International Journal of Advance Research in Science and Engineering
Vol. No.4, Special Issue No. (02), September 2015
www.ijarse.com
IJARSE
ISSN 2319 - 8354

COMPLEX MODULUS AND STIFFNESS MODULUS OF COLD RECYCLED MIXES

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ABSTRACT

This article introduces part of the research done within the international project CoRePaSol focused on cold recycled mixes. Standard design for cold recycled asphalt mixes specifies the use of bituminous emulsions, foamed bitumen or hydraulic binders. In Central European countries, often the combination of cement and bituminous binder is used as the most preferable solution because of increased bearing capacity which can be provided by the final structural layer similarly to cement stabilized materials. For this reason it is expected that strength properties as well as stiffness are improved, nevertheless the strain-related behaviour explained usually by stiffness modulus, resilient modulus or complex modulus is not largely assessed. During the experimental study, cold recycled mixtures with bituminous emulsion or foamed bitumen and different cement content were assessed by the repeated indirect tensile stress test (IT-CY) evaluating different curing periods. Since the main objective of this paper is to compare stiffness and dynamic complex modulus, testing has been done for selected mixes using the four-point beam test (4PB-PR). The focus was oriented on possible correlations and comparability of values gained by these two tests characterizing the strain behaviour of the material.

Keywords: Cold Recycled Mix, Complex Modulus, Stiffness Modulus, Strain-Related Behavior

I. INTRODUCTION

Cold recycled asphalt mixes are multiphase systems made from several components. Some of them have complicated internal structure and show increased thermal susceptibility. In fact, reclaimed asphalt pavement (RAP) consists of irregularly shaped aggregate, bituminous binder (usually of unknown origin and range of its ageing) and air voids. Despite the complex structure, the material behavior can be described by application of known theory of viscoelasticity [1, 2, 3, 4].

One of the determining characteristics of bituminous materials, and thus also cold recycled asphalt mixes, is that they have time-dependent behavior, which can be observed especially when deformation (strain) behavior is determined. When these mixes are subjected to a very small loading, it results in a combination of elastic, delayed elastic and viscous behavior. In the range of low temperatures and high loading frequencies, these mixes behave like elastic material in a solid phase with almost fully reversible response. At elevated temperatures and low stress frequency, the behavior of these mixes is similar to viscous liquids with irreversible response. In the range of moderate temperatures and for the whole given frequency range, asphalt mixes exhibit viscoelastic behavior, or more precisely delayed response combined with viscous flow.

Rheological performance-based measurements, which result in characterization tools like complex (master) curves, depict the behavior of the cold recycled mix in the most complex way and provide information about functionalities e.g. between the complex dynamical modulus and stress duration and frequency of loading. The value of the complex modulus and the slope of the master curve can be considered as valuable information for prediction of mentioned functional properties of cold recycled asphalt mixes. This is the reason why it is recommended to perform assessment of pavement structures by applying preferably time-demanding and more difficult but simultaneously more complex performance-based tests. One of the methods, which can be considered for the assessment of deformation behavior, is four point beam bending test (4PB-PR). With this test it is possible to get values of complex dynamic modulus for given temperatures and stress frequencies [5].

Another simple performance-based test which is also suitable for characterization the ability of a mix to resist the effects of loading is determination of the stiffness modulus, usually by the repeated indirect tensile stress test (IT-CY). Both tests are not required for the cold recycled mixes in many countries, where cold recycling is regularly used. Therefore the testing procedures were assumed from relevant European standard for hot asphalt mixes [6].

The main objective of this paper is a detailed investigation of the cold recycled mix behavior by applying these performance-based tests. Findings from these tests were compared to the results of the indirect tensile strength test (ITS), which is usually required for declaring the quality of cold recycled mixes in most countries because of its simplicity. The output of this test is, nevertheless, just one empiric value for a given temperature, frequency and time of specimen curing.

II. MATERIALS

For experimental evaluation of stiffness modulus and dynamic complex modulus different types of cold recycled mixes were designed representing possible options of used binders and their combinations. Table 1 summarizes the material composition of designed cold recycled mixes in terms of used binders with emphasis on mixtures, where either bituminous emulsion or foamed bitumen are used in combination with hydraulic binder (cement).

Within the cold recycled mix assessment it is differentiated which of the two binder types is dominant in the mix. Basic set for the laboratory evaluation consists of four mixtures, namely BCSM-BE (mixture containing 3 % of cement in combination with bituminous emulsion), BSM (mixture containing only bituminous emulsion), BCSM-FB (mix containing 3 % of cement and foamed bitumen) and BSM-FB (mixture containing only foamed bitumen). For these four basic mixtures the complex modulus at various temperatures and frequencies was tested as well. For the determination of the stiffness modulus by IT-CY this set was completed by four other cold recycled mixtures with different content of bituminous and/or hydraulic binder. In fact more cold recycled mix options have been tested including evaluating potential and impact of fly-ash or lime.

Table 1: Evaluated Experimental Mix Designs

Mix	Bituminous emulsion	Foamed bitumen	Cement
	[% by mass]		
BCSM-BE	3.5%	-	3.0%
BCSM-BE (ref 1)	3.5%	-	1.5%
BCSM-BE (ref 2)	3.5%	-	1.0%
BSM-BE	3.5%	-	-
BCSM-BE (ref 3)	2.5%	-	1.0%
BCSM-FB	-	4.5%	3.0%
BCSM-FB (ref 1)	-	4.5%	1.0%
BSM-FB	-	4.5%	-

All designed mixes contained the same type of screened RAP with 0/22 mm grading; cement CEM II / B 32.5 and bituminous emulsion C60B8 were used. For the production of foamed bitumen standard bitumen 70/100 according to EN 12591 was applied. When preparing the foamed bitumen 3.8 % of water was added. The amount was determined in accordance with the procedure which is recommended for cold recycling technology by [7]. Foamed bitumen was injected in the mix at the temperature of 170ºC by means of the Wirtgen WLB10S laboratory equipment. The mix as such was mixed using a twin-shaft compulsory mixing unit Wirtgen WLM 30. The optimal moisture content of the cold recycled mix for the composition specified in the Table 1 was determined according to [8].

III. METHODOLOGY

3.1 Determination of stiffness modulus by the IT-CY method

The bearing capacity of a pavement layer is usually characterized by stiffness or modulus of elasticity. Stiffness modulus is defined as a ratio of material stress and strain and it characterizes its ability to resist the effects of loading. Higher stiffness value means that the material is more resilient to traffic loading than the material with a lower value. It usually means that better resistance to permanent deformations can be expected by the mixes with higher stiffness, on the contrary it is more difficult to find a straight relation to fatigue life.

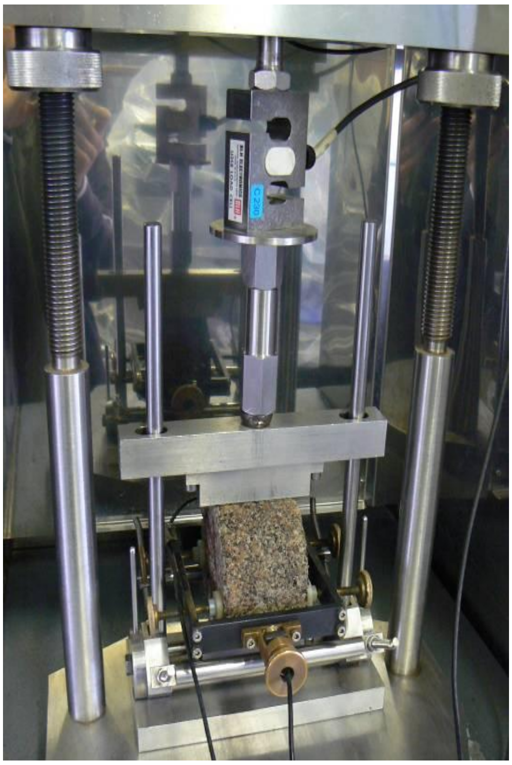


Figure 1: IT-CY test in Nottingham Asphalt Tester

Figure 2: Measuring device 4PB-PR

Stiffness modulus was determined according to repeated indirect tensile stress test (IT-CY) in compliance with [6]. It is a non-destructive performance-based test with good reproducibility and repeatability, during which e.g. the Nottingham Asphalt Tester device (Fig. 1) loads the test specimen by a vertical pulse characterized by the force (P), which causes horizontal deformation (Δ). Effects of the vertical force are transferred to the horizontal - perpendicular - direction by the Poisson ratio (μ), which is dependent on the type of material as well as on the specimen temperature. That is because the ratio of the perpendicular axial deformation or the ratio of orthogonal axial force varies at different temperatures. Stiffness modulus characterizes short term rheological behavior of asphalt mix taking into account deformations lasting only for tens or hundreds of milliseconds.

The cylindrical specimens of 150±1 mm diameter were prepared by putting the cold recycled mix in cylindrical moulds and compacting by the static pressure of 5.0 MPa. For all test specimens basic volumetric properties, as well as the indirect tensile strength according to [9] and stiffness modulus at 15°C according to [6] were determined. Specimens were tested after 7, 14 and 28 days. All cold recycled mixes were stored for one day at 90-100% relative humidity and temperature of (20±2) °C. Further the specimens were stored at laboratory conditions with 40-70 % relative humidity and temperature of (20±2) °C for the rest of their curing time.

3.2 Measurement of complex modulus by the 4PB-PR method

Measurement of complex modulus was performed according to [6]. This standard prescribes that a beam specimen with smooth surface and entire edges is clamped by clips in the test equipment in four points (4PB-PR). All clamps should allow free rotation and shift in the longitudinal direction. The outer clamps should be firm, to defend vertical movements. Inner clamps deduce vertical cyclic loading. The evaluation of the test results is based on Euler-Bernoulli theory.

4PB-PR is a simple test, which can be characterized by a simple mechanistic theory, whereas gained results are important values applicable to the pavement design purposes. Nevertheless such conclusion cannot be fully applied for several reasons which are further summarized. The respective testing is influenced by factors, which introduce to the testing methodology errors or deviations which influence the overall result. These conditions are not attended by the testing methodology in any manner. It is the only question if it is possible to avoid them.

Firstly, the testing beam has to be locked in by the clamps. Such clamping locally constitutes stress and deformation which is introduced to the beam material. This extra stress and deformation can represent fatigue damage or local non-linear effects not included in the calculation of complex modulus.

Secondly, it is not possible to design 4PB-PR apparatus, which would accept friction, allow at the same time free displacement and will not deteriorate during the life-time. Such deformations related to the apparatus might influence the test results.

Thirdly, shear forces act on the test beam in the area between the outer and inner clamps. These forces are causing additional testing beam deformation, whereas such deformations are not taken into account in the used test methodology. Forces related to the shearing strain in this area equal F/2, i.e. the half of applied total loading.

Fourthly, clamps limit the possibility of displacement in cross-section. This leads according to our experience to ineligible deformations of the testing beam in the areas close to the clamps and this is not in accordance with the deflection theory.

Fifth factor influencing the test results is the specimen shape factor, which can be defined as a function of shape and test specimen dimensions. Similarly weight factor should be considered as well. This can be defined as a function of beam weight and apparatus weight, which by its inertial force influences acting force. The magnitude of measurement error or inaccuracy is dependent on the shear modulus and Poisson’s ratio related to the tested material. These two factors are included in the calculation of complex modulus. [10]

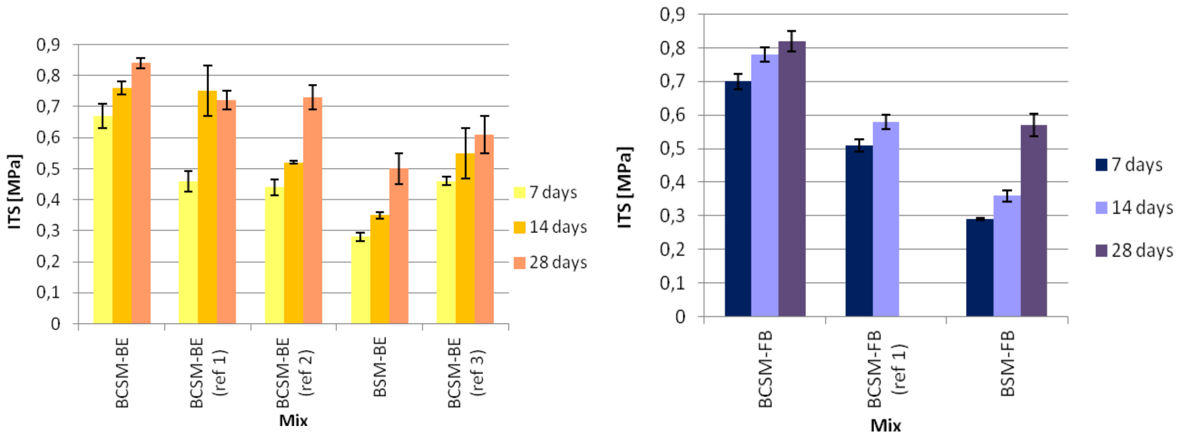
Dynamic complex modulus was determined by the 4PB-PR test method (Fig. 2) in the temperature range from -20 to +27 ° C and frequency from 0.1 to 40 Hz by the controlled deformation of 50 microstrain. These frequencies correspond to the real pavement loading caused by vehicles passing with different speed in the aforesaid temperature range.

Testing slabs were produced by segment compactor and after their curing as specified further the slabs were cut to required shape of beam specimens according to [6]. Respective curing of specimens (based on the CoRePaSol project recommendations) was as follows:

- Cold recycled mixes stabilized by cement and bituminous emulsion or foamed bitumen were firstly stored two days at 90-100% relative humidity and temperature of (20±2) °C. Further the test slabs were stored in dust free area of the laboratory at 40-70 % relative humidity for additional 26 days at the same temperature.
- Cold recycled mixes stabilized by bituminous emulsion or foamed bitumen were stored for 1 day at 90-100% humidity and temperature of (20±2) °C. Further the test slabs were conditioned at (50±2) °C in a climatic chamber for additional 4 days. The test specimens were then stored at 40-70 % humidity and the temperature of (20±2) °C for 14 days after this accelerated curing.

IV. RESULTS FOR STIFFNESS AND ITS TESTING OF COLD RECYCLED MIXES

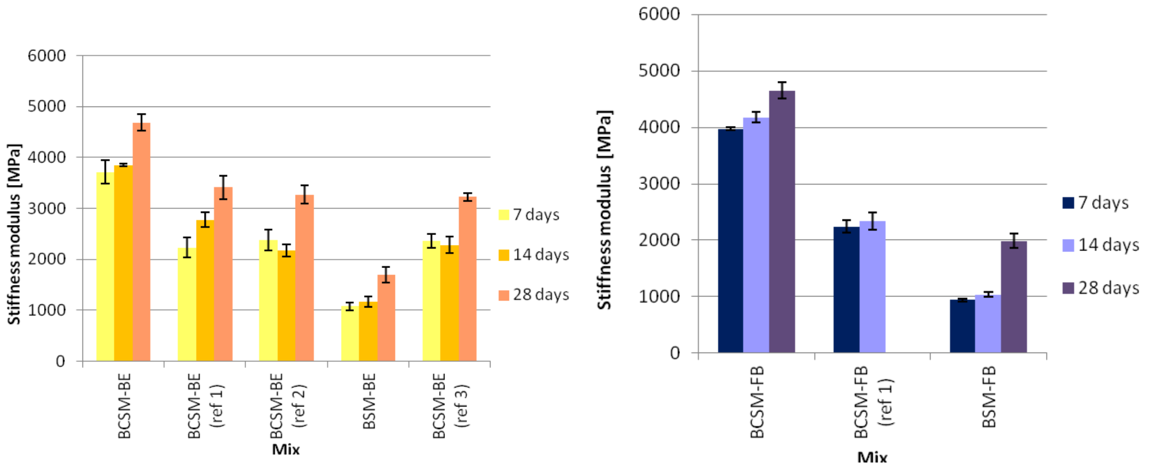
Fig. 3 and 4 show successive increase in both determined characteristics during the first 28 days of test specimens curing. At the same time the extent of characteristic increment in relation to the added hydraulic binder is illustrated.



a) mixes with bituminous emulsion b) mixes with foamed bitumen

Figure 3: Indirect tensile strength of all tested cold recycled mixes

In general it is possible to state, that time-dependent increase of stiffness modulus does very well correspond with indirect tensile strength values. From the point of view of both characteristics it is nevertheless possible to observe a difference if mixes with diverse content of cement are compared.



a) mixes with bituminous emulsion **b) mixes with foamed bitumen**

Figure 4: Stiffness modulus of all tested cold recycled mixes

Table 2: Time influence on ITS and stiffness modulus values

	Indirect tensile strength [MPa]					
	BSM-BE		BSCM-BE (ref2)		BSCM-BE	
7 days	0.28	100%	0.44	100%	0.67	100%
14 days	0.35	25%	0.52	18%	0.76	13%
28 days	0.50	79%	0.73	66%	0.84	25%
	BSM-FB		BCSM-FB (ref 1)		BCSM-FB	
7 days	0.29	100%	0.51	100%	0.70	100%
14 days	0.36	24%	0.58	14%	0.78	11%
28 days	0.57	97%	-	-	0.82	17%
	Stiffness modulus [MPa]					
	BSM-BE		BSCM-BE (ref2)		BSCM-BE	
7 days	1076	100%	2380	100%	3717	100%
14 days	1164	8%	2177	-9%	3852	4%
28 days	1695	58%	3274	38%	4687	26%
	BSM-FB		BCSM-FB (ref 1)		BCSM-FB	
7 days	941	100%	2240	100%	3971	100%
14 days	1036	10%	2331	4%	4175	5%
28 days	1988	111%	-	-	4652	17%

As can be induced from the Table 2 increase of both characteristics is always faster for mixes with higher cement content. The table summarizes selected values of ITS and stiffness for mixes with same bituminous binder content and 0 %, 1 % and 3 % cement. If comparing the assessed curing period between 7 and 28 days it can be stated that for mixes with higher content of hydraulic binders faster increase in strength properties is visible within the first 7 days. For the rest of the evaluated curing period the strength increase is rather slow. On the contrary for mixes containing only bituminous binder a very slow strength enhancement can be observed and even between the 14 and 28 days of curing there is still significant increase of the strength values.

From the presented stiffness and ITS results following conclusions can be made. There is an important difference in values determined after 7 days specimens curing for cold recycled mixes with cement and without cement. This difference then gradually decreases as can be seen in Table 3. Further, it is possible to show, that the use of cement has more positive influence on stiffness values than on indirect tensile strength values. Such finding does very well correlate with values gained also for other assessments done within the project CoRePaSol.

Table 3. Influence of cement content on ITS and stiffness

	7 days		14 days		28 days	
Indirect tensile strength [MPa]						
BSM-BE	0.28	100%	0.35	100%	0.50	100%
BSCM-BE (ref 2)	0.44	57%	0.52	49%	0.73	46%
BSCM-BE	0.67	139%	0.76	117%	0.84	68%
BSM-FB	0.29	100%	0.36	100%	0.57	100%
BCSM-FB (ref 1)	0.51	76%	0.58	61%	-	-
BCSM-FB	0.70	141%	0.78	117%	0.82	44%
Stiffness modulus [MPa]						
BSM-BE	1076	100%	1164	100%	1695	100%
BSCM-BE (ref 2)	2380	121%	2177	87%	3274	93%
BSCM-BE	3717	245%	3852	231%	4687	177%
BSM-FB	941	100%	1036	100%	1988	100%
BCSM-FB (ref 1)	2240	138%	2331	125%	-	-
BCSM-FB	3971	322%	4175	303%	4652	134%

V. RESULTS FOR 4PB-PR TESTING OF COLD RECYCLED MIXES

Results of dynamic resilient modulus determined by dynamic loading using 4PB-PR test method are summarized in the Table 4. The shown values are always determined as an average from last 10 measured values (complex dynamic modulus, loss angle) at different temperatures and for different frequencies. These results were used for decomposing the complex modulus to its real and imaginary part. These decomposed values are necessary, because they are used as input data in IRIS Rheo-Hub software. This calculation software (or any similar available on the market) allows successively to calculate and adjust the so called master curves.

The master curves were designed by using time-temperature superposition principle with relevant shift in horizontal and vertical plane. Shift factors were used to determine the temperature dependence of rheological behavior and extension of time-frequency range at given reference temperature.

Table 4. Dynamic complex modulus and phase angle values (4PB-PR test method)

Testing temp. (ºC)	Frequency (Hz)	BCSM-BE		BCSM-FB		BSM-BE		BSM-FB	
		E* (MPa)	δ (-)	E* (MPa)	δ (-)	E* (MPa)	δ (-)	E* (MPa)	Δ (-)
0	50	5 930	0.00	6 459	0.00	6 211	0.00	7 543	0.00
	30	5 482	0.00	6 162	0.03	5 619	0.52	7 509	0.00
	20	5 100	1.05	5 782	0.59	5 137	3.74	7 050	0.92
	10	4 745	4.65	5 482	3.45	4 761	7.00	6 570	4.79
	8	4 589	5.45	5 385	4.53	4 651	8.25	6 453	5.54
	5	4 472	7.00	5 149	5.80	4 396	9.82	6 095	7.25
	2	4 195	8.29	4 941	7.57	3 972	12.33	5 599	9.20
	1	4 012	9.24	4 702	8.39	3 627	13.83	5 249	10.82
	0.5	3 721	9.37	4 461	9.09	3 309	14.23	4 833	11.52
10	50	4 620	0.03	5 669	0.10	4 495	5.80	5 222	0.15
	30	4 210	3.03	5 203	1.22	3 960	5.78	4 723	5.43
	20	3 729	4.08	4 582	3.87	3 503	8.95	4 156	7.35
	10	3 482	7.13	4 152	6.76	3 164	12.24	3 651	11.97
	8	3 403	8.12	4 066	7.63	3 053	13.05	3 565	12.96
	5	3 243	9.38	3 851	9.29	2 855	14.88	3 261	14.90
	2	3 314	11.32	3 551	11.23	2 515	16.98	2 794	17.20
	1	2 844	11.56	3 247	12.28	2 298	18.21	2 438	19.10
	0.5	2 614	11.87	2 842	12.82	1 981	18.81	2 037	20.91
20	50	3 870	0.00	2 852	12.69	2 829	6.44	3 892	5.20
	30	3 441	4.20	2 411	14.71	2 605	11.95	3 416	9.93
	20	2 955	4.85	2 039	26.11	1 983	14.86	2 827	13.29
	10	2 631	8.92	1 946	14.57	1 693	19.41	2 432	17.10
	8	2 550	10.10	1 955	15.97	1 637	20.28	2 343	18.06
	5	2 413	11.42	2 421	13.33	1 500	22.37	2 157	20.18
	2	2 178	13.47	2 174	13.58	1 239	24.15	1 780	22.87
	1	2 001	13.95	2 181	16.28	1 062	25.18	1 565	23.78
	0.5	1 704	12.89	2 078	16.60	809	23.67	1 241	24.40
30	50	3 053	6.66	3 168	3.61	1 925	17.01	2 398	8.68
	30	2 701	9.26	2 732	6.87	1 566	20.79	2 107	16.65
	20	2 115	8.88	2 207	9.27	1 120	22.72	1 537	19.33
	10	1 872	12.08	1 967	14.35	910	23.81	1 260	23.35
	8	1 852	12.23	1 889	15.31	879	24.43	1 211	24.67
	5	1 769	13.55	1 784	16.51	820	25.55	1 085	26.39
	2	1 554	15.26	1 524	18.19	654	25.36	859	27.31

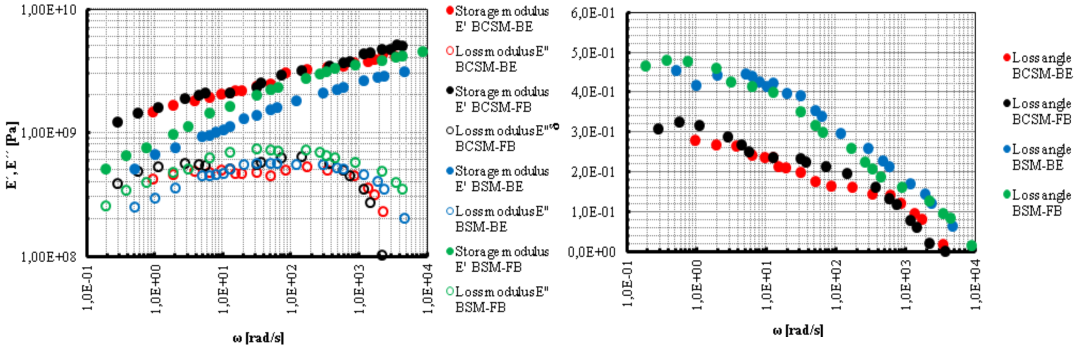
1	1 455	15.31	1 367	18.58	581	23.97	735	27.58
0.5	1 271	15.96	1 150	17.67	452	26.01	568	26.74

Table 5. Parameters of horizontal and vertical shift within the time-temperature superposition

Mix		BCSM-BE	BCSM-FB	BSM-BE	BSM-FB
$_{ref}$	[°C]	20			
T_{min}	[°C]	0			
T_{max}	[°C]	30			
Fit of horizontal shift aT [K]	C1	100	100	100	100
	C2	1458.3	1215.5	1249.9	1016.7
Fit of vertical shift bT [-]	a_0	1.07	1.01	9.89E-01	9.94E-01
	a_1	1.1E-02	1.00E-02	2.52E-02	6.5E-03
	a_2	-2.4E-05	3.50E-05	2.96E-04	-5.7E-04

For the description of the shift factor in horizontal plane Williams-Landel-Ferry equation with C1 and C2 parameters was used. For the description of the shift in vertical plane a polynomial equation is preferred [2, 11]. The parameters of the vertical and horizontal shift are listed in the Table 5. All calculations were made in the IRIS Rheo-Hub software tool. The reference temperature for master curve determination was set at 20 °C.

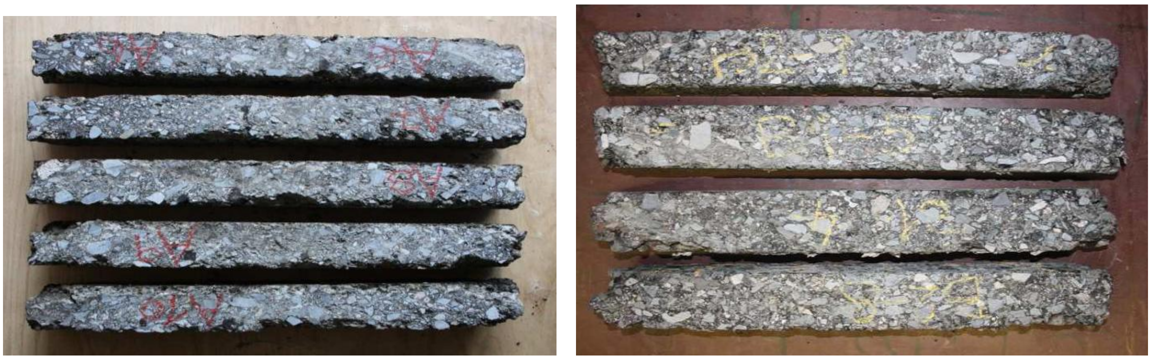
As generally known, temperature and time have dramatic influence on viscoelastic response of bituminous binders and asphalt mixes. This is the reason why viscoelastic properties are usually determined in wide spectrum of temperatures and/or stress levels. Behavior of an asphalt mix or bitumen depends on the temperature as well as frequency and duration of repeated loading. If these variables are in a range, where the material behavior is defined as viscoelastic and it is possible to characterize the material as temperature-rheologically „simple“, then it is possible to express the effect of time (frequency) and temperature by time-temperature superposition. Material characteristics given as a time-dependent function or frequency-dependent function (such as results of dynamic testing, or material spectrum measured at different temperatures), can be shifted along axes for creating various master curves [2]. The master curves of the researched cold recycled asphalt mixes with different binders (bitumen, cement, or their combination) are given in Fig. 5.



a) storage modulus and Loss modulus **b) loss angle**

Figure 5: Master curves of cold recycled mixes

When analyzing the master curves from the right to the left, it is evident, that in the field of the lowest tested temperatures and highest frequencies, the material has tendency to behave almost elastically. The transition from viscoelastic to elastic behavior is evident from the last determined values in the decreasing imaginary part of the master curves. The real part of the master curve is increasing proportionally to the raising frequency. At the same time the first derivation is decreasing and is reaching almost zero level for the last couple of values. This phenomenon correlates very well with the transition of the material properties to the elastic area, where equilibrium modulus is reached [2, 12]. From the loss angle change it is clear, that cold recycled asphalt mixes are thermo-mechanically sensitive materials [3]. Comparing assessed mixes in terms of used binders, the influence of cement is evident in enhanced elastic properties at high temperatures and low frequencies. At the same time thermal susceptibility is decreased if cement is used. This fact is evident from comparing the elastic modulus curves, where the slope of elastic curve is more gradual for mixes with cement (less difference between the lowest and the highest determined modulus).



a) mix BSCM-BE **b) mix BSCM-FB**

Figure 6: Damaged beam specimens before testing – mixes with cement

a) mix BSM-BE **b) mix BSM-FB**

Figure 7: Damaged beam specimens before testing – mixes without cement

The difference between foamed bitumen and bituminous emulsion is apparent especially in the elastic modulus master curve. The variation might be partly caused also by different residual binder content. The binder itself will not play a role since for foamed bitumen and the bituminous emulsion 70/100 bitumen was used. The applicability of the test for cold recycled mix assessment seems however to be complex, because the correct preparation of unpaired beam specimens came repeatedly up with certain problems. The clear reason is the brittle character of these stabilized materials. This leads to low reproducibility of the results as well.

First problem related to cold recycled asphalt mixes and 4PB-PR testing appeared already during demoulding of the test slabs. Because the material is more brittle, it is necessary to secure sufficient separation between the steel bottom plate of the mould and the compacted material. Even if the separation is made properly, sometimes the whole slab can be broken during demoulding. Another problem occurred when beam specimens were cut from the slabs to get the necessary test specimens. During the cutting the material has tendency to brake off edges of the beams (Fig. 6 and 7). This finding is not unique. The same was found out in the past within several studies and master student projects at the CTU in Prague, as well as during fatigue experiments on cold recycled asphalt mixes made e.g. at the University College in Dublin.

To compare the methodology of stiffness modulus testing by IT-CY and the dynamic modulus gained by 4PB-PR test, selected values of IT-CY stiffness modulus are shown in the Table 6. The comparison itself is a challenging and ambiguous because of different method of test specimen manufacturing (segment compactor for 4PB-PR vs. hydraulic press for IT-CY) as well as the principles of loading. However, the results show some trend or as the case may be it is possible to make some assumptions on the gained findings. Stiffness of cold recycled mixes with cement correlate more with the results of complex dynamic modulus at higher frequencies of loading (30-50 Hz), while the mixes with only bituminous binders have stiffness according to IT-CY more similar to lower frequencies (2-5 Hz) of 4PB-PR testing. The given comparison is just approximate due to the fact, that complex dynamic modulus were determined at temperatures of 10 °C and 20 °C, while the stiffness test is according to the standard procedure in the Czech Republic done at 15 °C.

Table 6. Stiffness modulus determined by IT-CY method

Mix	Stiffness modulus (IT-CY) @ 15ºC (MPa)
BCSM-BE	4 287
BCSM-FB	4 652
BSM-BE	1 745
BSM-FB	2 254

VI. CONCLUSIONS

Results presented mainly for determination of stiffness on cold recycled mixes represent only a small part of a more complex study done within the CoRePaSol project, where also other optional designs of this type of stabilized material were tested and compared, e.g. with various bituminous binders for foam production, with different types of reclaimed materials including recyclable concrete or unbound base layer material. Additionally stiffness values are available even for cold recycled mix options with multiple recycled asphalt, which was laboratory aged, re-crushed and re-used in a new cold recycled mix.

In general it can be stated that stiffness modulus determination by using IT-CY test method is a suitable procedure for cold recycled mix assessment and can be always done in parallel to indirect tensile strength test. This destructive test is so far used more often when characterizing cold recycled mixes. Stiffness determination is required in smaller number of countries using cold recycling techniques. It is therefore possible to recommend use both test methods – IT-CY and ITS test. Results from both these tests complement each other very well.

Additionally stiffness determination has so far better shown the curing time dependency as well. On the other hand, if comparing ITS and stiffness for mix design with increasing cement content, stiffness modulus seems to be less sensitive to cement content in the mix, if comparing results to cold recycled mixes with same RAP but only bituminous binder content. This is valid mainly for results gained after more than 14 days curing when the difference becomes very small.

On the other hand, complex modulus was assessed only by 4PB-PR test procedure. It was known that, in the past, doubts were raised about suitability of the test especially because of test specimen preparation. It was proven by the research study within CoRePaSol project that the test would provide more data and most probably could better explain the behavior of the tested material. Nevertheless, reproducibility of the test seems to be very low mainly influenced by the quality of gained test specimens. Solving initial problems of demoulding 30x40x5 cm test slabs it was then usually very problematic to properly cut test beams. Gained test specimens showed always some damages like loss of aggregate particles or impaired edges, which immediately influence the test results. Despite these facts, it was possible to get data for a selected temperature and frequency interval and even plot master curves. Nevertheless, the variation of measured values is much higher than in case of IT-CY stiffness modulus test.

Simple comparison of IT-CY and 4PB-PR was done to evaluate whether there is any correlation between IT-CY stiffness and complex modules at some frequency, ideally concurrent for all tested cold recycled mix designs. As was discussed in the article, such correlation was not found, only presumptions can be made for cold recycled mixes with or without cement.

From the practical point of view and expectations of the National Road Authorities as defined within the CoRePaSol project, if the 4PB-PR test would be required for cold recycled mix characterization, it could be performed only by a limited number of laboratories requiring suitable test apparatus and expecting more time demanding procedure for test specimen preparation.

VII. ACKNOWLEDGEMENT

This paper is an outcome of the research project “Characterization of Advanced Cold-Recycled Bitumen Stabilized Pavement Solutions (CoRePaSol)” carried out as part of the CEDR Transnational Road Research Programme. The project was funded by the National Road Administrations of Belgium (Flanders), Denmark, Finland, Germany, Ireland, Netherlands, Norway, Sweden and UK.

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