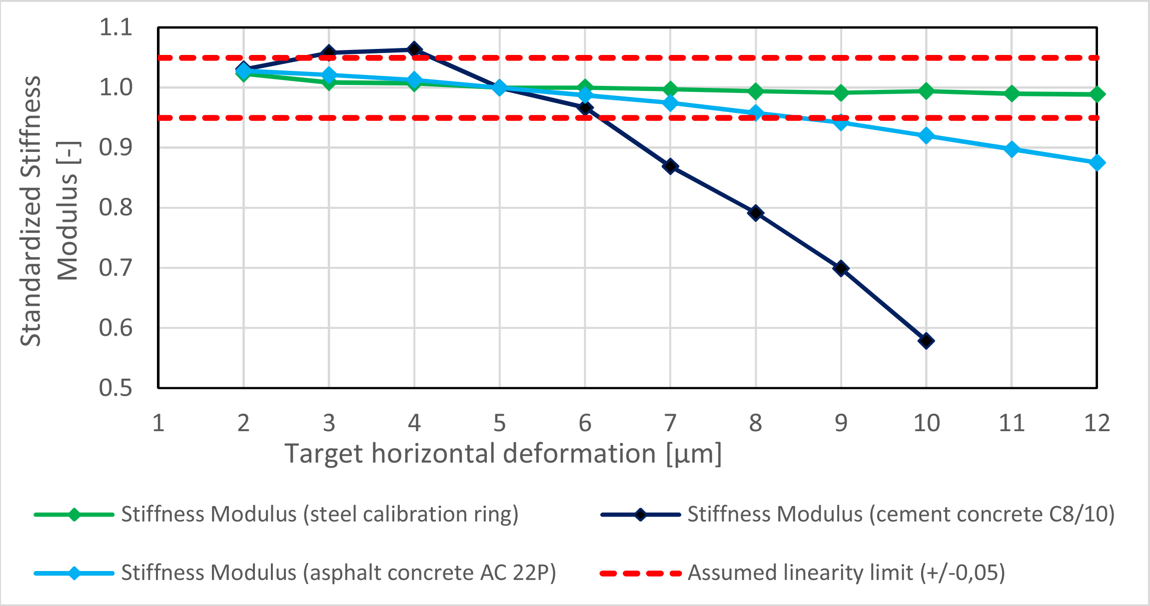
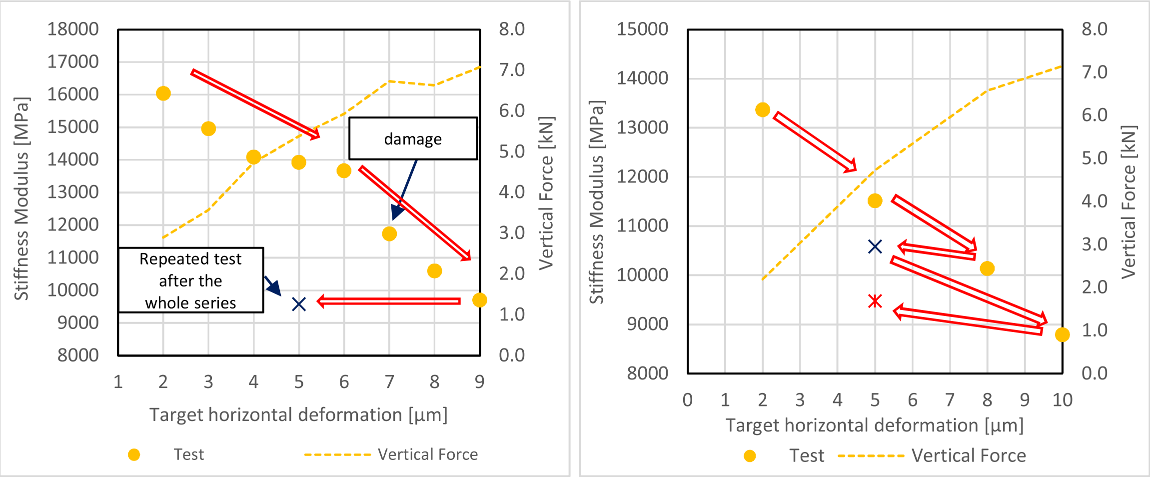


Fig. 6. Standardized results of stiffness modulus test for steel calibration specimen, cement concrete C8/10, asphalt concrete AC 22 P.

In the case of CRM, laboratory test in scheme 2) was performed on mixtures C6E2 and C6E4. Target horizontal deformation was gradually increased from 2 µm to 10 µm with periodical checks of the reference target horizontal deformation of 5 µm. The obtained results are presented in Figs. 7a and 7b. Red arrows show the order of target horizontal deformations used in the test. This approach enabled determination of the limit of target horizontal deformation for which the IT-CY test can be assumed as non-destructive. For the tested mixture C6E2 (Fig. 7a) such limit was determined as 6 µm. At 7 µm the observed distinct decrease in stiffness and lesser increment of force (deviation from the straight line) needed to apply the target horizontal deformation suggest that the specimen was damaged in the test. The character of change in stiffness modulus between 6 µm and 7 µm also indicates brittle damage of the tested specimen. In the case of C6E4 (Fig. 7b) the damage appears between 5 µm and 8 µm and it deepens for higher target horizontal deformation. It is also visible in the decreased stiffness modulus in the additional tests performed at the target horizontal deformation of 5 µm and in the deviation (a decrease in increment) from the straight increase in the force needed in the test. Test scheme 2) allowed the authors to define the test procedure in scheme 3) more precisely.

Mixture C4E6 was subjected to varied load schemes:

- The target horizontal deformation was decreased from one of three values (6, 7 and 8 µm) to 2 µm (Fig. 8a).



(a) (b)

Fig. 7. Results of stiffness modulus test for mixtures: a) CRM C6E2, b) CRM C6E4.

- The target horizontal deformation was increased from 2 μ to 7 μm and later decreased back to 2 μm (Fig. 8b).

Taking into consideration the values of force needed to cause the target horizontal deformation, none of the tested specimens were damaged in the test – the change of force with the decrease in the target horizontal deformation was linear for the entire range (both in unloading and loading schemes). For all the tested specimens of the C4E6 mixture, the following aspects are visible: a) for the target horizontal deformation of 2 μm the obtained stiffness modulus values are the least homogeneous and are significantly higher than for other values of deformation (relatively by more than 5 %); b) for the range of target horizontal deformation from 3 μm to 8 μm the change in stiffness modulus is less than 5 % in comparison to the reference value of 5 μm; c) for the target horizontal deformation range from 3 μm to 6 μm the change in stiffness modulus with the change in target horizontal deformation is almost linear; for values of deformation of 7 μm and 8 μm, flattening of the values is visible; d) for the scheme of loading and consecutive unloading there are visible differences in values of stiffness modulus for the same values of target horizontal deformation (Fig. 8b) without clear evidence of specimen damage (identical force values, no visible physical damage) – it shows that the material load history can have evident impact on further mechanical and rheological behavior.

Standardized results of all the performed laboratory tests are summarized in Fig. 9. It is visible that regardless of the combination of binding agents, the changes in stiffness modulus display the same trend for all specimens, up to the point of specimen damage. The results of tests performed at the target horizontal deformation of 2 μm present very high variability and their relative differences with the results obtained at the current reference value of 5 μm always exceed 5 %. The main difference between the tested specimens is the moment of specimen damage – for specimens with higher amount of cement the character of damage is brittle and similar to cement concrete. The deformation value at which the damage appears is also similar – 6–7 μm. The damage is visible in the rapid decrease in the value of stiffness modulus and in the nonlinearity in the force line in figures. In the case of mixtures with 4 % of cement, the damage of material is not as brittle and evident – it is visible in the decreasing values obtained in the tests performed at the target horizontal deformation of 5 μm, but the decrease is more gradual. Further research will concentrate on mixtures with smaller amount of cement (between 0.5 % and 2 %) and higher amount of bitumen, as their behavior could be much different.

4.2. Indirect tensile strength (ITS)

Results of the ITS test are presented in Fig. 10 (legend). Three specimens were tested for each mixture, and the presented result is the mean value. In order to determine the relationship between the vertical force needed to cause the target horizontal deformation in the IT-CY test and the vertical force needed to fail the material in the indirect tensile strength test, the ratio of the horizontal stress during the stiffness modulus test to the maximum horizontal stress in the strength test was determined. Based on the vertical force *F*, the horizontal stresses $\sigma_{horizontal,ITSM}$ in the IT-CY test were calculated using formula (3)

$$\sigma_{horizontal,ITSM} = 2F/\pi hD \tag{3}$$

where: *F* – vertical load to achieve the target horizontal deformation in ITSM test [N], *h* – specimen height [mm], and *D* – specimen diameter [mm].

The obtained value was divided by $\sigma_{horizontal,\max} = ITS$ determined in the strength test, using formula (4)

$$\%ITS = \frac{\sigma_{horizontal,ITSM}}{\sigma_{horizontal,\max}} \times 100\% \tag{4}$$

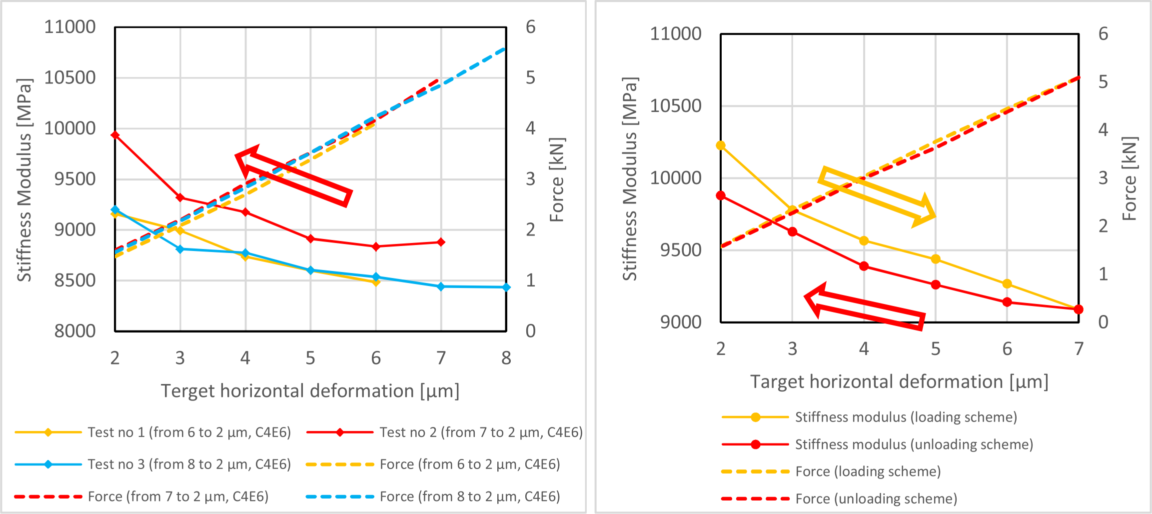
Results are shown in Fig. 10.

On the basis of the conducted research – even for the AC 22 P HMA mixture tested using the conditions stated in the EN 12697-26 standard (target horizontal deformation of 5 μm) – it can be stated that the tests are conducted at a stress level of around 30 % of the indirect tensile strength. In the case of CRM and cement concrete, at a given constant value of target horizontal deformation the stress level also increases with an increase in the b/c (bitumen/cement) ratio. In the case of the most bituminous CRM C4E6 mixture (with b/c ratio of 0.9), stress level is similar to the value obtained for HMA. On the other hand, in the case of the most cementitious CRM C6E2 mixture (with b/c ratio of 0.2), stress level reaches the value of 60 % of the indirect tensile strength. For such a CRM mixture, if one wanted to maintain the same stress level as that observed in HMA, the target horizontal deformation should be set to the value of 3 ± 1 μm.

5. Summary and conclusions

Based on the performed research of indirect tensile strength and indirect tensile stiffness modulus, the following conclusions and recommendations may be formulated:

1. Cold-recycled mixtures present different linearity characteristics than bitumen and asphalt concrete. For a relatively wide range of horizontal deformation (from 3 μm to at least 8 μm) the value of stiffness modulus remains in the range of ± 5 % from modulus measured at reference horizontal deformation; however, there is no evident plateau range as it appears for bitumen and asphalt concrete. Each change of the target horizontal deformation results in a change in stiffness modulus value.
2. In the range of target horizontal deformation from 3 μm to 6 μm the combination of binding agents (cement and bituminous emulsion) does not have impact on the character of stiffness modulus changes. In terms of the standardized values, the changes



(a) (b)

Fig. 8. Results of stiffness modulus test for CRM C4E6: a) unload test, b) load and unload test.

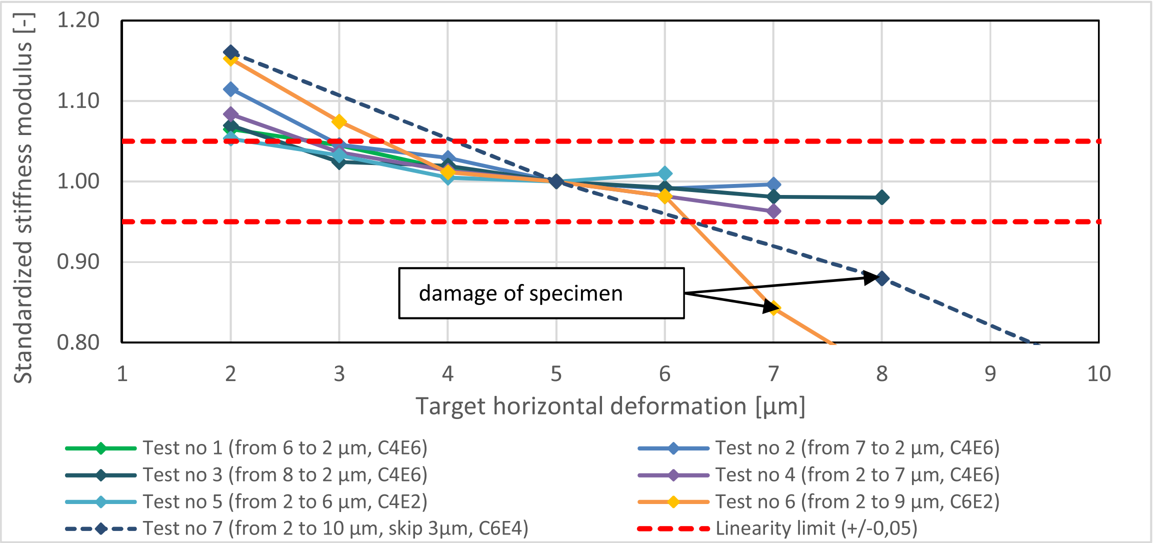


Fig. 9. Results of standardized stiffness modulus test for all tested MCE specimens.

were similar for all the tested mixtures. The difference is visible in the moment and character of specimen damage (brittle for cement-dominated specimen, and more viscous for bitumen-dominated specimen).

3. Depending on the combination of binding agents used in a CRM mixture, the stress level for a selected target horizontal deformation displays very wide variability of values, higher than in the case of HMA. To maintain conditions of the test similar to those of HMA, CRM mixtures should be tested at lower values of target horizontal deformation.
4. The recommended target horizontal deformation in IT-CY test for cold recycled mixtures with higher amount of cement is 3 µm (to avoid high strain of specimen and the consequent damage of specimen). In the case of mixtures with less cement, values of target horizontal deformation could be greater.

The presented research was conducted on specimens whose properties related to cement hydration had already stabilized. Further research will be concentrated on specimens with curing period of 7 and 28 days, as their strength is lower than in the case of current research (even by 40 %).

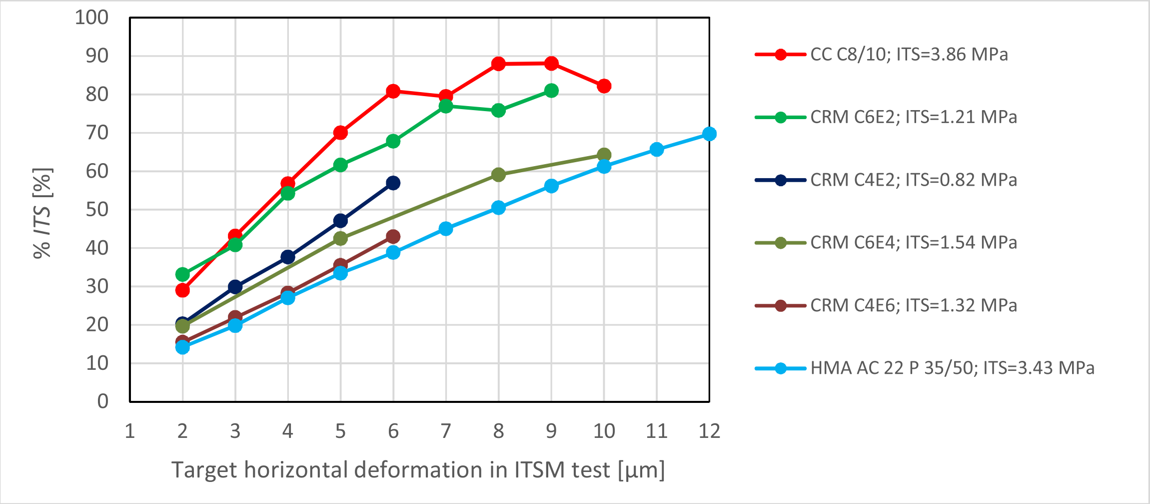


Fig. 10. Results of the ITS test and the ratio between horizontal stress in the ITSM test and the strength test.

CRediT authorship contribution statement

Mariusz Jaczewski: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Supervision, Writing – original draft, Writing – review & editing. **Cezary Szydłowski:** Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Bohdan Dołżycki:** Resources, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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