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Report on Durability of cold-recycled mixes: Test procedures for stiffness determination

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CoRePaSol

Characterization of Advanced Cold-Recycled Bitumen Stabilized Pavement Solutions

Report on Durability of cold-recycled mixes: Test procedures for stiffness determination

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Executive summary

Main objective of this report is to summarize assessment and research of stiffness modulus determined according to repeated indirect tensile stress test (IT-CY). In most cases the stiffness modulus values are compared to the values of indirect tensile strength (ITS), which is currently the most commonly used characteristic for proving the quality of a cold recycled mix. The first part of experimental measurements was focused on standard cold recycled mixes, thus mixes whose aggregate skeleton is entirely/almost entirely formed by RAP and which contain either just the bituminous binder (bituminous emulsion or foamed bitumen), or a combination of one of these binders and a hydraulic binder (cement).

Stiffness modulus and in most cases also the indirect tensile strength values were investigated from many points of view, e.g. the effect of different bituminous / hydraulic binder content on these characteristics, time-dependent progress in growth of these characteristics, effect of testing temperature or addition of fines on these characteristics or the effect of voids content on the stiffness modulus value.

Chapter 4 of this report is focused on a detailed analysis of stiffness modulus and indirect tensile strength values of mixes, whose grading curve was partly or completely formed by recycled concrete or recycled gravel/sand. Some mixes containing pulverized (micromilled and activated by means of high speed milling/disintegration) concrete were investigated as well. By all these mixtures the development of stiffness modulus and indirect tensile strength depending on curing time was observed. Another set of tests was performed to evaluate the effect of conditions to which the specimens are subjected during the application of various procedures of moisture susceptibility testing and determination of corresponding ratios. Some parts at the end of this report discuss practical issues related to laboratory testing of cold recycled mixes which affect stiffness modulus determination.

Additional studies focused on the optimum time of specimens conditioning for the testing temperature and discussing the influence of specimen size on resulting stiffness values. Further investigation of the practical issues associated with laboratory testing of the cold recycled mixes which influence stiffness modulus values is included in other separate reports, e.g. report D1.2 which, among other topics, deals with the influence of specimen compaction method on final characteristics of a cold recycled mix (i.e. on the indirect tensile strength and stiffness modulus values) and to the effect of the applied specimen curing method.

Following conclusions can be drawn from the stiffness assessment studies presented in this report:

- In general it can be recommended that if stiffness is determined according to EN 12697-26 by test method IT-CY then for mixes containing at minimum 2 % cement the stiffness after 14 days curing (according to the procedure described e.g. in the Project report D1.1) determined at 15 °C should be at least **3,500 MPa**. Similarly for mixes without cement and bitumen content not exceeding 3 % the stiffness determined after accelerated curing shall be at 15 °C at least **1,000 to 1,500 MPa** (depending on the type of bituminous binder). Comparing use of RAP or recycled

concrete no clear final conclusions can be made. In general it seems that mix design containing RAP has slightly higher stiffness values which might be given also by the activity of the bitumen. On the other hand of higher content of bituminous binder would be used in combination with higher content of cement and the recycled concrete would demonstrate a good grading, such mix can easily reach stiffness >4,000 MPa.

- The stiffness modulus of bitumen stabilized materials as well as of other cold recycled mixtures depends on test conditions like applied test temperature and strain velocity (loading speed). This can be explained by viscoelastic material behavior originating from the reclaimed asphalt material (RA/RAP) as well as from the fresh bituminous binder applied.
- The stiffness evaluation procedure as specified in EN 13286-43 using indirect tensile strength tests can be applied besides test procedures defined in EN 12697-26 for cold recycled materials after some necessary modifications.
  - To allow mechanistic pavement design calculations, the stiffness of the mixture shall be evaluated at varied temperature and loading speed conditions to evaluate the viscoelastic behavior of the mixture.
  - To apply stiffness modulus values during mix design, the test conditions like temperature and loading rate has to be specified in detail in order to allow for comparable test results. This is similar to the approach for indirect tensile strength as assessed e.g. in report D1.2.
- CBR method can be applied as simple evaluation tool for stiffness and/or permanent deformation assessment. Though, the results don't allow for mechanistic pavement design because of non-controlled loading conditions during the test.
- The specimen dimensions have an effect on the stiffness obtained from indirect tensile tests:
  - Specimens of 100 mm diameter cored from the centre of specimens compacted to 150 mm indicate reduced stiffness. This can either be explained by a size effect or by diverse grain interlock at the specimen edges resulting from the boundary to compaction mould.
  - The specimen height has no significant effect on the ITS result. This would enable the preparation of specimens with reduced height which would be advantageous due to improved compactibility in laboratory. At the same time non-destructive tests of stiffness and indirect tensile strength test could be run on same specimens.
- Stiffness tests should be conducted at controlled specimen temperature. The temperature conditioning should be long enough for guaranteeing homogeneous temperature in the specimen. A conditioning time of 4 h is even required for test temperature ≥10 °C.

1 Introduction

The durability of pavement materials highly depends on the construction material long-term mechanical properties. Therefore, laboratory assessment procedures are applied during mix design in order to optimise the pavement performance. However, often these assessed material characteristics only represent the short-term properties of the material. During traffic loading the material is subjected to several distresses that affect its mechanical properties:

- Traffic loading results in fatigue crack initiation and in permanent deformation.
- Initiated cracks will propagate.
- Moisture in form of precipitation (rainfall, dew) or subsoil saturation and its effect on durability.
- Temperature effects (frost/thaw cycles).
- Chemical effects in the pavement material (e. g. long-term ageing).

In order to assure feasible long-term performance of the pavement material, the relevant long-term performance has to be assessed already during mix design in order to avoid pavement failure due to improper long-term performance.

This report summarises experimental campaigns for stiffness evaluation.

2 Stiffness evaluation of pavement materials

The pavement material stiffness is a key parameter determining the ability of the pavement structural layer to bear traffic loads and to spread the loads and related stresses for reducing the load for the pavement layers beyond. In mechanistic or mechanistic-empirical pavement design procedures, usually the material stiffness is applied in the form of elasticity modulus “E”. This is a simplification of the real behaviour of the road material depending on the type of layer, applied binder as well as its content, also plastic and viscous deformations appear.

During mix design the stiffness modulus is evaluated often in order to optimise the pavement material towards high bearing capacity. Therefore, various test procedures are available:

- Stiffness test methods for unbound road layers:
  In order to assess the stiffness of unbound road materials for evaluation of the bearing capacity of an unbound base layer, CBR tests (California Bearing Capacity), according to EN 13286-47 can be applied. In the test the load needed to penetrate a plunger into the laboratory compacted road material is assessed. In several pavement design procedures, the CBR of a substrate is applied in order to calculate the needed thickness of pavement courses above.
- Stiffness test methods for bituminous bound/stabilized road layers (asphalt):
  Asphalt mixture stiffness is measured by various test procedures described in EN 12697-26. Common for these test procedures is that the stiffness tests are applied at various test temperatures and load frequencies or deformation rates in order to assess the time-temperature affected viscoelastic properties of bituminous bound road materials. Besides cyclic test methods where the specimen is loaded by a sinusoidal strain-controlled loading, uniaxial tension test according to EN 12697-26, Annex E, prescribes monotonic deformation-controlled loading with varied deformation (strain) rates.
- Stiffness test methods for hydraulically bound road layers (lean concrete):
  For the assessment of the stiffness of hydraulically bound road materials, EN 13286-43 is applied. By installing additional displacement transducers on a specimen during strength tests, the stiffness of the material is measured.

This study introduces and evaluates the test methods and summarises experimental results obtained on cold recycled materials.

As above referred, for asphalt mixtures, the test procedure for stiffness assessment is specified in EN 12697-26. Several test methods can be applied for the assessment of the materials stiffness. Despite the wide application of these tests, the cyclic loading demands for special laboratory test devices not usually available for standard pavement material laboratories, e.g. 4-point beam test described in a separate project report D2.1_complex modulus. Therefore, the applicability of monotonic tests for the stiffness assessment of cold recycled materials is assessed in a laboratory test program. It is understood as a possible alternative to more common a widely used indirect tensile stress test (IT-CY test method according to EN 12697-26). A methodology for modification of EN 13286-43 indirect tensile stress test procedure is elaborated which allows the assessment of the stiffness modulus parameter by varying temperature and/or loading time.

3 Stiffness assessment of road materials

3.1 *State of the Art*

The stiffness of a pavement material is defined as its ability to spread/distribute the traffic loads over a large area in order to reduce the loading of layers beneath. The load distribution properties of a pavement layer are controlled by two properties:

- Internal angle of friction of unbound road material,
- Bending properties of bound road layers.

Later bonding can have brittle characteristics (for hydraulically bound materials) as well as visco-elastic characteristics (bituminous bound material).

Depending on the content of bituminous and hydraulically binders as well as on the curing, cold recycled materials can show characteristics of all three types. Therefore, several test procedures may be feasible to assess the material stiffness properties.

For typical assessment of unbound pavement material, several empirical pavement design procedures use results of CBR test for estimating the layers bearing capacity. For example, Heukelom and Klomp (1953) found correlation between CBR and layer stiffness (compare equation (1)), where the correlation factor varies between 50 and 200 kg/cm²/CBR, corresponding to 5 to 20 MPa/CBR.

$$E = \{5 \ldots 10 \ldots 20\} \, . \, CBR \qquad (1)$$

Technical standard EN 12697-26 specifies the stiffness evaluation for asphalt mixtures. Due to the viscoelastic material properties, cyclic tests are applied which allows the assessment of the time-temperature-dependent viscoelastic behaviour of the pavement material. These tests are applied in deflection-control mode with low strains applied in order to avoid deterioration of the tested specimen during the test. For the cyclic test methodology special test equipment is necessary, which is not standard so far to most road laboratories providing regularly mix designs for cold recycled materials.

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

The used bituminous binder, that secures the whole bond of the structure together, is highly depended on the temperature since being a viscoelastic material. While at low temperatures the bitumen is almost stiff and brittle, with increasing temperature the material’s stiffness is reduced and its viscous properties predominate resulting in non-recoverable visco-plasticity. Therefore the mechanical properties of all types of asphalt mixtures including the cold recycled mixtures are similarly thermally unstable. That is the reason why the values of stiffness modulus are higher at lower temperature and lower at higher temperature.

3.2 *Test methods applied*

3.2.1 California bearing ratio (CBR) test

In the CBR test method (EN 13286-47); a specimen is compacted according to Proctor Standard test procedure (diameter 150 mm, thickness 125 mm). After conditioning, the specimen is placed into a fresh mould. A steel plunger with a diameter of 50 mm is penetrated into the specimen surface with a strain velocity of 1.27 mm/min). The force needed to maintain the penetration velocity is recorded and – if needed – corrected. The force values measured for a penetration depth of 2.5 mm and 5.0 mm are monitored and compared to the force values obtained for a standard soil (13.2 kN for 2.5 mm; 20.0 kN for 5.0 mm), which are defining the CBR value of 100 %. The ratios between the measured forces and the force of a standard soil are calculated. The higher of both values is the CBR-value describing the materials bearing capacity.

3.2.2 Theoretical principle of stiffness modulus calculation by indirect tensile test

All values of stiffness modulus were determined according to repeated indirect tensile stress test (IT-CY) in compliance with EN 12697-26. The test is based on following principles. Asphalt Tester device loads the test specimen by a vertical pulse characterized by the force (P), which causes horizontal deformation (Δ). Effects of the vertical forces are transferred to the horizontal – perpendicular direction by the Poisson's ratio (μ), which is dependent on the type of material as well as on the specimen temperature. That is because the ratio of perpendicular relative axial deformations or the ratio of orthogonal axial forces varies at different temperatures. The value of stiffness modulus (S) is then calculated from equation 2, where (h) is the thickness of tested specimen.

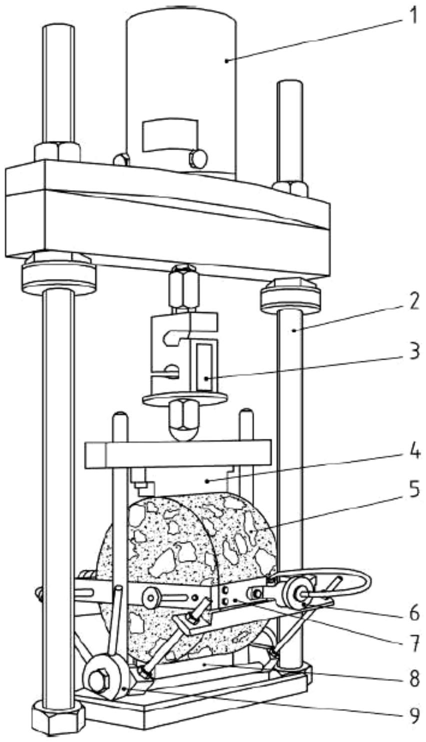
$$S = \frac{P.(\mu + 0{,}273)}{\Delta.\boldsymbol{h}} \tag{2}$$

The force (P) and horizontal deformation (Δ) is measured and the resulting value of stiffness modulus is calculated by software using the above mentioned formula (including additional correction algorithms). The Poisson's ratio (μ) for the testing temperature and the type of material and also the average thickness of the test specimen (h) must be specified to the software by the operator. For the testing temperatures used by experimental measurements described below following values of Poisson's ratio were used: For 5 °C is μ=0.27, for 15 °C is μ=0.31 and for 27 °C is μ=0.38.

3.2.3 Test description of IT-CY according to EN 12697-26

In case of the IT-CY method stiffness modulus is most commonly determined by using a testing apparatus called NAT (Nottingham Asphalt Tester) or testing frame with similar use. The original purpose of successful NAT development was to design and manufacture a device, which will enable efficient measurement of standard properties of asphalt mixtures. The device, however, allowed a widespread use in road laboratories all around the world. Since the fact that the empirically based tests such as e.g. the Marshall Test or the Indirect Tensile Strength Test can not sufficiently describe the behavior of asphalt mixtures in its whole stress range (different temperature, frequency of loading which simulates passes of heavy vehicles, or fatigue characteristics caused by repeated stress), the asphalt mixtures have been increasingly tested by the performance-based tests using devices such as e.g. NAT or its newer version called UTM (Universal Testing Machine). These devices simulate better the real conditions in the pavement structure thanks to their possibilities of different loading, different temperature etc.

In Figure 1 there is a description of important parts of the device. Figure 2 depicts the positioning of the specimen during the testing of stiffness modulus according to repeated indirect tensile stress test (IT-CY).



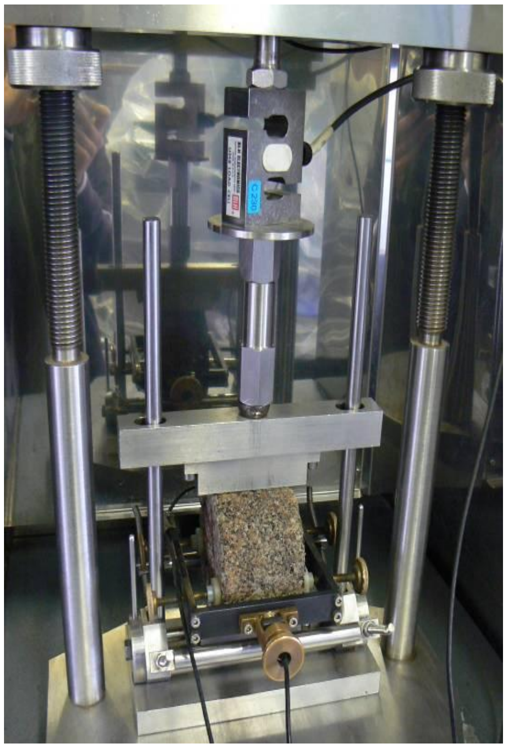


Figure 1: Testing frame of the NAT device (1-pneumatic or hydraulic loading device, 2-steel frame, 3-dynamometer, 4-upper loading plate, 5-tested specimen, 6- adjuster of the LVDT sensor, 7-frame for deformation measurement, 8-lower loading plate, 9-equalizing chuck)

3.2.4 Test procedure according to EN 13286-43 (Indirect Tensile Test)

For the stiffness assessment of hydraulically bound base layers, EN 13286-43 advances the static test methods for the assessment of uniaxial compressive and/or tensile strength as well as indirect tensile strength by monitoring the specimen deformation during the strength test.

For the indirect tensile tests, the deformation of specimen diameter is measured along the horizontal diameter (90° to the loading axis) as well as shifting the transducers by an angle of 60° to the horizontal diameter.

According to the test procedure specified in EN 13286-43, the specimen deformation is measured during strength test. Deformations associated with a force of 30 % of the maximum force measured during the test are applied for calculating stiffness modulus and Poisson’s ratio according to equation (1.3) and (1.4).

$$\nu = \frac{1+0.4\cdot\Xi}{1.73-1.07\cdot\Xi}\;; \qquad \Xi = \frac{\Delta\phi_{60}}{\Delta\phi} \tag{1.3}$$

$$E = \left(0.273 + \nu + 0.726\nu^2\right)\cdot\frac{0.3F}{H}\cdot\frac{1}{\Delta\phi_0} \tag{1.4}$$

where: ν Poisson's ratio

E_{it} stiffness as evaluated by indirect tensile test

$\Delta\Phi_0$ deformation of horizontal diameter (horizontal deformation) [mm]

$\Delta\Phi_{60}$ deformation of diameter with shifted transducers by an angle of 60° from the horizontal axis [mm]

F maximum force [N]

H specimen height [mm]

This test procedure was developed for the assessment of brittle, hydraulically bound pavement materials. For road materials with a significant percentage of bituminous or hydraulic binder allowing the production of stable specimens, the procedure is generally applicable. Though, for each test condition (temperature, frequency) one specimen is needed. For the assessment of temperature-dependent and time-dependent stiffness parameters, this procedure would result in a high test effort.

Therefore, the indirect tensile test was combined with loading conditions as described in EN 12697-26, Annex E. Here, the specimen is not loaded until failure but the strain-controlled loading is stopped after reaching a specific strain in order to avoid specimen failure. Afterwards, the specimen is allowed to relax and then loaded again with a varied strain rate. This test should be conducted in a temperature-control cabinet allowing prolonged testing time.

Among the tests performed within CoRePaSol project for the stiffness assessment within CoRePaSol project, both test procedures according to EN 13286-43 and EN 12697-26, Annex E, were combined. This means that the principle of the used combined test consisted of submitting a cylindrical specimen to indirect tensile load at given temperatures and loading times according to an imposed monotonous and increasing law of strain, and measuring the specimen deformation both on the horizontal diameter and on a diameter having an angle of 60 ºC with the horizontal one. Therefore, a specimen (diameter 150 mm, height 80 mm) was temperature conditioned to selected temperatures of -10 °C, +10 °C, +15 C and +30 °C. The specimen was taken from the temperature cabinet and equipped with the deformation measurement frames. The specimen was then placed between the loading strips of the static test device and automatic test program was started composed of four monotonic loading phases with varied force-controlled loading rates (50 kN/min, 10 kN/min, 5 kN/min and again 50 kN/min) up to a vertical maximum force of 2 kN.

After each loading phase, the load was reduced to a minimum force of 300 N allowing clamping the specimen in the test device. After reaching a force of 300 N the next loading phase was started. In the second stiffness experiment, a rest period of 20 s was introduced before starting each new loading phase in order to allow the specimen to relax viscoelastic strains. The test composed on four loading phases was ended after maximum of 3 minutes after the specimen was taken from the temperature-control cabinet to avoid unacceptable temperature change during the test conducted at ambient temperature (~20 °C).

Examples for the force and deformation measurements during the IDT stiffness test are plotted in Figure 2. It can be observed, that all three measured deformations (vertical, horizontal and at the angle of 60°) differ significantly in their magnitude. Therefore, they are plotted with varied axes. During each loading phase, the deformation increases approximately linearly. Further during the rest periods, the deformations are reduced which shows the elastic properties of the test specimen. Nevertheless, the reduction is not complete and time-dependent which implies viscoelastic material behavior. Nevertheless, also viscoplastic or plastic properties can be observed as identified by non-recoverable deformations at the beginning of the second, third and fourth loading period.

The application of the loading speed of 50 kN/min at the start and the end of each test allows to control if the specimen was deteriorated during the stiffness test.

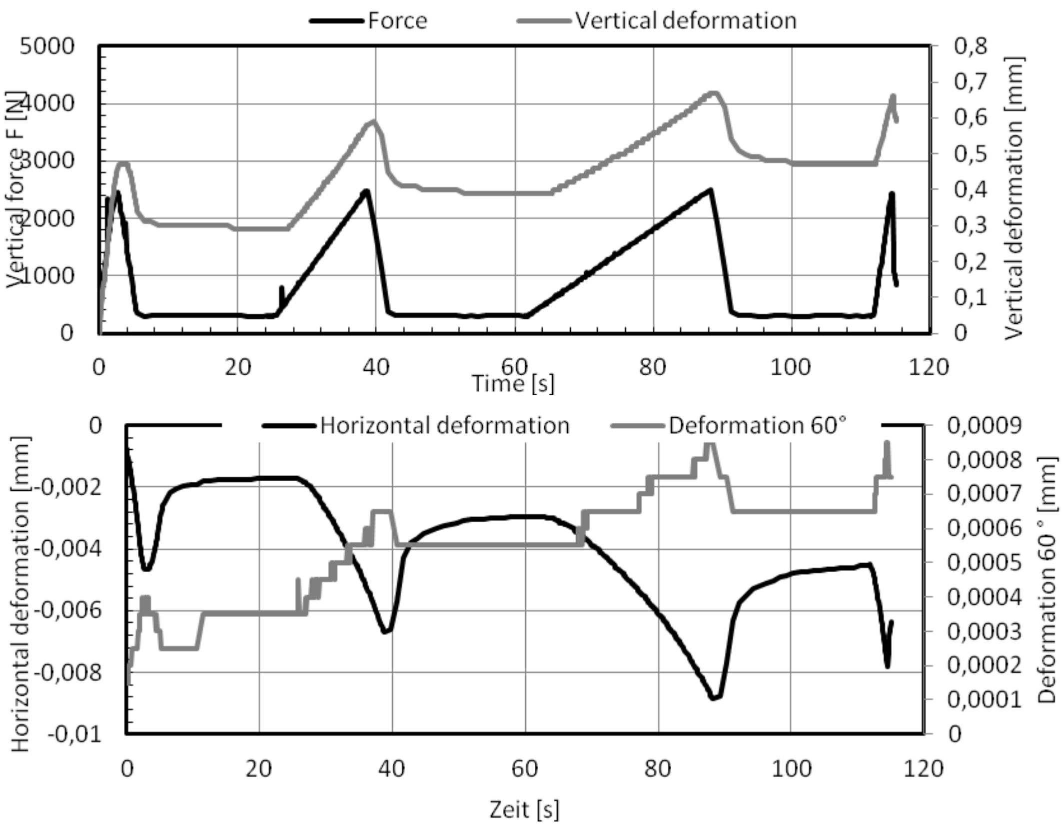


Figure 2: Example for force and deformation measurements during an IDT stiffness test

For the stiffness assessment of hydraulically bound mixtures, EN 13286-43 specifies the measurement of specimen diameter in two directions:

- horizontal deflection,
- deflection at an angle of 60° to the horizontal diameter.

The test principle as well as the test device applied in this study is shown in Figure 3.

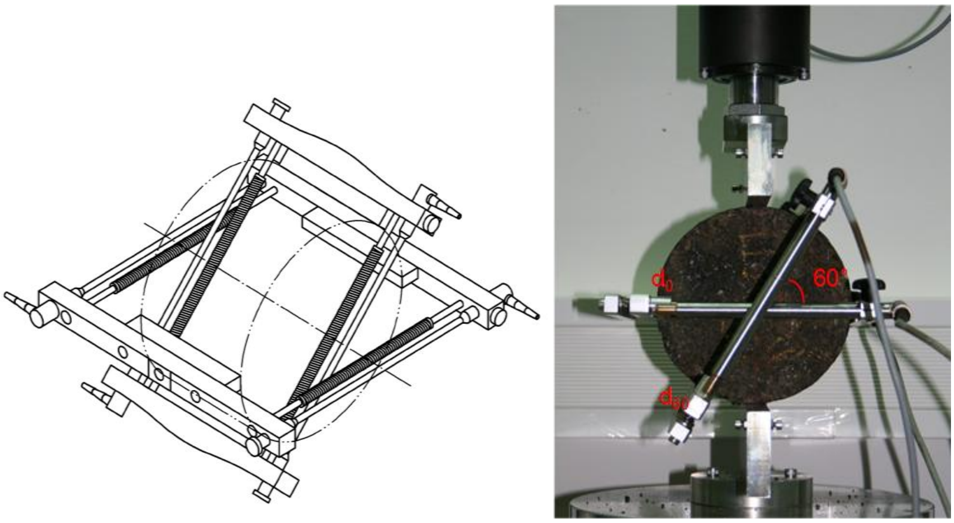


Figure 3: Principle for deformation measurement in indirect tensile strength tests (EN 13286-43) and test device applied in the study

3.2.5 Comparative summary of indirect tensile tests applied for stiffness evaluation

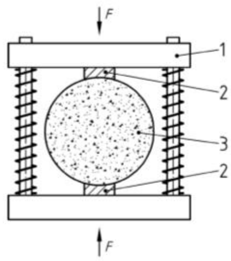
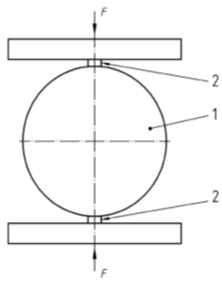
NAT device allows monitoring the rheological characteristics of both traditional compacted asphalt mixtures and mastic asphalts and thus determine their resistance to the repeated stress and resistance to the permanent deformation. The testing device is used not only for the asphalt mix design optimization and performance testing, but it has its place also in the quality control of plan produced mixes or freshly paved mixes. One of the advantages is also the possibility of using either the laboratory specimens or the cores from existing pavement. Another important advantage of the IT-CY method is that it is a non-destructive test and if necessary, it is possible to repeat the test on identical specimen after any period of its curing. The possibility of excluding the influence of material heterogeneity is very advantageous especially for such non-homogeneous mixtures as cold recycled mixes.

On the other hand, monotonic tests are usually applied in order to assess the pavement materials strength properties. Besides the widely assessed uniaxial compression strength tests, especially indirect tensile strength tests are most common for the assessment of cold recycling materials. In these tests, a specimen is usually loaded continuously by controlled deformation or loading increase until it fails due to cracking or permanent deformations. As an example, the indirect tensile strength test is applied for asphalt mixtures (specified according to EN 12697-23) as well as for hydraulically bound materials (EN 13286-42). The most distinct differences between the specified test procedures are summarised in Figure 3.

The applied type of loading of the specimen results in a specific stress distribution which is only dependent of the specimen dimensions. For the central part of the specimen, a vertical compression stress σ_c is superimposed by a horizontal tensile stress σ_t for which is: $\sigma_t = \sigma_c/3$. Generally, indirect tensile strength tests are applied in order to assess the strength characteristics of the tested material. However, by recording the specimen deformation during the test, also stiffness modulus parameters can be derived (calculated) from the test.

The two-dimensional stress state demands for the assessment of the strain reaction of the specimen also in two directions in order to allow the assessment of the Poisson's ratio. If only horizontal strain is measured, a Poisson's ratio has to be estimated in order to calculate the stiffness modulus of the material. The easiest way would be to measure the horizontal and vertical deformations. However, for the later it is difficult to apply deformation transducers because of the direction of loading and the loading strips in this region of the test device. The distance between the loading strips can't be use for deformation measurement, because of timber loading strips applied and high compressive stresses in the loaded area of the specimen.

Table 1: Differences in monotonic indirect tensile strength tests for asphalt mixtures (EN 12697-23) and hydraulically bound mixtures (EN 13286-42)

	EN 12697-23 **Asphalt mixtures**	**EN 13286-42** **Hydraulically bound mixtures**
Type of loading	Vertical deflection controlled: 50 mm/min	Monotonic force rate resulting in indirect tensile stress rate of ≤ 0.2 MPa/min
Loading strips	Concave to fit well to specimen diameter (width: 19 mm)	Timber strips (width: ≥ 15 mm)
Specimen dimensions (for D ≤ 40 mm)	Diameter: 150 mm Height: 35-70 mm	Height / diameter factor: 0.8 to 2.0
Test temperature	5 ≤ T ≤ 25 °C, to be reported	Not specified
Figure of test principle		

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4 Results of stiffness assessment studies

4.1 IT-CY study

4.1.1 The influence of bituminous / hydraulic binder content

The stiffness modulus and indirect tensile strength (ITS) values were determined after 14 days of specimen curing. Tested specimens had diameter 150 mm, height 60 mm and were prepared from sorted RAP with 0/22 mm grading. During the testing reclaimed asphalt was acquired from the same location but in different batches. Grading of the material was therefore assessed repeatedly and results are shown in Figure 4 including the grading envelopes according to the Czech technical specifications TP208.

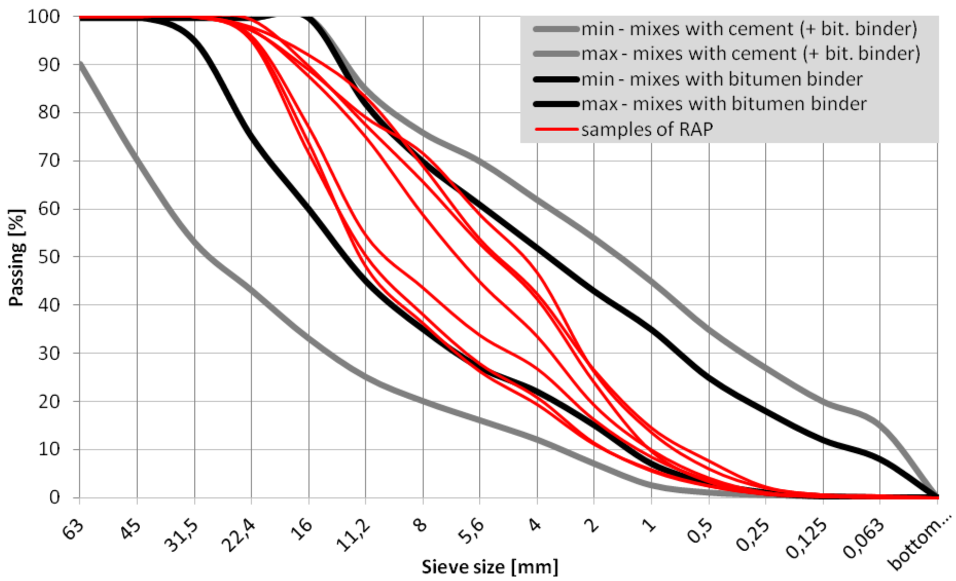


Figure 4: Grading curves of used RAP 0/22 mm (location Středokluky, repeated analyses)

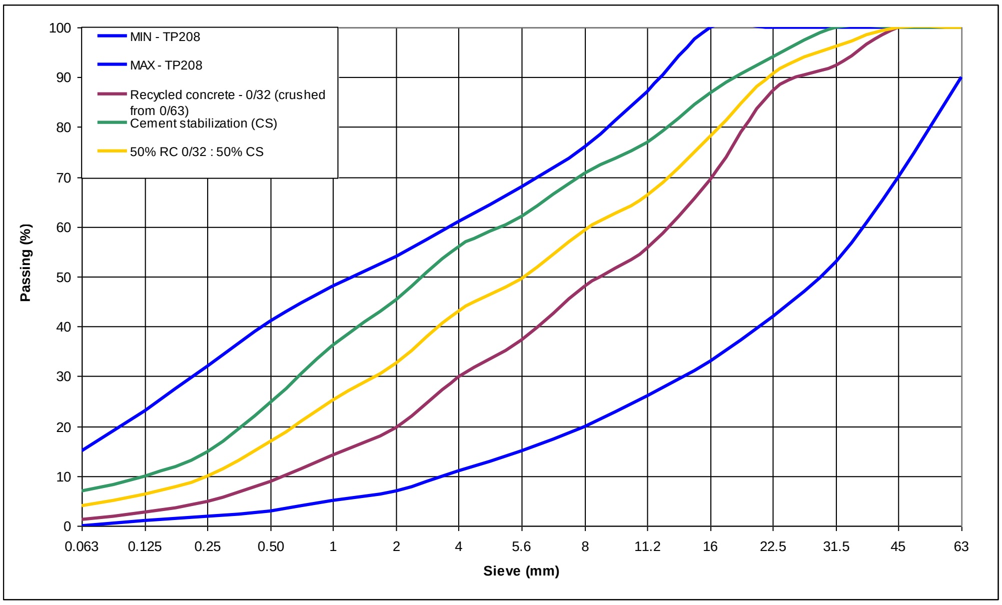


Figure 5: Grading curves of used recycled concrete (location D1 motorway, lot 14)

Similarly Figure 5 shows the grading curves of recycled concrete (RC) which originates from the modernization of the Czech motorway D1 (lot 14). In this case RC of grading 0/32 mm was analyzed and at the same time RC 0/63 mm was recrushed to get 0/32 mm as well. Additionally cement stabilization below the concrete slabs was recrushed as well and analyzed as another type of material. Parallel to CoRePaSol there were additional mix designs containing also different combinations of recycled concrete and cement stabilization.

Cold recycled mixes with foamed bitumen

Table 2: Experimental mix designs of mixes with foamed bitumen

	Mix D	Mix P1	Mix B	Mix P2	Mix V	Mix P3	Mix P4	Mix P5
RAP	93.5%	92.5%	90.0%	88.0%	94.5%	93.5%	91.0%	89.0%
Water	2.0%	2.0%	2.5%	2.5%	2.0%	2.0%	2.5%	2.5%
Foamed bitumen	**4.5%**	**4.5%**	**4.5%**	**4.5%**	**3.5%**	**3.5%**	**3.5%**	**3.5%**
Cement	**0.0%**	**1.0%**	**3.0%**	**5.0%**	**0.0%**	**1.0%**	**3.0%**	**5.0%**
	Mix K	**Mix L**	**Mix M**	**Mix N**	**Mix R**	**Mix S**	**Mix T**	**Mix U**
RAP	95.5%	94.5%	92.0%	90.0%	96.0%	95.0%	92.5%	90.5%
Water	2.0%	2,0%	2.5%	2.5%	2.0%	2.0%	2.5%	2.5%
Foamed bitumen	**2.5%**	**2.5%**	**2.5%**	**2.5%**	**2.0%**	**2.0%**	**2.0%**	**2.0%**
Cement	**0.0%**	**1.0%**	**3.0%**	**5.0%**	**0.0%**	**1.0%**	**3.0%**	**5.0%**

Table 3: Matrix of combinations cement vs. foamed bitumen

		Foamed bitumen:			
		2.0%	2.5%	3.5%	4.5%
Cement:	0%	R	K	V	D
	1%	S	L	P3	P1
	3%	T	M	P4	B
	5%	U	N	P5	P2

Figures 6 and 7 show the obtained results.

For cold recycled mixtures with foamed bitumen the influence of bituminous/hydraulic binder content is similar in case of gained stiffness modules and in terms of indirect tensile strength values. The increase of stiffness modulus due to the cement addition is proportionally higher than the increase of the indirect tensile strength. Using additional cement has significantly more impact on both characteristics than higher content of foamed bitumen. From all the examined variants the highest values of stiffness modulus and ITS were registered by the mixes with highest cement content (5 % by mass), but this increase has its limits (in the literature like Czech technical specifications TP208, it is recommended to add max. 6 % of cement, because too rapid growth in initial strength could lead to formation of hydration cracks or microcracks). The optimal amount of included foamed bitumen in terms of the highest stiffness modulus (and also the indirect tensile strength) values appears between 2.0

% and 2.5 %. On the contrary higher content of foamed bitumen leads to lower stiffness modulus. Table A.1-A.8 in the Annex summarizes all stiffness modulus values determined according to the repeated indirect tensile stress test (IT-CY) and the values of indirect tensile strength.

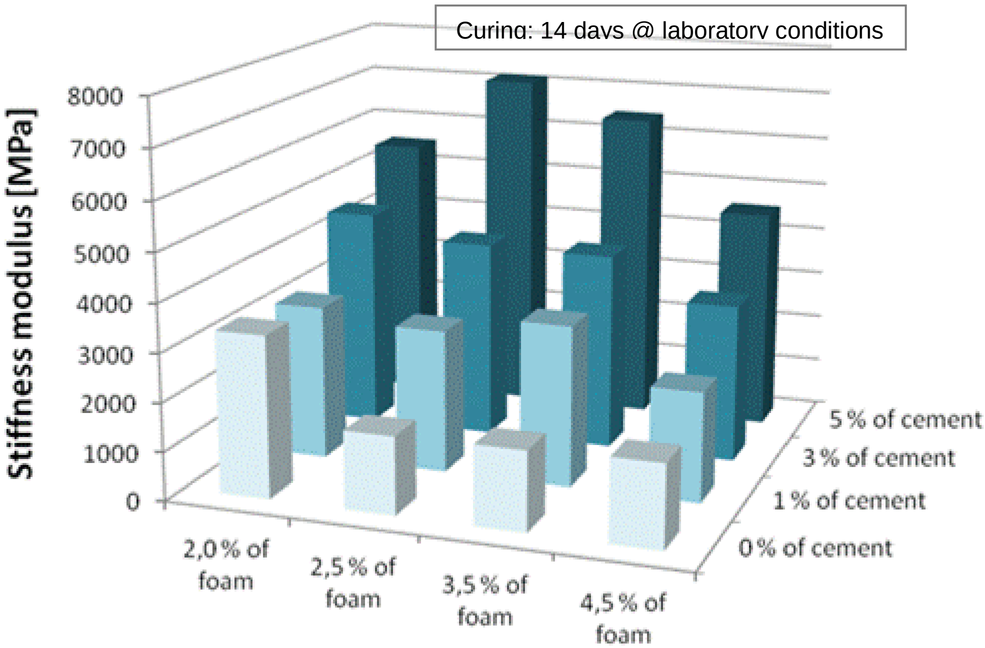


Figure 6: Stiffness modulus of cold recycled mixes with different content of foamed bitumen

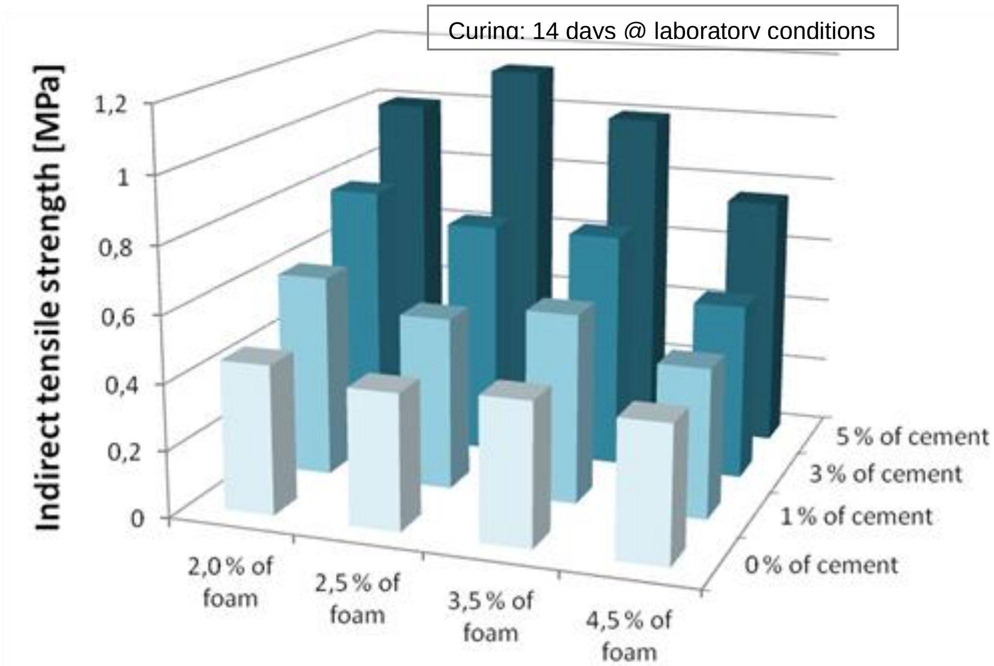


Figure 7: Indirect tensile strength of cold recycled mixes with different content of foamed bitumen

These results indicate the differing effects of bituminous and hydraulic binder content. The increase in bituminous binder content above an optimum will increase the materials flexibility which results in a decrease of stiffness. This stiffness decrease will also result in decreasing indirect tensile strength values obtained in deflection-controlled monotonic indirect tensile tests. The strain at specimen failure is still high.

On the other hand the stiffening effect of increased cement content does not increase the indirect tensile strength in the same magnitude. This results in an increased brittleness and therefore in lower crack resistance at enforced strain loading.

Cold recycled mixes with bituminous emulsion

Table 6: Matrix of combinations cement vs. bituminous emulsion

		Bituminous emulsion			
		2.5%	3%	3.5%	4.5%
Cement:	0%	2.5E	3E	C = 3.5E	4.5E
	1%	W	-	E	-
	1.5%	-	-	G	-
	3%	-	-	A	-

Table 7: Experimental mix designs of mixes with bituminous emulsion

	Mix A	Mix C	Mix E	Mix G	Mix W
RAP	91.0%	94.0%	93.0%	92.5%	94.0%
Water	2.5%	2.5%	2.5%	2.5%	2.5%
Bituminous emulsion	**3.5%**	**3.5%**	**3.5%**	**3.5%**	**2.5%**
Cement	**3.0%**	**0.0%**	**1.0%**	**1.5%**	**1.0%**

Figures 8 and 9 show the obtained results.

Curing: 14 days at laboratory conditions

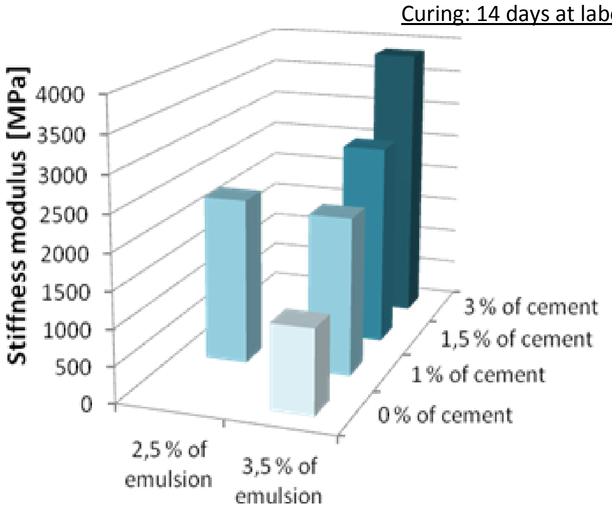


Figure 8: Stiffness of cold recycled mixes with different content of bituminous emulsion

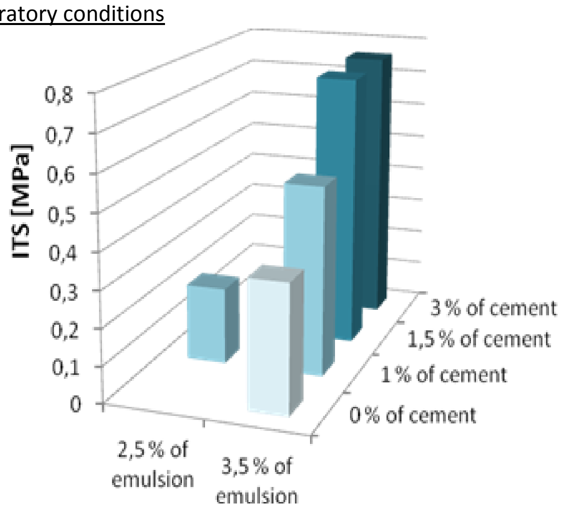


Figure 9: ITS of cold recycled mixes with different content of bituminous emulsion

For cold recycled mixes with use of bituminous emulsion the influence of bituminous and/or hydraulic binder content on stiffness modulus values is not as similar to the effect on indirect tensile strength as it was shown in the previous case of mixtures with foamed bitumen – see e.g. the difference between the indirect tensile strength and stiffness modulus values for mixes with 1 % of cement. Cold recycled mixes with bituminous emulsion also show that the addition of cement has more significant positive effect on the increase of stiffness modulus than on the increase of ITS. The above mentioned findings were not sufficient for determining the optimum bituminous emulsion content. Table summarizing all stiffness modulus values determined according to the repeated indirect tensile stress test (IT-CY) and the values of indirect tensile strength is given in Annex A.

Based on presented results a comparison of impact of bituminous emulsion content was additionally done by testing cold recycled mixtures without cement, which contained varying amount of bituminous emulsion, as shown in the following table. These specimens were cured according to the accelerated curing method (described in the Project report D1.2), and therefore the results of these measurements were not included into the charts above, which depict the results for specimens cured for 14 days at laboratory conditions.

Table 8: Experimental mix designs of mixes with bituminous emulsion and without cement

	Mix 2.5E	Mix 3E	Mix 3.5E	Mix 4.5E
RAP	94.5%	94.5%	94.0%	93.5%
Water	3.0%	2.5%	2.5%	2.0%
Bituminous emulsion	**2.5%**	**3.0%**	**3.5%**	**4.5%**
Cement	**0.0%**	**0.0%**	**0.0%**	**0.0%**

This part of the complex cold recycled mix stiffness assessment showed clearly that the optimal range of bituminous emulsion content for this type of cold recycled mixtures is 2.5 – 3 %. Further addition of bituminous emulsion, which makes the mix more expensive, leads on the contrary to a reduction in evaluated properties. The table summarizing the stiffness modulus and indirect tensile strength values is given in Annex A.

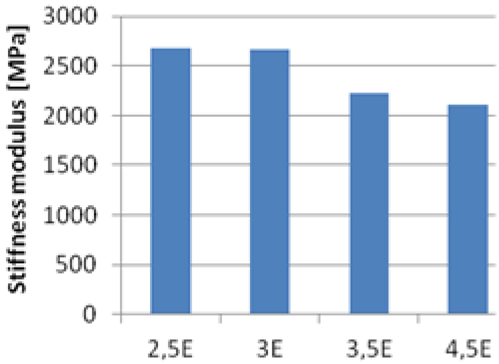


Figure 10: Stiffness of cold recycled mixes with different content of bituminous emulsion

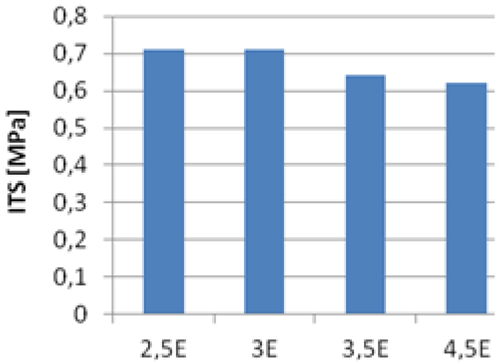


Figure 11: ITS of cold recycled mixes with different content of bituminous emulsion

4.1.2 Influence of specimen curing time

This part of the experiment was focused on observing the rate of increase in stiffness modulus and indirect tensile strength in time. In total 8 mixtures with different combination of hydraulic and bituminous binders were tested. Testing of the stiffness modulus according to the repeated indirect tensile stress test (IT-CY) and the indirect tensile strength (ITS) were performed after 7, 14 and 28 days of specimen curing at standard condition of laboratory temperature (20±2) °C and relative humidity of 40-70 %. Mix designs are summarized in Table 9.

Table 9: Experimental mix designs of mixes with combined binders

	Mix A	Mix G	Mix E	Mix C	Mix W	Mix B	Mix F	Mix D
RAP 0/22	91.0%	92.5%	93.0%	94.0%	94.0%	90.5%	92.5%	93.5%
Water	2.5%	2.5%	2.5%	2.5%	2.5%	2.0%	2.0%	2.0%
Bituminous emulsion	**3.5%**	**3.5%**	**3.5%**	**3.5%**	**2.5%**	**0.0%**	**0.0%**	**0.0%**
Foamed bitumen	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**4.5%**	**4.5%**	**4.5%**
Cement	**3.0%**	**1.5%**	**1.0%**	**0.0%**	**1.0%**	**3.0%**	**1.0%**	**0.0%**

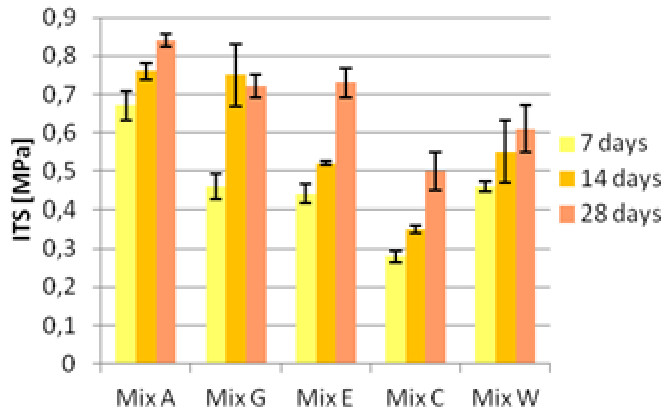


Figure 12: ITS of cold recycled mixes with combined binders

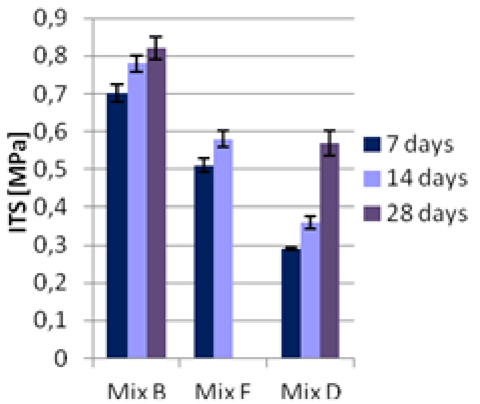


Figure 13: ITS of cold recycled mixes with combined binders

From Figure12 to Figure15 is shown 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 there.

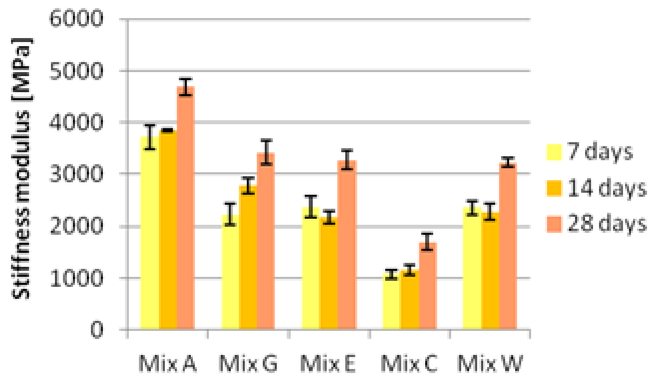


Figure 14: Stiffness of cold recycled mixes with combined binders

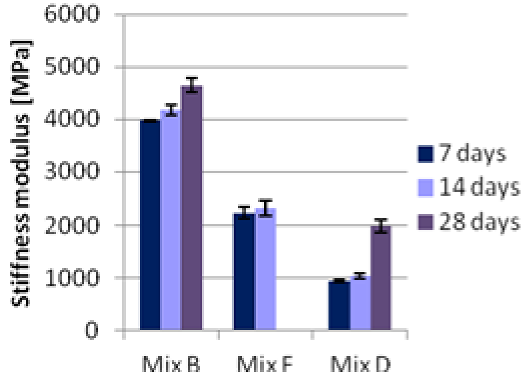


Figure 15: Stiffness of cold recycled mixes with combined binders

In general it is possible to state, that time-dependent increase of stiffness modulus does very well correspond with indirect tensile strength values. If mixes with different content of cement are compared, then from the point of view of both assessed characteristics it is possible to observe an important difference. As can be seen digestedly in the Table 10 increase of both characteristics is always faster for cold recycled mixes with higher content of hydraulic binder. The table summarized selected values of ITS and stiffness modulus 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 period the strength increase is rather slow. On the other hand for mixes containing only bituminous binder a very slow strength improvement can be observed and even between the 14th and 28th day of curing there is still significant increase of the strength values.

Table 10: ITS and stiffness values for selected mixes – time dependence

ITS [MPa]							Stiffness modulus [MPa]					
	Mix C		Mix E		Mix A			Mix C		Mix E		Mix A	
	0 % cem.		1 % cem.		3% cem.			0 % cem.		1 % cem.		3% cem.	
7 days	0.28	100%	0.44	100%	0.67	100%	**7 days**	1076	100%	2380	100%	3717	100%
14 days	0.35	+25%	0.52	+18%	0.76	+13%	**14 days**	1164	+8%	2177	-9%	3852	+4%
28 days	0.50	+79%	0.73	+66%	0.84	+25%	**28 days**	1695	+58%	3274	+38%	4687	+26%

ITS [MPa]							Stiffness modulus [MPa]					
	Mix D		Mix F		Mix B			Mix D		Mix F		Mix B	
	0 % cem.		1 % cem.		3 % cem.			0 % cem.		1 % cem.		3 % cem.	
7 days	0.29	100%	0.51	100%	0.70	100%	**7 days**	941	100%	2240	100%	3971	100%
14 days	0.36	+24%	0.58	+14%	0.78	+11%	**14 days**	1036	+10%	2331	+4%	4175	+5%
28 days	0.57	+97%	---	---	0.82	+17%	**28 days**	1988	+111%			4652	+17%

From the above presented results following conclusions can be made. There is an important difference in values gained after 7 days curing of test specimens for mixes with cement and without cement. This difference then gradually decreases as can be seen in Table 3. Further, it is possible to show in this table, that the use of cement has markedly bigger positive influence on stiffness values than on indirect tensile strength values. Such finding correlates very well with values gained for other evaluations done within the chapter 5.1.1.

4.1.3 Mixes with recycled concrete, recycled gravel/sand and pulverized concrete – case study Czech Republic

The range of performed experiment

In total 11 different mixtures were designed within this sub-task. From these mixtures cylindrical test specimens (Ø 150 mm, h = 60 mm) were produced. For all the mixtures maximum and bulk densities were determined, from which voids content was calculated. Voids content ranges from 10-20 %. The highest values were achieved for mixes with only recycled concrete, whereas the lowest values were achieved by mixes, which contained only RAP (Reclaimed Asphalt Pavement). The specific values of all tests are listed in Annex A.

After determining the voids content, for all mixtures the stiffness modulus by the non-destructive repeated indirect tensile stress test (IT-CY) was carried out in accordance with [15]. After that the indirect tensile strength test (ITS) after 7, 14 and 28 days was performed. Both tests were performed at 15 °C. For the first 24 hours, all the specimens were cured in a plastic bag (i.e. at 90-100 % relative humidity). This part of the performed experiments is enclosed by outputs of the moisture susceptibility, which was determined by three different test procedures as already mentioned earlier in this report.

Used mix designs

Composition of the designed and tested mixes is summarized in Table 1. The used recycled concrete was partly re-crushed in the laboratory of the Department of Road structures at CTU in Prague for 0/22 mm grading. The original material comes from the ongoing modernization and reconstruction of the key Czech D1 motorway. The recycled gravel/sand comes also from this construction site, from its unbound base course. All mixtures contained cationic slow-breaking bituminous emulsion C60B7 (according to the designation in EN 13808 valid until 2014). Some mixtures contained also standard Portland slag cement classified CEM II / B 32.5 according to EN 197-1.

Table 11: Composition of designed and tested mixtures

Mix type	**Mix BA**	**Mix BC**	**Mix OA**
RAP 0/22	45.5%	47.0%	45.5%
Recycled concrete 0/22	45.5%	47.0%	45.5%
Water	2.5%	2.5%	2.5%
Bituminous emulsion	**3.5%**	**3.5%**	**3.5%**
Cement	**3.0%**	**0.0%**	**0.0%**
Pulverized concrete	**0.0%**	**0.0%**	**3.0%**

Mix type	Mix DA	Mix DE	Mix DB	Mix DO	Mix PA	Mix PC
Recycled concrete 0/22	44.75%	45.75%	68.625%	43.75%	0.0 %	0.0 %
RAP 0/22	0.0 %	0.0 %	0.0 %	0.0 %	68.25%	70.5%
Sand	44.75%	45.75%	22.875%	43.75%	22.75%	23.5%
Water	4.0%	4.0%	4.0%	4.0%	2.5%	2.5%
Bituminous emulsion	**3.5%**	**3.5%**	**3.5%**	**3.5%**	**3.5%**	**3.5%**
Cement	**3.0%**	**1.0%**	**1.0%**	**0.0%**	**3.0%**	**0.0%**
Pulverized concrete	**0.0%**	**0.0%**	**0.0%**	**5.0%**	**0.0%**	**0.0%**

Mix type	Mix 3O	Mix 5O
RAP 0/22	89.5%	87.5%
Water	4.0%	4.0%
Bituminous emulsion	**3.5%**	**3.5%**
Cement	**0.0%**	**0.0%**
Pulverized concrete	**3.0%**	**5.0%**

Another used material was pulverized concrete (micro-milled, mechanically activated by high-speed milling technique). This concrete originates from the reconstruction of the main runway of Vaclav Havel International Airport Prague. The crushed concrete was milled by a co-partner company Lavaris s.r.o.

Methods for determination of the moisture susceptibility

Following set of measured values contains results of moisture susceptibility. This feature was determined by three different available test procedures. The first method was a method according to [15] (key Czech technical specifications for cold recycled mixes), further it was the procedure for hot mix asphalt defined by [16] and the last one was a method according to existing American standard [17] also used for HMA.

EN 12697-12

The basic procedure applied as a standard for asphalt mixes is described in EN 12697-12 and used in all countries associated in CEN for hot or warm mix asphalts. The specification describes three methods which can be used for determination of the moisture susceptibility of an asphalt mix. In case assessments done within CoRePaSol project in the standard described method A was used which prescribes following procedure. Moisture susceptibility is determined by the ratio of two sets of laboratory specimens. The first set called "saturated/wet specimens" is saturated by water in a vacuum chamber at pressure of (6.7±0.3) kPa and at a temperature of (20±2) °C. Subsequently the specimens are immersed in water at a temperature of (40±1) °C for 68 to 72 hours. Before testing of the indirect tensile strength the specimens are conditioned for the right temperature in a water bath. The so-called "dry specimens" are cured at laboratory conditions before tested for ITS.

AASHTO T283 test protocol

The procedure defined in the US specifications AASHTO T283 is similar to the procedure given in EN 12697-12, however, there is an extra freezing cycle added. Moreover the prescribed way of HMA specimen curing is different as well. The first set of laboratory specimens is saturated with water in a vacuum chamber similarly to the method according to EN 12697-12 the saturation period is shorter. Subsequently, the degree of saturation is determined and should reach 70-80 %. Specimens which meet this requirement are then subjected to the freezing cycle with temperature (-18±3) °C for a minimum period of 16 hours. After that specimens are immersed in water at a temperature of (60±1) °C for 24 hours. Before testing the indirect tensile strength the specimens are conditioned for the desired testing temperature in a water bath. The second set of specimens is cured at laboratory conditions similarly to previous test method.

In Europe there is currently no legislation that would set the allowable rate of decrease in the indirect tensile strength if on freezing cycle is applied. Within the long-term research at CTU in Prague acceptable decline has been usually used, which is about 10 % worse than in case of moisture susceptibility assessment according to EN 12697-12.

TP 208 test protocol

Current Czech technical specifications for cold recycled mixes TP 208 prescribe for determining the moisture susceptibility following procedure. Laboratory specimens are cured at laboratory conditions for 7 days. After that the first set is tested for the indirect tensile strength (ITS). The second set of specimens is immersed in water at the temperature of (20±2) °C for further 7 days. Then the test specimens are also tested for ITS. If cold recycled mixtures contain only hydraulic binder or a combination of bituminous and hydraulic binder, the ITS value of test specimens conditioned in water has to achieve at least 75 % of the dry strength of specimens cured for 7 days at laboratory conditions. For mixes containing just the bituminous binder it has to be at least 60 %.

In terms of specimen curing all tested mixes were divided into two groups (as described in chapter 4.1.1). All specimens containing more than 1 % of cement (BA, DA, PA) or pulverized concrete (OA, DO, 3O, 5O) were tested after 14 days of regular curing. The duration of specimen curing at laboratory conditions before applying the procedure described in [16] or [17] was modified to achieve total time of specimen curing 14 days. The values gained from evaluation of specimens treated according to [16] and [17] were compared to values of moisture susceptibility according to [15] and to values gained by testing the specimens cured for 14 days at laboratory conditions. The second group consisted of mixes, which contained less than 1 % of cement (mix BC, DE, DB and PC). The specimens from this group were cured by the accelerated curing procedure and after that conditioned according to [16] and [17]. Obtained values of stiffness modulus and ITS were compared to values determined according to [15] and to reference values of ITS and stiffness modulus determined in specimens tested directly after accelerated curing procedure and with specimen which were cured for 3 additional days at laboratory conditions after the accelerated curing procedure. Therefore specimens of different age were tested and compared.

The resulting values of stiffness modulus and indirect tensile strength after 7, 14 and 28 days of curing are summarized in Figure16 and Figure17. These summary charts serve to overall quick orientation in comparing all individual groups of mixes between each other. For better clarity further chapters comprise charts demonstrating some specific phenomena separately. All the measured values are listed in Annex A.

Test specimens made from mix BC for testing after 7 and 28 days of curing and specimens made from mixes BA and OA for testing after 28 days of curing were produced from a different batch of RAP. Columns representing these mixes are marked by black hatch in the charts. Because of RAP heterogeneity (i.e. different RAP composition) these specimens achieved lower bulk density (see Annex A). The gained results of these specimens were affected by that – they were a bit lower than they were expected to be.

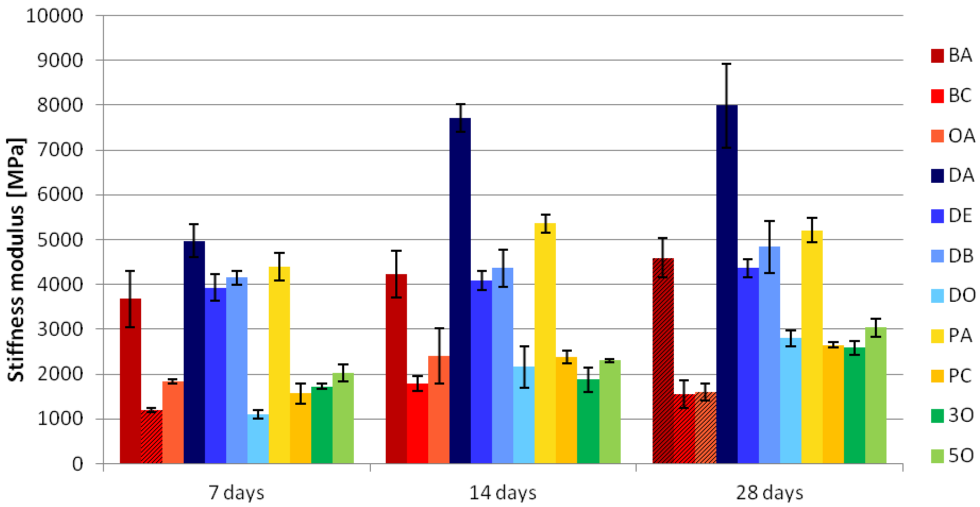


Figure 16: Stiffness modulus after 7, 14 and 28 days of curing

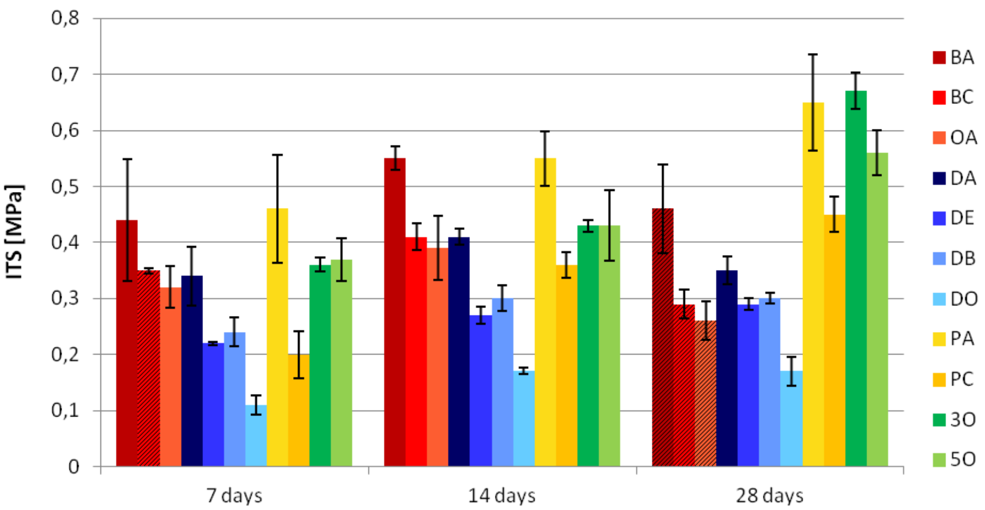


Figure 17: Indirect tensile strength after 7, 14 and 28 days of curing

The main finding, which is clearly visible from the summary charts, is a large difference among the trends, which follow the values of stiffness modulus and trends of ITS values. Considering that during both ITS and stiffness modulus test specimens are strained by indirect tension, and also due to so far obtained findings, this phenomenon is relatively surprising. Boldest difference occurs for mixes with recycled concrete and gravel (blue marked bars in the charts). While in terms of stiffness modulus the achieved values are comparably high their indirect tensile strength on the general average or even lower The reason for that is the irreplaceable role of a suitable grading curve. In case of mixes containing gravel/sand with spherical grains the limited potential of these mixtures is obvious. Mixture DO (the sample with lowest ITS) achieves similar values of stiffness modulus as mixes BC and PC and also mixes 3O and 5O, while in terms of ITS the measured values are rapidly lower. It is necessary to add 3 % of cement to simply level up the negative effect of present gravel used instead of RAP (mix DA achieves similar results as mix BC). Similar trend can be observed by comparing cold recycled mixes with recycled asphalt material and/or sand, which achieved the highest values (BA, DA, PA), i.e. mixes with 3 % of cement described in detail in chapter 5.1.4.

Generally it can be stated, that the highest ITS values were achieved by mixes containing only RAP. Replacing 25 % of RAP by recycled gravel/sand or substitution of 50 % of RAP by recycled concrete didn't result in a significant reduction or increase of ITS. Nevertheless the RAP content is crucial for this characteristic, which is proven by low values of ITS measured by mixes, which contained only recycled concrete and gravel/sand. In terms of stiffness modulus the situ findings are totally different. The highest values were achieved by mixes without RAP, thus mixes with recycled concrete and recyclable gravel/sand.

This indicates the difference of mechanical properties between these mixtures. The reclaimed asphalt granulates introduce flexible characteristics to the cold recycled material which reduce the brittleness of the mix and increases its cohesion.

An interesting finding comes up from the comparison of stiffness modulus and ITS values for mixes DE and DB. Even though mixes with RAP and recycled concrete achieve lower values of stiffness modulus and ITS compared to mixes with RAP and recyclable gravel/sand, it is not right to consider the gravel/sand to be a better material, which will always achieve higher values. Cold recycled mixes are very complex materials and one of their most important characteristics is the suitable grading curve. Therefore, it is more important to look for the quality of the whole mix, instead of the quality of single components and also to care for the appropriate proportions of particular components, which will guarantee the optimal grading curve with good aggregate skeleton. The comparison of both stiffness modulus and ITS values showed, that the skeleton consisting of 50 % of coarse recycled concrete with 0/22 mm grading and 50 % of recyclable gravel/sand (mix DE) is less advantageous, than the aggregate skeleton where the proportion is changed to 75 % : 25 % on behalf of the recycled concrete (mixture DB). This is caused by better cooperation of coarse grains.

4.1.4 Cold recycled mixes with 3 % of cement

Significant difference between the trends of stiffness modulus and ITS values described above is proven also by values measured for mixes, which contained beside the bituminous emulsion also 3 % of cement (mixes BA, DA, PA). The distinctively highest values of stiffness modulus from all the 11 tested mix variations were achieved by mix DA, i.e. a mix, which contains no RAP. Mixes BA and PA achieved high values of stiffness modulus as well because of higher content of hydraulic binder (cement). However, substitution of RAP by recyclable gravel/sand results in approximately 35 % reduction of stiffness modulus values (mix BA), and substitution of RAP by recycled concrete caused a 25 % reduction of stiffness modulus values (mix PA) (see Figure18).

The situation is significantly different when comparing the ITS values of these mixes. The highest and most comparable values of ITS were achieved with mixes BA and PA, except the measurements after 28 days of specimen curing. Mix BA achieved in this case much lower values than mix PA, which is probably caused by using a different batch of RAP. Compared to mixes BA and PA, the ITS values measured with mix DA (i.e. a mix without RAP) were about 25 % lower.

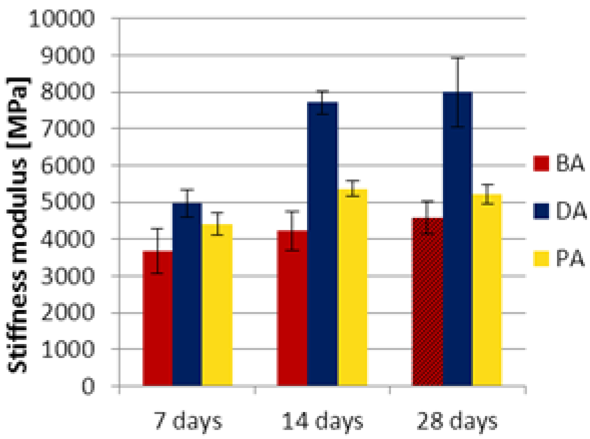


Figure 18: Stiffness modulus of cold recycled mixes with 3 % of cement

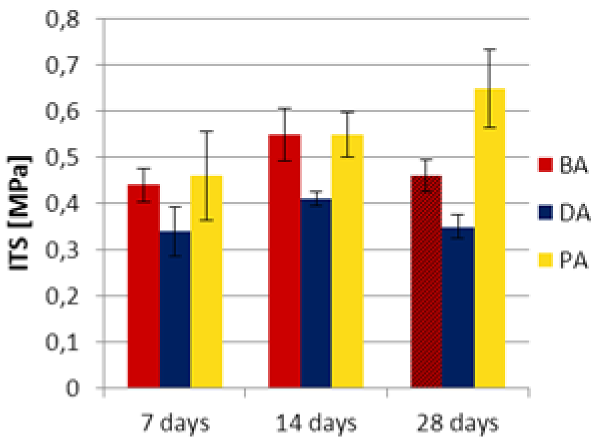


Figure 19: ITS of cold recycled mixes with 3 % of cement

<u>**Moisture susceptibility of cold recycled mixes with 3 % of cement**</u>

Stiffness modulus and ITS values, which were measured after application of particular methods for moisture susceptibility determination, basically confirm the findings listed above. Mix DA (recycled concrete and recyclable gravel/sand) achieved again the highest values of stiffness modulus and very low values of ITS. The results of both tests were comparable for mixes BA and PA. In terms of comparison of particular procedures among each other, the most conservative results were measured when applying the procedure according to American test procedure [17]. Specific values of all performed tests are listed in Annex A.

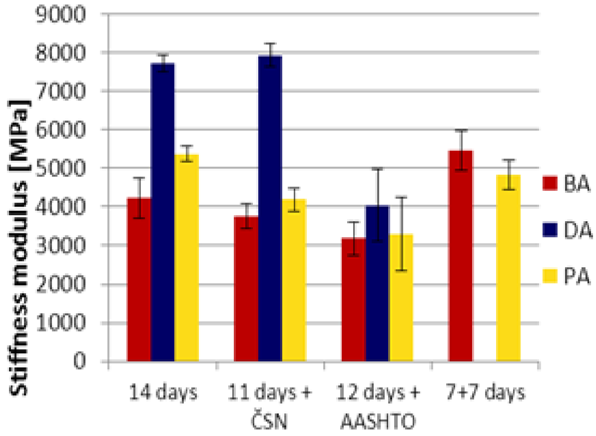


Figure 20: Stiffness – moisture susceptibility of cold recycles mixes with 3 % of cement

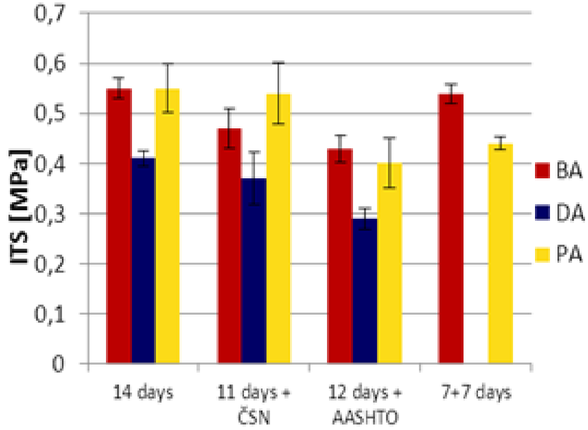


Figure 21: ITS – moisture susceptibility of cold recycles mixes with 3 % of cement

4.1.5 Cold recycled mixes with application of pulverized concrete

Mechanically activated pulverized (micro-milled) recycled concrete was used in four mix designs – OA, DO, 3O and 5O. Comparison of stiffness modulus and ITS average values of these mixes are depicted in Figure 0 and Figure 1. Detailed values are listed in Annex A.

In accordance with the findings described above, the most significant observation is that there is a big difference between high stiffness modulus values of mix DO combined with low ITS values. Other mixes which contained RAP achieved more than double values of ITS compared to the mix DO. The highest ITS values were achieved by mixes 3O and 5O, i.e. mixes whose aggregate skeleton is formed entirely by RAP. On the basis of performed testing it is possible to state, that the influence of aggregate skeleton appears to be much more important than the amount of pulverized concrete added.

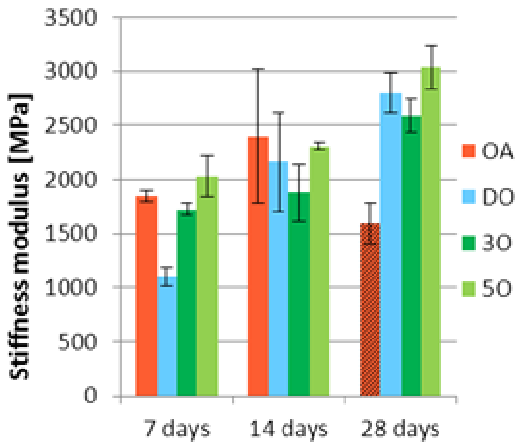


Figure 22: Stiffness of cold recycled mixes with pulverized concrete

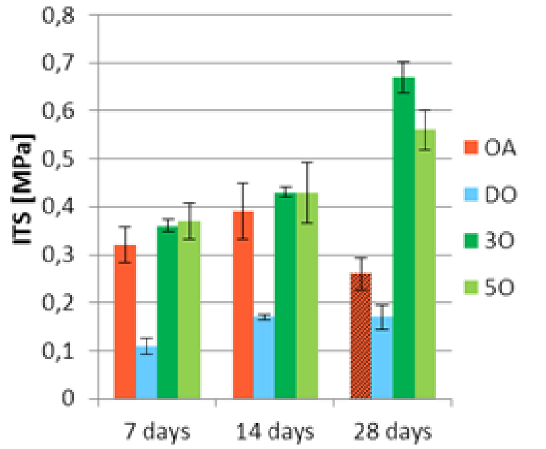


Figure 23: ITS of cold recycled mixes with pulverized concrete

The effect of pulverized concrete addition can be observed from Figure 22 and 23, if mixes 3O and 5O (RAP and 3 % or 5 % of pulverized concrete) are compared. This effect can be also observed when comparing the values of mixes BC and OA i.e. mixes with RAP, recycled concrete and 0 % or 3 % of pulverized concrete (see Figures 22 and 23). In both mentioned cases, significantly higher stiffness modulus values were achieved by mixes with higher content of pulverized concrete. On the other hand the ITS values of mixes with higher content of pulverized concrete were similar or lower than the values measured in mixes with lower content of this admixture or in mixes which contained no pulverized concrete at all.

Moisture susceptibility of cold recycled mixes with pulverized concrete

Findings depicted in Figure 24 and 25 confirm again the results listed above. Stiffness modulus values are again higher for mixes with higher content of pulverized concrete. In case of ITS, similarly to what has been referred previously, it is not possible to confirm that the alternative binder causes any positive effect. From the viewpoint of moisture susceptibility characterization the lowest values were gained by applying the American procedure according to [17]. Cold recycled mix DO achieved again comparable or a slightly lower values of stiffness modulus than other mixes, whereas the ITS values were significantly lower than in other cases. It is possible to deduce, that the recyclable gravel/sand should have probably inappropriate behavior when immersed in water, which comes out especially when there is no cement in the cold recycled mix, which would help to reduce this negative effect. Interesting in this respect is the comparison of DE and DO cold recycled mixes. In both cases there is same ratio between applied recycled concrete and sand, there is same content of mixing water and bituminous emulsion. The only difference is use of cement in case of DE (1 %) and use of pulverized concrete (3 %) in case of DO.

This clearly indicates the lacking hydraulic properties of the milled concrete, which reacts as inactive filler. The hydraulic properties of the cement in the initial concrete pavement were spent during the initial construction.

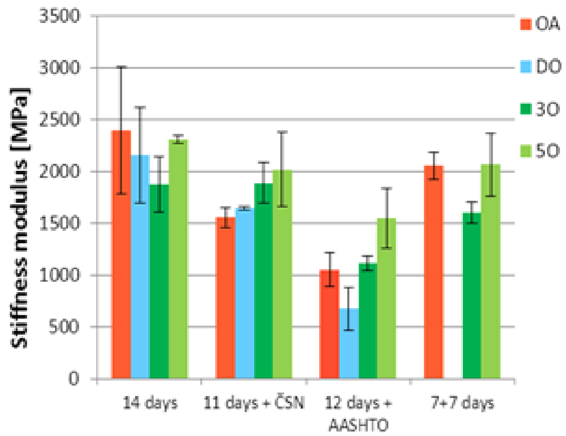


Figure 24: Stiffness modulus – moisture susceptibility of cold recycles mixes with pulverized concrete

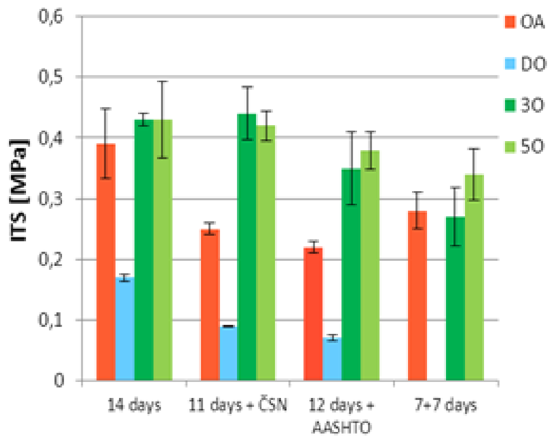


Figure 25: ITS – moisture susceptibility of cold recycles mixes with pulverized concrete

4.1.6 Cold recycled mixes with ≤1 % of cement

Figure 26 and Figure 27 depict unambiguously the negative effect of RAP absence on ITS values. Despite the fact that mixes DE and DB unlike mixes BC and PC contain 1 % of cement i.e. they will have slightly increased costs, cement doesn't guarantee the ITS values similar to values of mixes BC and PC. On the other hand and with fully opposite conclusions the difference between mixes without RAP and mixes BC and PC in terms of stiffness modulus values is in this comparison even more significant. It could be caused by the presence of the 1 % of cement, which cold recycled mixes DE and DB contain. Nevertheless this does not answer the question of the different results if comparing stiffness modulus and ITS values. Figures further show quite well the effect of suitable grading, which results in all cases in higher values of mix DB compared to mix DE.

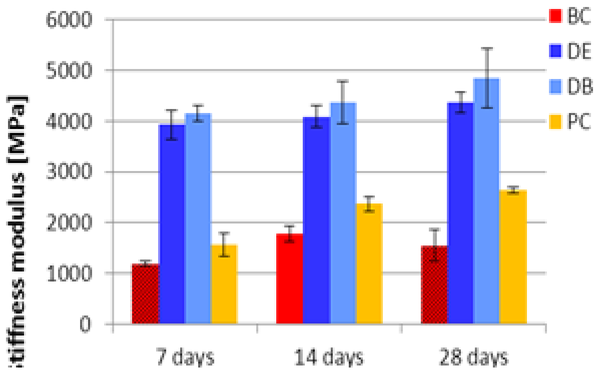


Figure 26: Stiffness modulus of cold recycled mixes with ≤ 1 % of cement

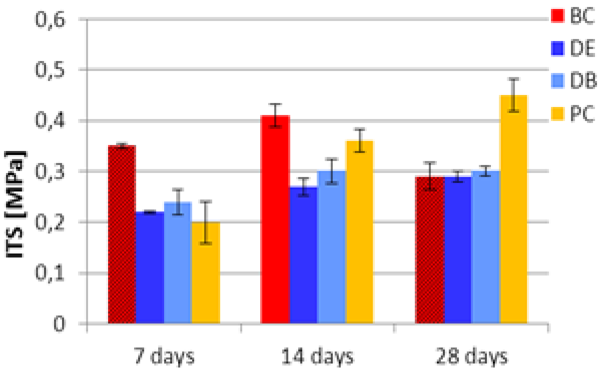


Figure 27: ITS of cold recycled mixes with ≤ 1 % of cement

<u>Moisture susceptibility of cold recycled mixes with ≤1 % of cement</u>

Also in the case of cold recycled mixes containing not more than 1 % of cement, the lowest stiffness modulus and ITS values were gained when applying the procedure according to the American testing procedure [17]. Alongside the high stiffness modulus values, which were achieved again by mixes without RAP it is possible to observe one fact, which didn't occur so far within the performed experiments. Missing values of mix PC were not caused by unrealized testing (as it was in a few cases earlier), but the specimens from mix PC fell apart during curing in water. In the case of specimens conditioned according to EN, two stiffness modulus and ITS measurements were successful, but the values were very low as can be seen from Figure 28 and 29. This finding prove, that it is very important to execute the research comprehensively, because when evaluating other tests, mix PC appeared comparable to other cold recycled mixes and sometimes even better. The performed measurements of moisture susceptibility showed, that especially in cases of mix variations without cement, which would diminish the negative effect of recyclable gravel/sand, the contained gravel/sand has quite destructive consequences when it gets in contact with water. Usage of these mixes into the pavement structure would have far-reaching consequences. The simple answer could be that it is not only the material but also the fact that the grading of cold recycled mixes where content of gravel/sand was successively increased were not optimized and therefore the content of fine grained particles might be too high as well.

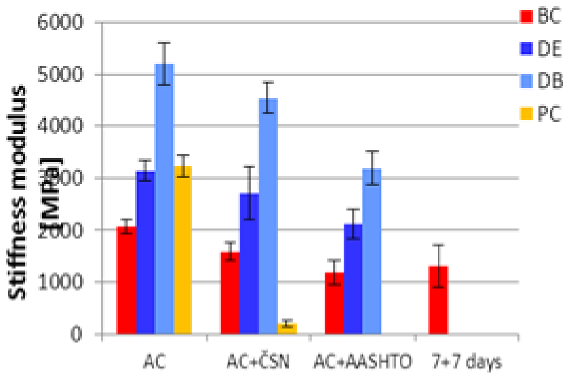


Figure 28: Stiffness – moisture susceptibility of CR mixes with ≤ 1 % of cement

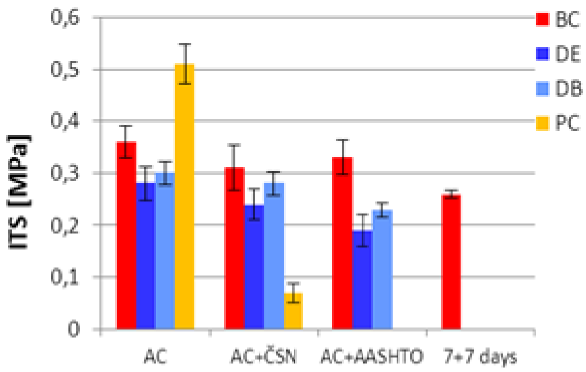


Figure 29: ITS – moisture susceptibility of cold recycled mixes with ≤ 1 % of cement

4.1.7 Progress of cold recycled mixes characteristics in time

The progress of stiffness modulus and ITS values in time (period between 7 to 28 days curing) is listed in Table 12 and Table 13. The decrease of values measured after 28 days of curing for mixes BA, BC and OA is probably caused by different batch of RAP used for specimens´ production (influence of material heterogeneity). As mentioned above, these values should have been a slightly higher. Except these values and decrease in one case shown for the mix PA, caused probably by material heterogeneity, stiffness modulus and ITS values of mixes containing RAP develop in time as expected. On the other hand mixes with recycled concrete and recyclable gravel/sand don't show such a large increase, especially between 14 and 28 days of curing. Additional possible explanation for this fact could be that insufficient amount of water was used since for these mixes modified Proctor test was not done and mixing water content was derived from previous mixes containing RAP, nevertheless material not coated by bitumen like in the case of RAP might have higher water absorption. Water, which is necessary for cement hydration process or which has to be released faster because of curing and consolidation of the bituminous emulsion soaks into the absorptive grains of recycled concrete and/or recyclable gravel/sand. Consequently, the lack of water necessary for correct course of the cement hydration process may occur.

Table 12: Time dependent progress of stiffness modulus

Stiffness modulus [MPa]														
	BA		BC		OA		PA		PC		3O		5O	
7 days	3675	100%	1193	100%	1843	100%	4399	100%	1571	100%	1724	100%	2032	100%
14 days	4226	15%	1784	50%	2398	30%	5363	22%	2376	51%	1874	9%	2307	14%
28 days	4595	9%	1554	-13%	1592	-34%	5211	-3%	2649	11%	2587	38%	3035	32%
	DA		DE		DB		DO							
7 days	4976	100%	3931	100%	4151	100%	1103	100%						
14 days	7716	55%	4085	4%	4369	5%	2161	96%						
28 days	7988	4%	4361	7%	4841	11%	2800	30%						

Table 13: Time dependent progress of ITS

	ITS [MPa]													
	BA		BC		OA		PA		PC		3O		5O	
7 days	0.44	100%	0.35	100%	0.32	100%	0.46	100%	0.2	100%	0.36	100%	0.37	100%
14 days	0.55	25%	0.41	17%	0.39	22%	0.55	20%	0.36	80%	0.43	19%	0.43	16%
28 days	0.46	-16%	0.29	-29%	0.26	-33%	0.65	18%	0.45	25%	0.67	56%	0.56	30%
	DA		DE		DB		DO							
7 days	0.34	100%	0.22	100%	0.24	100%	0.11	100%						
14 days	0.41	21%	0.27	23%	0.3	25%	0.17	55%						
28 days	0.35	-15%	0.29	7%	0.3	0%	0.17	0%						

4.1.8 Effect of fine grained aggregate and fines

Laboratory specimens of 12 different cold recycled mixtures with diameter 100 mm were subjected to the testing according to repeated indirect tensile stress test (IT-CY). Tests were performed at temperatures of 5 ° C, 15 ° C and 27 ° C and the tested specimens were cured 28 days in the laboratory conditions. The used mix designs are summarized in the following table. Values gained during the testing are shown in detail in table in Annex A.

Table 14: Used experimental design

	REC1	REC2	REC3	REC1a	REC2a	REC3a
Water	5.00	5.00	5.00	5.00	5.50	5.50
Cement	3.00	2.00	1.50	3.00	2.00	2.00
Bituminous emulsion	2.50	2.50	2.50	2.50	2.50	2.50
RAP 0/11	80.55	72.40	72.80	80.55	72.00	63.00
Aggregate 0/2	0.00	0.00	0.00	8.95	18.00	18.00
Waste filler	8.95	18.10	18.20	0.00	0.00	9.00
	REC4	**REC5**	**REC6**	**REC7**	**REC8**	**REC9**
Water	5.10	5.10	5.10	5.00	5.00	5.00
Cement	3.00	3.00	3.00	3.00	3.00	3.00
Bituminous emulsion	2.50	2.50	2.50	2.50	2.50	2.50
RAP 0/11	89.40	71.50	62.60	0.00	0.00	0.00
RAP 0/22	0.00	0.00	0.00	89.50	71.60	62.65
Aggregate 0/4	0.00	17.90	26.80	0.00	17.90	26.85
Waste filler	0.00	0.00	0.00	0.00	0.00	0.00

Influence of fine grained aggregates and fines

The potential of utilizing fine grained aggregates and fines in cold recycled mixes has already been observed for a longer time. These secondary materials usually originate during the aggregate production as a byproduct during crushing or during washing/dedusting of aggregate or as a result of some nonstandard production. The potential of these waste materials lies in the assumption that these components may partially substitute standard filer. If additionally pulverized and activated, they can even be used as a partial substitute to cement. During the performed experiments there were two types of fine grained aggregates used, namely the aggregate of 0/2 mm grading or 0/4 mm grading. Some mixes also included waste fillers, whose addition to the cold recycled mixtures seems to be particularly advantageous.

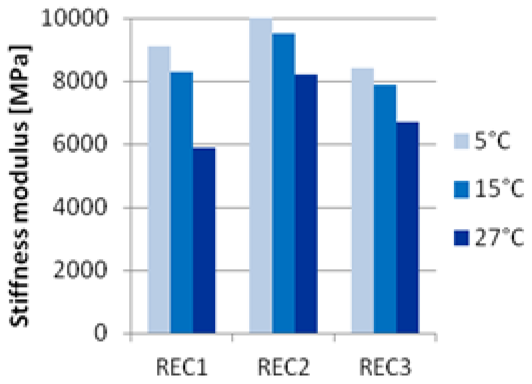


Figure 30: Stiffness modulus of cold recycled mixes containing waste filler

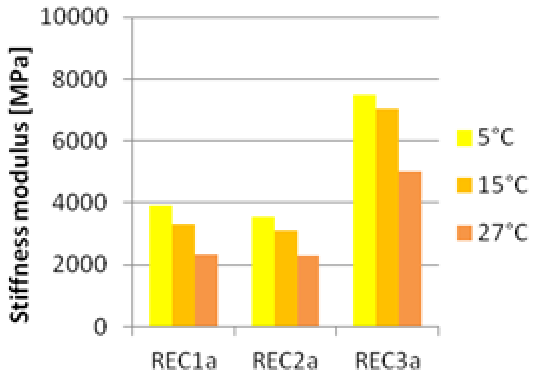


Figure 31: Stiffness of cold recycled mixes containing fine grained aggregates

Figure 30 to Figure 31 show the expected evidence concerning the effects of temperature, namely that with the increased temperature the stiffness modulus decreases. Most efficient is to use cold recycled mixes in the base course of a pavement structure and therefore the specimens were not tested for extreme temperatures, but only for temperatures in the interval of 5-27 °C. The chosen testing temperatures correspond with the previously used division representing firstly the low temperature 5 °C typical for winter months, secondly the medium temperature 15 ° C which is considered in designing methods for stiffness modulus and ITS values and thirdly the temperature 27 ° C which has been considered previously as a suitable temperature for the simulation of slightly increased moderate temperatures occurring during the year in continental European regions.

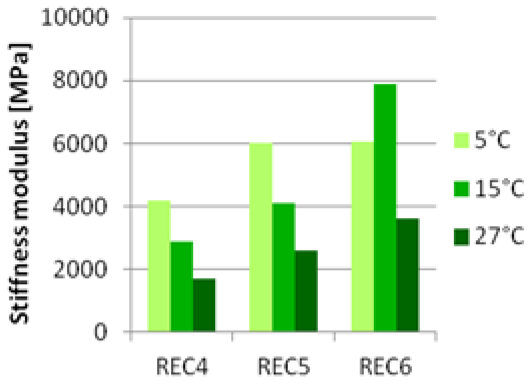


Figure 32: Stiffness modulus of cold recycled mixes containing waste filler

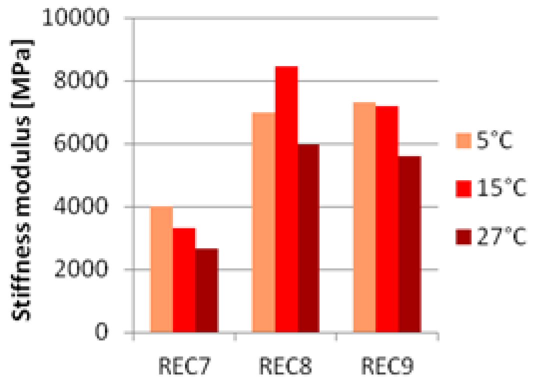


Figure 33: Stiffness modulus of cold recycled mixes containing waste filler

Other findings can be related to the effect of mix composition. Mix REC2 containing 20 % of waste filler and 2 % of cement achieves much higher stiffness in comparison with mix REC1 which includes 10 % waste filler and 3% of cement. This fact confirms the assumption of possible replacement of cement by waste filler while slightly improving the quality of a cold recycled mix. On the other hand the mixture REC3 containing 30 % waste filler and only 1.5

% of cement achieved worse results compared to mixture REC2, which stresses the fact that the convenience of this substitution has its limits and therefore it is obviously not possible to replace the cement totally and expect to achieve better performance. Another reason for this decrease is most probably too high content of fine particles which results in the inappropriate grading curve of the cold recycled mix.

Similar conclusions can be drawn from comparing other triads of cold recycled mixes containing fine grained aggregate and waste filler. Mix REC1a with 10 % of fine grained aggregate of 0/2 mm grading seems to be comparable with mixture REC2a containing 20 % of the same fine grained aggregate, whereas mix REC2a contains about 1 % less cement than mixture REC1a. Mix REC3a contains 20 % of fine grained aggregate of 0/2 mm grading, i.e. the same amount as mix REC2a, but moreover it contains 10 % of waste filler, which causes the fact that this mixture achieved disproportionately higher stiffness modulus values than mixtures REC1a and REC2a.

Further, results of stiffness modulus according to the repeated indirect tensile stress test (IT-CY) measured by mixtures REC4 – REC9 repeatedly confirmed that adding of fine aggregates to some extent improves the mechanical properties of a cold recycled mix even if the cement content remains the same. A few illogically low or high values of stiffness modulus (REC 6 at 5 °C, REC8 at 15 °C) were probably caused by the RAP heterogeneity.

Effect of waste filler content

Aim of the following sub-section was to identify the impact of waste filler compared to the effect of utilizing fine grained aggregates of 0/2 mm or 0/4 mm grading. Mixtures REC1 – REC3 have very similar composition to mixtures REC1a – REC3a, as shown in the following table. Each pair of mixes has almost identical composition with one significant difference. Mixtures REC1 – REC3 contain only waste filler, while mixtures REC1a – REC3a contain similar amount of fine grained aggregate of 0/2 m grading.

Table 15: Mix compositions

	REC1	REC1a	REC2	REC2a	REC3	REC3a
Water	5.00	5.00	5.00	5.50	5.00	5.50
Cement	3.00	3.00	2.00	2.00	1.50	2.00
Bituminous emulsion	2.50	2.50	2.50	2.50	2.50	2.50
RAP 0/11	80.55	80.55	72.40	72.00	72.80	63.00
Fine aggregate 0/2	**0.00**	**8.95**	**0.00**	**18.00**	**0.00**	**18.00**
Waste filler	**8.95**	**0.00**	**18.10**	**0.00**	**18.20**	**9.00**

Presented Figures 34 to 36 clearly show that mixtures containing waste filler achieve much better results than mixtures with the same content of fine grained aggregates. The difference is not so significant in the third graph, but this fact only confirms the positive effect of waste filler. Both mixes whose results are shown in the third chart contain 20 % of fine grained aggregate / waste filler, whereas mixture REC3a contains additional 10 % of waste filler, and therefore the measured stiffness modules demonstrate high values for mixtures REC1 –

REC3. Moreover the mix REC3 contains about 0.5 % less cement than mix REC3a, which also contributes to smaller difference between these two mixes.

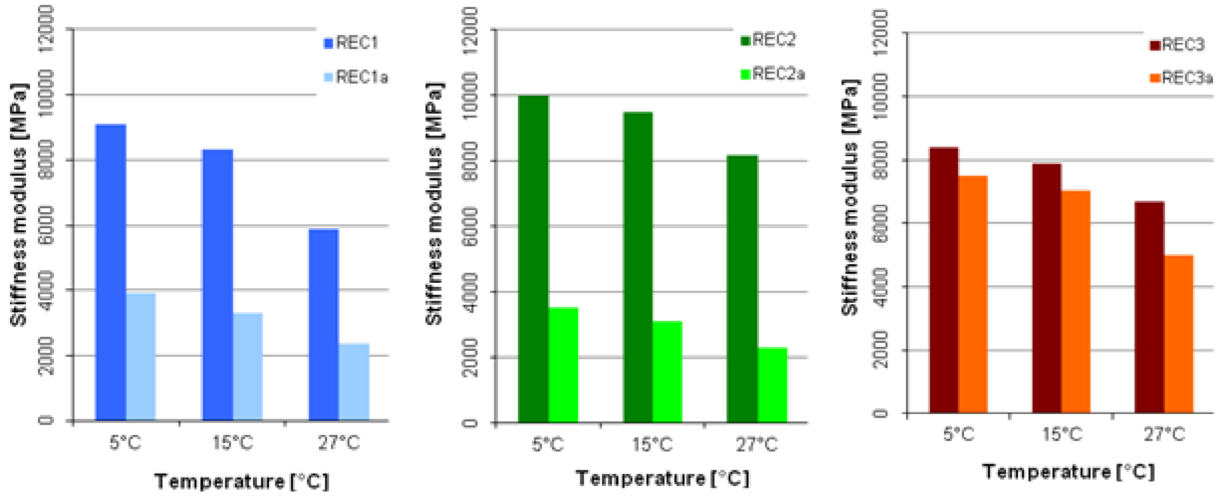


Figure 34-36: Stiffness modulus of cold recycled mixes containing waste filler or fine grained aggregates

4.2 CBR/IDT-study

4.2.1 Design and materials of the stiffness assessment study (CBR/IDT study)

To assess the applicability of CBR and indirect tensile tests for the assessment of cold recycled materials, several cold recycled materials with varied contents of bituminous and hydraulic binders were prepared in laboratory and tested by CBR and indirect tensile test.

Bituminous emulsion, hydraulic road binder as well the granulated reclaimed asphalt (RA) was sampled at a cold recycling construction site. Based on the mix properties applied during the road construction (represented by simple B3H4), the binder contents were varied according to Table16.

Table 16: Variation of bitumen emulsion and cement in CBR/IDT study

Sample name	Content of bituminous emulsion (residual bitumen) C60B1 – BEM	Content of hydraulic road binder HRB 32.5 E
B4H4	6.7 (4.0)	4.0
B3H4	5.0 (3.0)	
B2H4	3.0 (1.8)	
B1H4	1.7 (1.0)	
B4H1	6.7 (4.0)	0.5
B3H1	5.0 (3.0)	
B2H1	3.0 (1.8)	
B1H1	1.7 (1.0)	

The mix granulate was sampled from a cold recycling construction site near Fulda in central part of Germany. After pre-crushing of the existing pavement composed of tar-contaminated asphalt the mix granulate was sampled from the pre-compacted surface prior of application of the hydraulic road binder and the mix preparation by the used recycler (see Figure 37).

In the laboratory, the mix granulate was sieved with a 16 mm sieve in order to obtain homogeneous specimens. The resulting mix granulate gradation is plotted in Figure 38. The optimum water content of the mix granulate was evaluated to 4.5 %.

Figure 37: Mix granulate sample obtained from cold recycling site

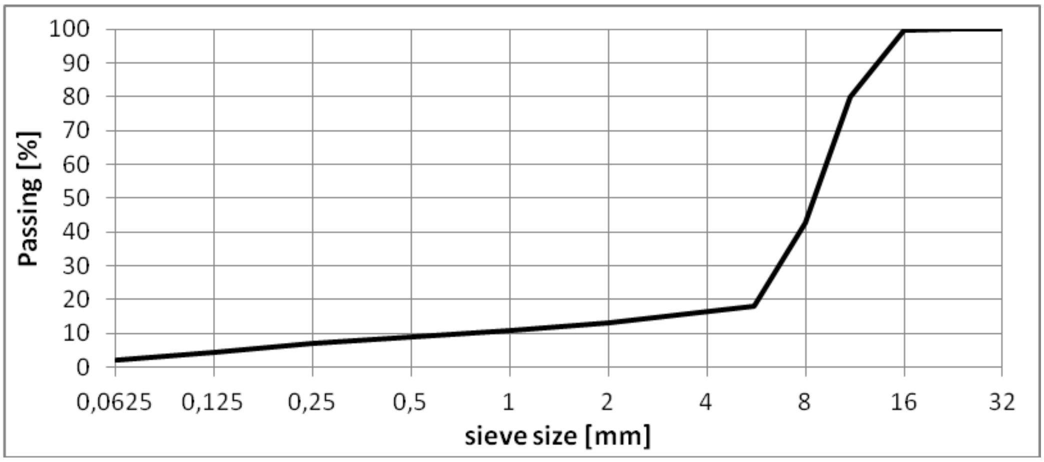


Figure 38: Gradation of the mix granulate applied in CBR/IDT study

From Proctor Standard compaction test an optimal water content of 5 % was obtained which was applied for all mix types. The cold recycled mix was laboratory prepared in a pug-mill mixer WLM30 and afterwards compacted statically by applying a force of 50 kN for 10 minutes. The specimens were demoulded one day after compaction and stored at room conditions for 28 days.

4.2.2 Results of CBR tests

As an example, the force development in CBR tests are shown in Figure 39 for the test samples E4H1, representing flexible, bituminous-dominant cold recycled mixture (BSM) as well as sample E1H4, representing stiff, hydraulically dominant cold-recycled mixture. The tests were conducted in a test device with maximum force of 50 kN. Therefore, for the mix E1H4, only the CBR value associated to 2.5 mm penetration depth could be evaluated.

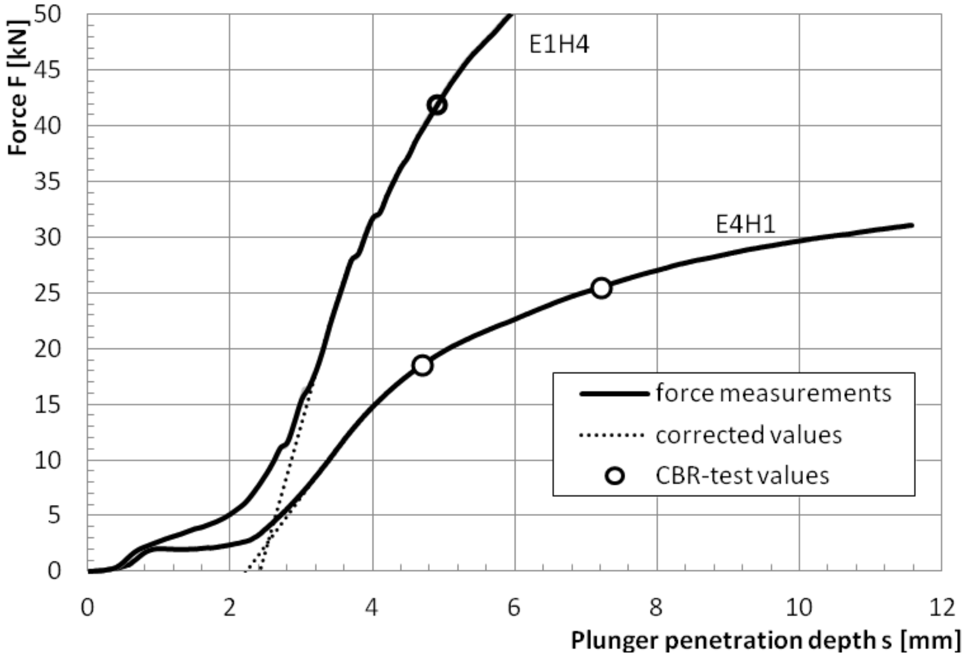


Figure 39: Example for force development in CBR tests conducted on cold recycled road materials (here: sample E1H4 and E4H1)

The results obtained on the eight samples tested are summarized in Table 17 and plotted in Figure 40. The addition of 4 % hydraulic road binder results in significantly higher CBR values compared to a hydraulic binder content of 0.5 %. Below the residual bitumen content of 3 % the actual bitumen content doesn't affect the obtained CBR value significantly. Though, for comparably high bitumen content which can be compared to asphalt base layer binder content, the CBR value reduced considerably. For assessed mixes the elevated hydraulic binder content has less stiffening effect compared to lower bitumen contents.

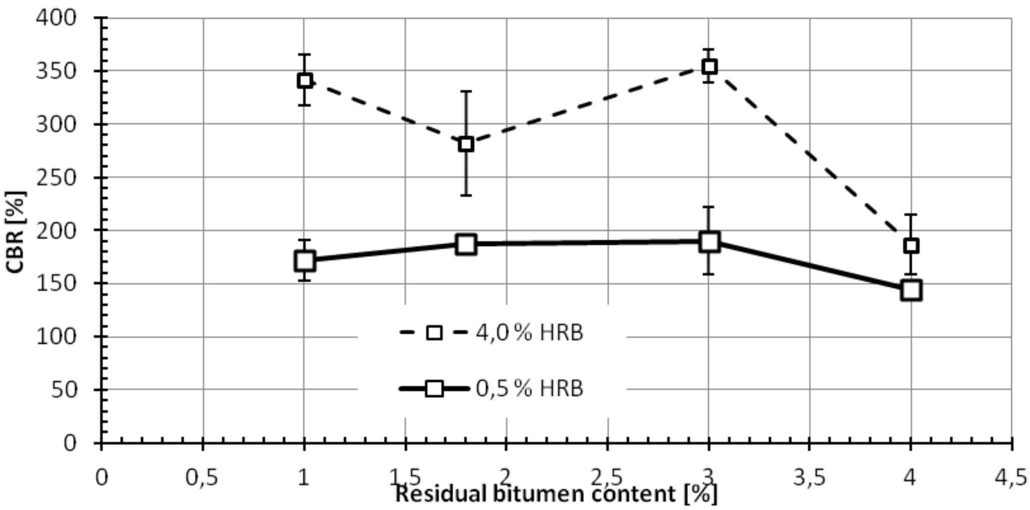


Figure 40: Effect of binder content on the CBR values obtained for cold recycled materials (HRB = hydraulic road binder).

Table 17: Results of CBR test conducted on cold recycled mixtures

Sample name	CBR (1st test)	CBR (2nd test)	**Mean CBR**
B4H4	158	214	**186**
B3H4	370	339	**355**
B2H4	331	233	**322**
B1H4	366	317	**342**
B4H1	148	140	**144**
B3H1	158	222	**190**
B2H1	189	187	**188**
B1H1	153	192	**172**

4.2.3 Results of IDT stiffness tests

A typical development of force, horizontal and 60°- deformation obtained from a modified IDT tests based on EN 13286-43/12697-26 is plotted in Figure 41. The viscoplastic properties can be clearly observed by the increasing deformation values during the test, in which a vertical load is applied continuously.

During the loading phases an acceleration of the deformation measurements can be observed. This development was described by linear regression lines. From these results the deformation rate was obtained for each loading phase and used to calculate the stiffness modulus and Poisson’s ratio with modified equations (1.5) and (1.6).

$$\nu = \frac{1 + 0.4 \cdot \dot{\Xi}\Xi}{1.73 - 1.07 \cdot \dot{\Xi}\Xi} \; ; \qquad \dot{\Xi} = \frac{\Delta\dot{\phi}_{60}}{\Delta\dot{\phi}} \tag{1.5}$$

$$E = \left(0.273 + \nu + 0.726\nu^2\right) \cdot \frac{0.3\dot{F}F}{H} \cdot \frac{1}{\Delta\dot{\phi}_0 \Delta\phi_0} \tag{1.6}$$

where: ν Poisson’s ratio

- E_{it} stiffness as evaluated by indirect tensile test
- $\Delta\Phi_0$ deformation of horizontal diameter (horizontal deformation) [mm/s]
- $\Delta\Phi_{60}$ deformation of diameter with shifted transducers by an angle of 60° from the horizontal axis [mm/s]
- F maximum force [N/s]
- H specimen height [mm]

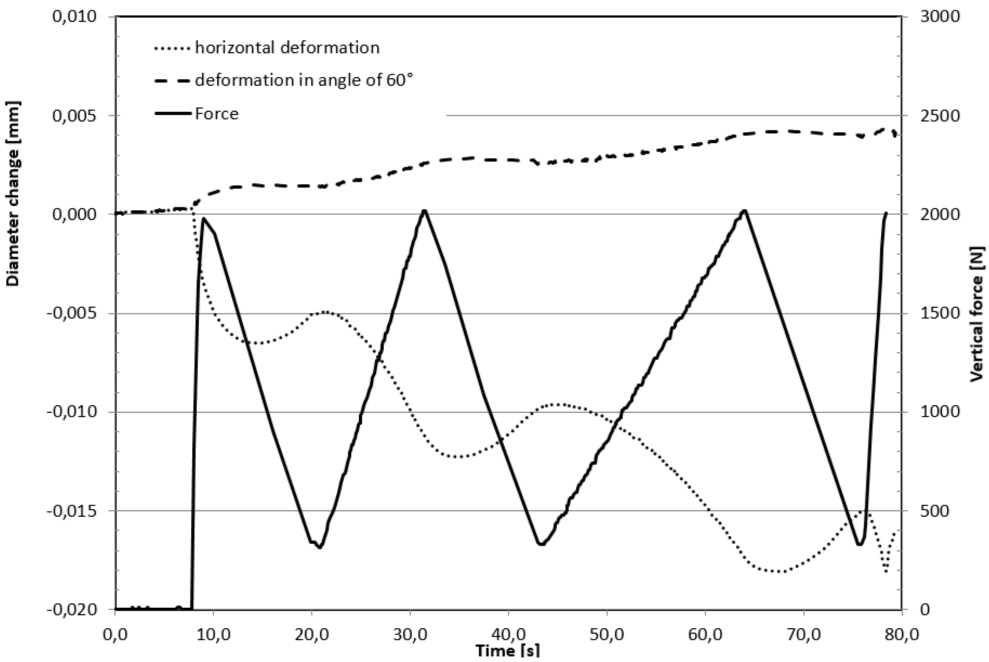


Figure 41: Development of force and deformation measured during IDT stiffness tests

The results of the stiffness tests are summarized in Table 18 and plotted in Figure 42. All mixes indicate a temperature-dependent stiffness modulus. The stiffness measured at specimen temperatures of -10 °C is higher compared to the stiffness at +10 °C and +30 °C for most mixtures tested. Still, the test shows considerable test scatter which indicates that further effort is necessary to improve the frame for deformation measurement if this test procedure should be used regularly.

For all temperatures, it can be observed that an increase in hydraulic binder content will increase stiffness modulus significantly.

For CBR tests and a modified stiffness test procedure based on indirect tensile tests according to EN 13286-43 and EN 12697-26 the effect of binder contents was evaluated on mixtures containing bituminous emulsion.

Table 18: Results of stiffness tests conducted at loading rate of 10 kN/min

Sample	Residual bitumen content	HRB content	-10 °C		+10 °C		+30 °C	
			ν [-]	E [MPa]	ν [-]	E [MPa]	ν [-]	E [MPa]
B1H1	1.0	0.5	0.19	1.601	0.35	2.247	0.50	969
B2H1	1.8		0.47	2.267	0.38	2.886	0.51	508
B3H1	3.0		0.28	9.660	0.40	3.439	0.51	1.280
B4H1	4.0		0.51	3.962	0.50	2.617	0.50	674
B1H4	1.0	4.0	0.61	6.950	0.23	5.741	0.48	2.905
B2H4	1.8		0.30	8.907	0.44	5.609	0.25	3.061
B3H4	3.0		0.48	5.370	0.30	5.806	0.48	4.207
B4H4	4.0		0.47	5.851	0.21	7.062	0.36	3.647

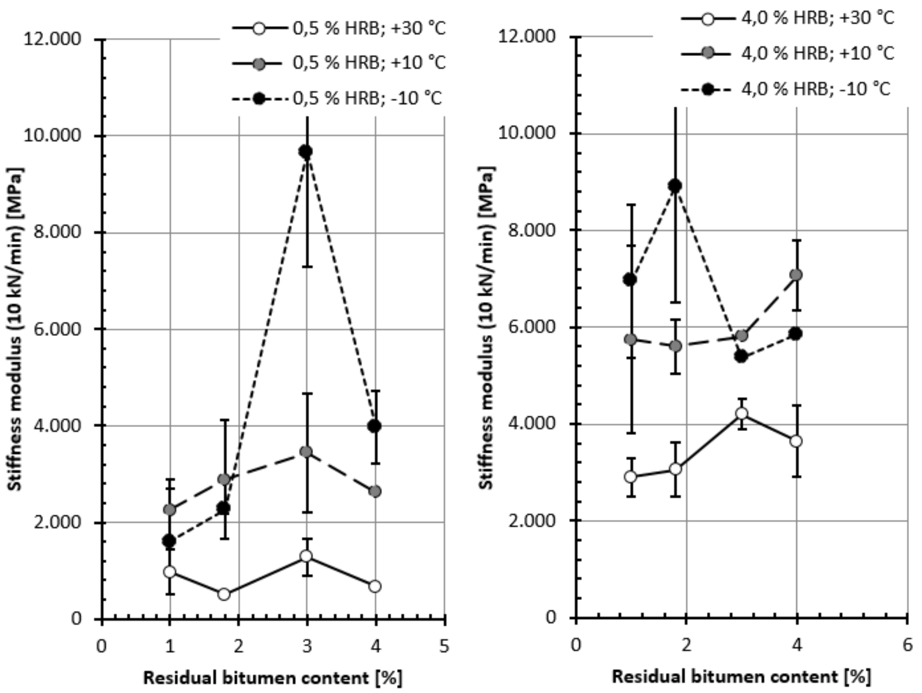


Figure 42: Results of stiffness tests at temperatures -10 °C, +10 °C and +30 °C (left diagram: 0.5 % HRB, right diagram: 4.0 % HRB)

Generally, both test procedures and resulting material properties are plausible. Furthermore, in Figure 43 the results of CBR test and stiffness test at +10 °C and +30 °C are compared. It can be observed, that both tests results in good correlation. The linear regression parameter between the CBR value obtained at 20 °C to the stiffness modulus at +10 °C is 17.8 and to the stiffness modulus at +30 °C is 15.8 (compare equation (1.1)).

Note that the results obtained for the mixture with 4 % residual binder and 4 % hydraulic road binder were identified as outliers and should be excluded from this analysis.

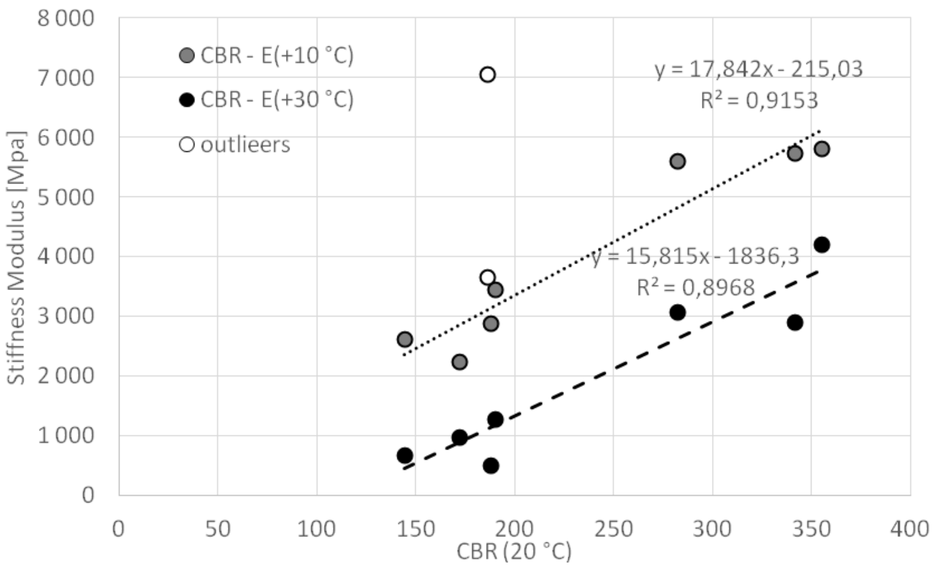


Figure 43: Correlation between CBR, obtained at 20 °C and stiffness modulus obtained in indirect tensile tests with a force rate of 10 kN/min at +10 °C and +30 °C

Further tests will be continuously conducted even after the project CoRePaSol is finished focused on:

- Improvement of stiffness modulus test to improve the test precision.
- Evaluation of foamed bitumen mixtures with varied binder contents.
- Test of pavement materials with known material properties (e. g. hot-mix asphalt with known stiffness modulus results).

4.3 IDT-stiffness study

4.3.1 Design and materials of IDT stiffness study

In order to further improve the applicability of EN 13286-43 IDT stiffness test, a new study was conducted based on additional cold recycling material samples.

The mix granulate used in this part of the study was sampled at an asphalt plant in Rhünda (Germany) and represents milled reclaimed asphalt. The grading of the asphalt granulate is plotted in Figure 44. The bitumen content of the asphalt granulate was evaluated to 5.4 %.

In order to raise the content of fines in the granulate material, 5 % of limestone filler was added to the mixture.

By Proctor Standard test, the optimum water content was evaluated at 7.8 %, which was held constant for all mixtures.

From the mix granulate cold recycling mixtures were prepared in a pug-mill mixer by applying the binder contents as summarised in Table 19. For preparing the foamed bitumen water content of 4.5 % by mass, bitumen temperature of 180 °C and a foaming pressure of 5.5 bar was applied. Details to the mix design can be obtained in CoRePaSol Report D2.1 “Ageing”.

Table 19: Variation of bitumen emulsion and cement in IDT-stiffness-Study

<table>
<tr><th>Sample name</th><th>Content of bitumen emulsion (residual bitumen) C 60 B1 – BEM</th><th>Content of foamed bitumen (50/70)</th><th>Content of cement CEM I</th></tr>
<tr><td>A</td><td>3.5 (2.0)</td><td rowspan="4">-</td><td>0.0</td></tr>
<tr><td>B</td><td>3.5 (2.0)</td><td>1.5</td></tr>
<tr><td>D</td><td>2.0 (1.2)</td><td>0.0</td></tr>
<tr><td>E</td><td>3.5 (2.0)</td><td>3.0</td></tr>
<tr><td>G</td><td rowspan="4">-</td><td>2.0</td><td>0.0</td></tr>
<tr><td>H</td><td>2.0</td><td>1.5</td></tr>
<tr><td>I</td><td>3.0</td><td>0.0</td></tr>
<tr><td>J</td><td>3.0</td><td>1.5</td></tr>
</table>

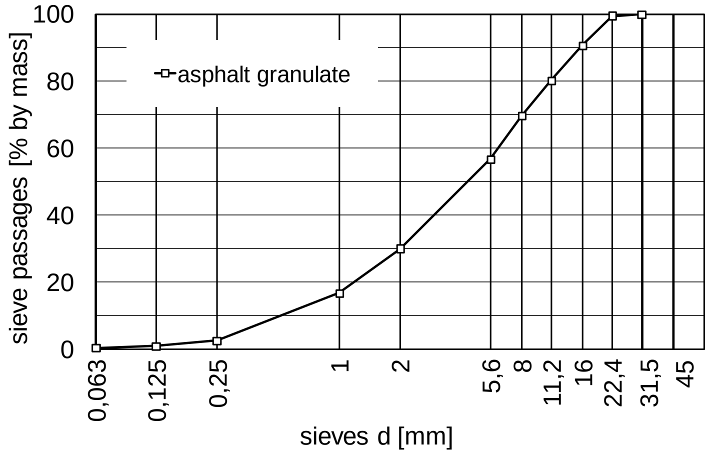


Figure 44: Grading of particle size for reclaimed asphalt

After the mix preparation, the specimens were compacted by double-plunger static compaction. For 10 minutes a force of 50 kN was held constant. After compaction, the specimens were demoulded after one day and then conditioned in a heating cabined for 3 days at 50 °C.

On three of the specimen, the indirect tensile strength was evaluated according to EN 12697-23 / EN 13286-42 by applying a vertical deflection rate of 50 mm/min. On additional three specimens the modified IDT stiffness test according to EN 13286-43 were conducted in which the specimens were tested repeatedly with varied loading rates. Afterwards the indirect tensile strength of these specimens was evaluated in order to compare the assessed strength results with and without stiffness evaluation. Therefore, it can be assessed if the specimen is deteriorated during the stiffness test with repeated loading or not.

4.3.2 Results of IDT-stiffness study

In a second study, rest periods were introduced between the loading phases of IDT stiffness tests. The mean stiffness values measured during the three different loading rates are summarized in Table 20 and plotted in Figure 45. The error bars added to the plots indicate the range of the stiffness modules obtained in the three single tests conducted.

Table 20: Results of IDT stiffness study: Mean stiffness modulus at varied loading rates

Sample mix		**A**	**B**	**D**	**E**	**G**	**H**	**I**	**J**
Bitumen		Bitumen Emulsion				Foamed Bitumen			
Residual bit. content		2.1 %	2.1 %	1.2 %	2.1 %	2.0 %	2.0 %	3.0 %	3.0 %
Cement content		0.0 %	1.5 %	0.0 %	3.0 %	0.0 %	1.5 %	0.0 %	1.5 %
Stiffness modulus [MPa]	5 kN/min	1817	6135	722	4491	349	4168	545	3450
	10 kN/min	1257	7393	972	5258	482	5129	628	4129
	50 kN/min	1931	10158	1613	9642	816	10296	1374	5208
Poisson ratio [-]		0.543	0.447	0.553	0.507	0.531	0.516	0.539	0.517

Regarding the test parameters it can be clearly observed, that an increased loading speed will result in a raised stiffness. This clearly indicates viscous or viscoelastic properties in all analyzed mixtures. Addition of cement to the mix won't reduce these viscoelastic properties.

In case of cement effect it can be observed, that already addition of a small quantity of cement (1.5 %) will significantly increase the stiffness modulus of the cold recycled mixture. Nevertheless, when comparing sample B and E, a further increase of cement content didn't result in an increased stiffness modulus. A reason for this could be the method of conditioning specimens after compaction. All samples were conditioned for three days at 50 °C. This didn't allow a complete hydration of the cement in sample E.

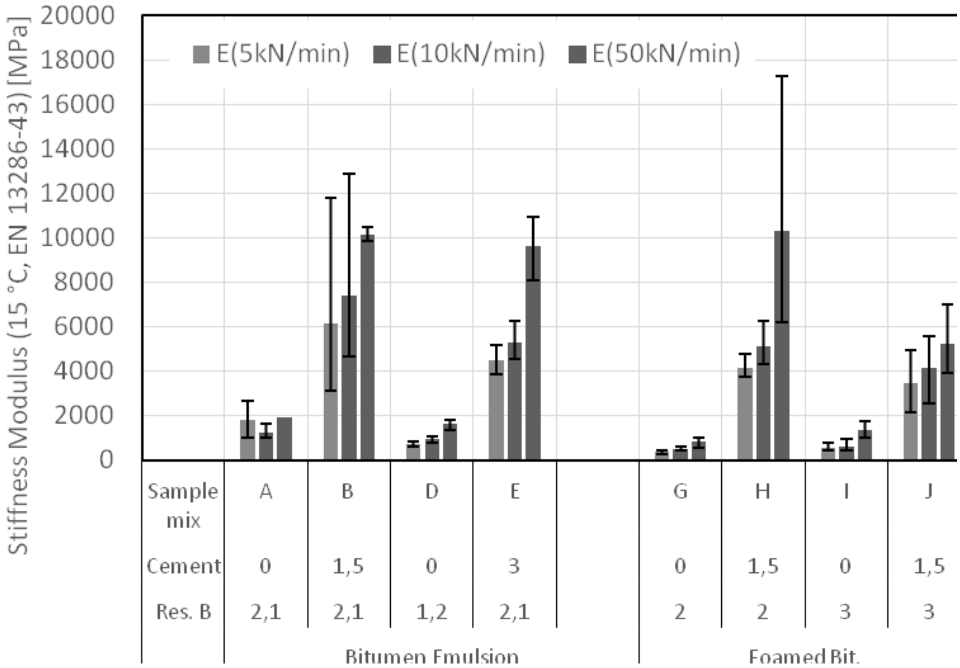


Figure 45: Results of repeated IDT stiffness tests according to EN 13286-43 at varied loading rates.

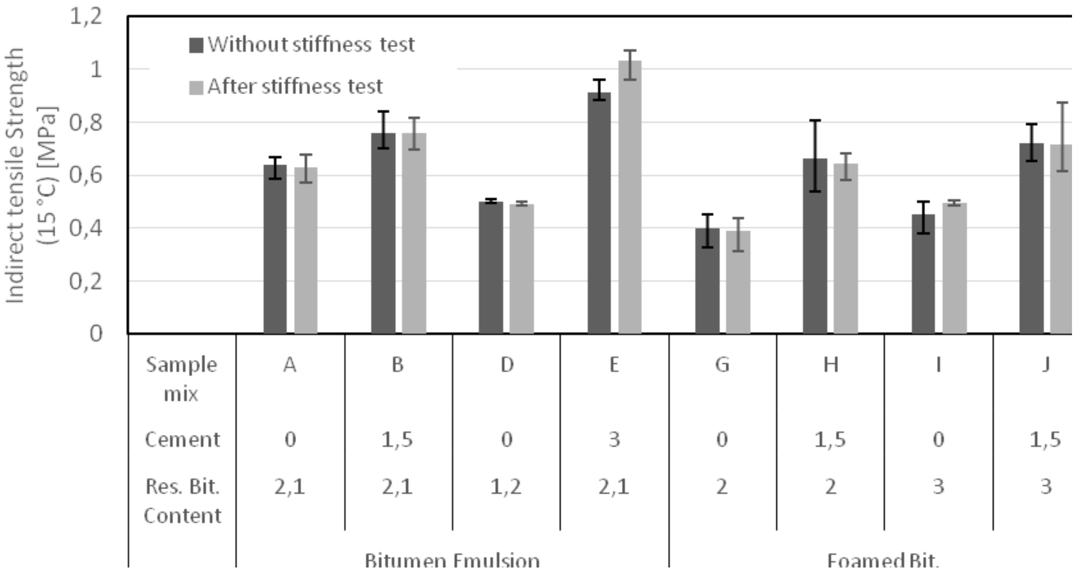


Figure 46: Effect of stiffness test on the indirect tensile strength

Some samples indicate a large test scatter. This can be partly explained by the deformation measurement frames applied during the test. The frames were clamped by springs to the specimen. For some specimen this fixture may have not been perfectly fitted, which may have resulted in misreading of the deformation measurements.

The stiffness modulus is calculated from the determined vertical force and horizontal deflection as well as from the Poisson's ratio itself calculated from the horizontal and 60° deflection. The Poisson's ratio effect on the calculated stiffness is significant. For the tests conducted in this study, the obtained Poisson's ratio was evaluated to 0.5. This indicates incompressible material properties usually found for unbound materials.

In this study it was further checked, if specimens have been deteriorated during the loading phases applied in the stiffness test. Therefore, the indirect tensile strength was evaluated on the specimens after stiffness determination and compared with the strength of specimens without loading history. The found strength results are plotted in Figure 46. It can be clearly observed, that the specimens, that were tested with the multi-phase stiffness test prior the strength test indicate similar strength values compared to unloaded specimens.

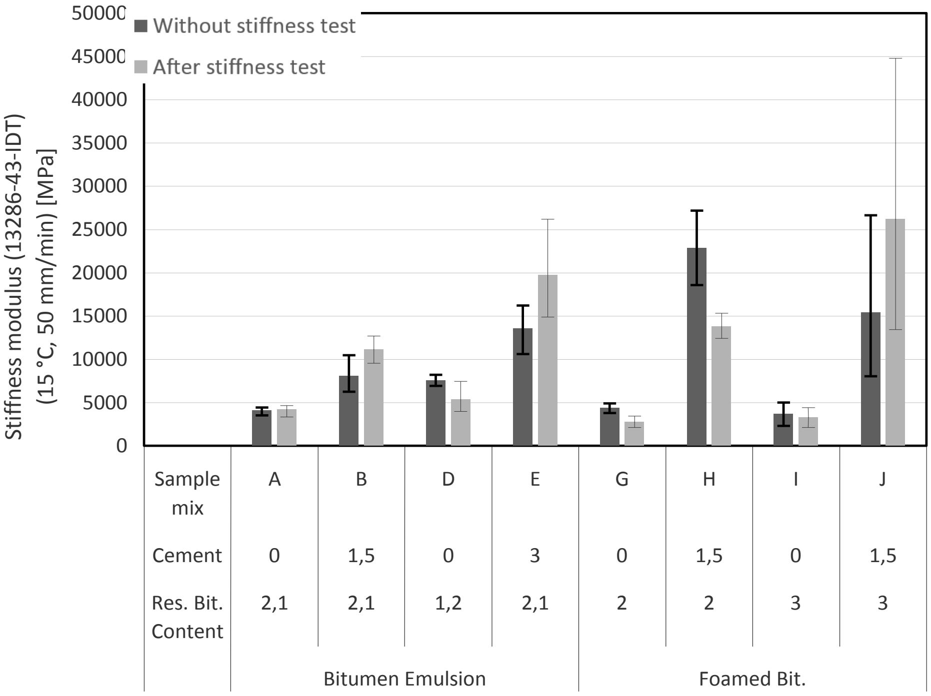


Figure 47: Stiffness according to EN 13286-43

During the indirect tensile strength tests, also the horizontal and 60°- deformation was measured. Therefore, the stiffness modulus could be evaluated directly according to EN 13286-43 specification without applying repeated loading phases. The obtained stiffness results are plotted in Figure 47. Besides the large scatter of the results which may be again explained by the application of a spring-held measuring frame, it can be observed, that the determined stiffness values are significantly higher compared the values obtained during the multiple-force-rate tests (compare Figure 45) even for the same tested specimen. A reason for this observation is the applied vertical-deflection-controlled test mode during the strength test. Here, a deformation rate of 50 mm/min was applied. This resulted in vertical force rates of up to 500 kN/min which therefore were significantly higher compared to the force rates applied in the multiple-phase study, where 5, 10 and 50 kN/min were applied. This indicates the viscoelastic character of the tested bitumen stabilised mixtures as well as the importance of specifying exactly the test conditions when stiffness or strength tests are applied.

4.4 Experimental study addressing performance related properties, namely stiffness modulus

Main objective of this partial study was the evaluation of the effect of low content of cement on the stiffness modulus, fatigue and permanent resistance of cold recycled mixes with bituminous emulsion. Wheel tracking tests in order to address permanent deformation behaviour were only performed within this study since it was not expected to be used as a standard test procedure for cold recycled mixes. Fatigue and permanent deformation results are because of study complexity included in this part even if there is a separate CoRePaSol report focused only on fatigue behaviour (Report D2.1 – Fatigue).

4.4.1 Materials

The reclaimed asphalt material used in this study was originated from the milling of the upper layers of a Portuguese National Road pavement, within its rehabilitation works. The grading curve of samples of the reclaimed asphalt was determined, as well as its average particles distribution (RA-Average). With regard to achieve a grading curve fitting the Wirtgen (2012) recommended envelop, some filer or cement should be added to the mixture. The first composition adopted comprised 97% RA and 3% filler, as shown in Figure 48.

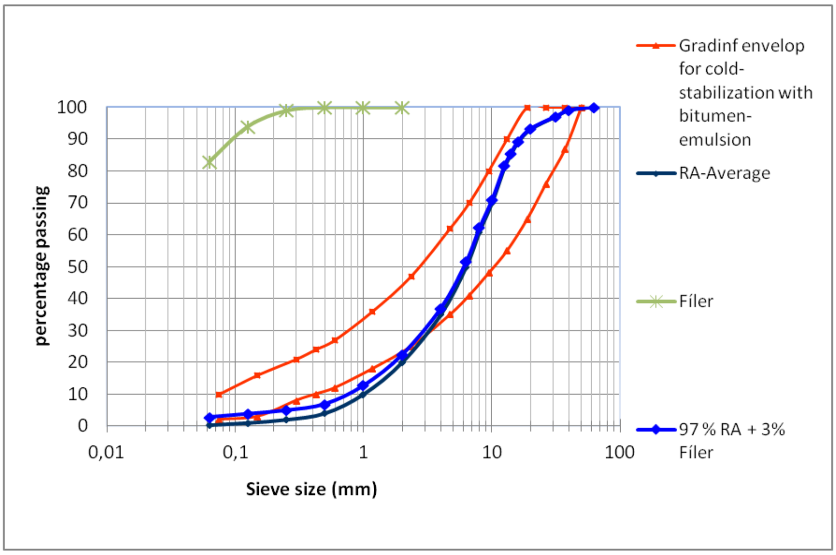


Figure 48: RA, filler and final granulate material grading curves

In the studies developed at LNEC, a cationic slow setting bituminous emulsion (C60B5 according to EN 13808:2013, which corresponds to former C60B7) was selected.

Furthermore, a 42.5 resistance strength Portland cements with rapid (higher) early strength (CEM I 42.5 R) was also used.

In order to investigate the influence on the cement content on performance related properties of cold recycled mixtures, such as stiffness modulus and resistance to fatigue and to permanent deformation, three mixtures were produced with the same amount of bitumen binder content (about 4 % of bituminous emulsion), and varying the cement content from 0 to 2 %. Table 21 shows the compositions that were adopted for these mixtures.

Table 21: Used mix compositions for bituminous emulsion stabilized materials and for bitumen emulsion & cement stabilized materials

Cold recycled mix ID		CM-E4C0	CM-E4C1	CM-E4C1
Content of each mix component	Reclaimed Asphalt	91.8 %	91.8 %	91.8 %
	Filler	2.8 %	1.8 %	0.8 %
	Cement	-	1.0 %	2.0 %
	Emulsion	3.8 %	3.8 %	3.8 %
	Added water	1.6 %	1.6 %	1.6 %

For each of the referred three mix compositions, it maximum density was determined (based on EN 12697-5, method A) as shown in Table 22.

Table 22: Maximum density of cold recycled mixtures

Cold mix ID		CM-E4C0	CM-E4C1	CM-E4C1
Maximum density (Mg/m^3)	ρ_{mv}	2.417	2.422	2.418

With each one of the referred cold recycled mixes, test specimens were prepared according to the shape and dimensions required for the test.

4.4.2 Description of the study

Cold recycled mixtures are known as evolutive materials, behaving similarly to unbound materials at early ages (short-term curing process), and more similarly to bound materials (i.e. hot asphalt mixes) when curing is completed. Thus, as curing develops, cold recycled mixes stiffness modulus and resistance to permanent deformation increases, and the fatigue behaviour gets closer to the typical behaviour of hot asphalt mixes (since the slope of the fatigue curve increases with curing). Nevertheless, it should be noted that, the “final” properties of cold recycled mixes using bitumen binder (bituminous emulsion or foamed bitumen), are different of those from conventional hot asphalt mixes [2], namely, in terms of:

- Voids content, which generally is higher for cold recycled mixes;
- Stiffness modulus, which is usually lower for cold recycled mixtures present;
- Ductility, which is, in general, higher for cold recycled mixtures.

As so, the addition of a certain amount of cement to cold bitumen stabilised mixtures has as one of his main aims to reduce the risk of damage during early-life trafficking due to deformation. However, the addition of cement can be a drawback at later ages (medium/long-term curing process) by increasing mix stiffness modulus too much and by leading to highly brittle material.

Taking this into account, test specimens were submitted to different curing/ageing, depending on the type of performance related property to be addressed, with the aim to evaluate the possible advantages and disadvantages of adding cement with low content level (1 % and 2 %), as follows:

- Resistance to permanent deformation: in this case, test specimens were previously subjected to a curing process that intended to simulate an early stage, being adopted 7 days in air at room temperature (approx. 20 °C).
- Stiffness modulus and resistance to fatigue: in this case, two different test specimens condition programs were adopted, one simulating an advanced curing process (1 day in mould + 3 days @ 50 °C), and other simulating also aged cold recycled mixes (test specimens firstly submitted to the referred accelerated curing procedure and after to an accelerated ageing of 5 days @ 85 °C, according to SHRP/AASHTO ageing method, which is further included in the newly proposed EN 12697-52).

Furthermore, the effect of ageing on the water sensitivity of cold recycled mixes with or without a small amount of cement was also addressed. Thus, in this case, the same two different test specimens condition programs above presented were adopted.

4.4.3 Permanent deformation resistance of cold recycled mixtures

In order to evaluate cold recycled mixes resistance to permanent deformation, wheel tracking tests were performed based on the method of EN 12697-22, small size devices, procedure B, in air. Slab test specimens (30.5 x 30.5 x 5 cm^3) were prepared using the roller compacter (based on the procedure of EN 12697-33, method using a steel roller sector).

As referred before, prior to testing, test specimens were allowed to cure for 7 days in air at room temperature (about 20 °C).

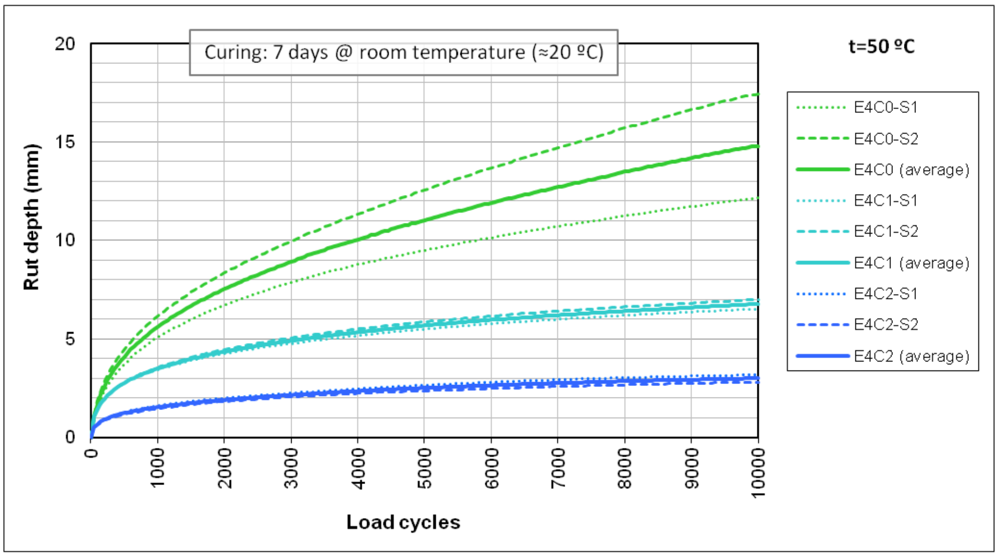


Figure 49: Rut depth evolution with load cycle

Wheel tracking tests were performed at a temperature of 50 ºC, not only because this is a temperature considered more representative for Portugal [6], but also to minimise the effect that a higher temperature (e.g. 60 ºC traditionally used in hot bituminous mixes) would have in the curing of the test specimens during wheel tracking tests. Table 23 and Figure 49 show the results for the tested mixtures, all of them previously cured for 7 days at room temperature (approx. 20 °C).

Table 23: Summary of wheel tracking results for cold recycled mixes with 7 days of curing at room temperature

Wheel tracking test t=50 ºC		Cold recycled mix ID		
		CM-E4C0	**CM-E4C1**	**CM-E4C2**
Rut depth, *RD*, after 1 000 load cycles (mm)	S1	12,15	6,53	3,18
	S2	17,42	7,00	2,81
	Mean	**14,8**	**6,8**	**3,0**
Wheel-tracking slope in air, WTS_{AIR} (mm/10^3cycles)	S1	0,53	0,21	0,11
	S2	0,97	0,23	0,09
	Mean	**0,75**	**0,22**	**0,10**
Proportional rut depth, PRD_{AIR}, in air (%)	S1	21,82	12,39	6,14
	S2	31,57	13,12	5,39
	Mean	**26,7**	**12,8**	**5,8**

Table 23 and Figure 49 show that even a small amount of cement (1 %) has a great influence on the resulting permanent deformation of the tested cold recycled mixtures. In fact, mixture CM E4C0, not only shows vey high rut depth values (RD), but also a very high variability.

4.4.4 Stiffness modulus and fatigue resistance of cold recycled mixtures

In order to evaluate cold recycled mixes stiffness modulus and resistance to fatigue, cylindrical test specimens were prepared by static compaction according to the procedure described in NLT 161 standard (based on ASTM D1074), but applying a compressive load of about 7.5 MPa. All test specimens were than submitted to an accelerated curing process of 1 day in the mould at room conditions and for additional 3 days in air (unsealed) at 50 °C.

As referred previously, the specimens were then separated into two groups:

- The first group was immediately tested;
- The second group was further submitted to an accelerated laboratory ageing procedure, of 5 days in the oven at 85 °C, and then tested.

At the end of the conditioning period (curing / curing + ageing), the stiffness modulus (E) and the fatigue life was determined by using an indirect tensile test on cylindrical specimens, based on the methods described, respectively, in EN 12697-26 (Annex C: IT-CY) and in EN 12697-24 (Annex E: ITT on cylindrical shaped specimens), at a temperature of 20 °C.

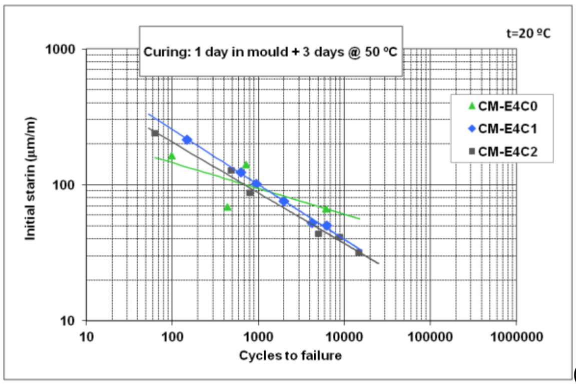
Table 23 summarises the stiffness modulus (IT-CY) of all mixtures at varying conditioning programmes.

As it can be observed in Table 24, the voids content of the obtained test specimens showed some variety, and in the case of the set of test specimens tested after accelerated curing process (1 day in mould + 3 days @ 50 °C) the values achieved were relatively high. In case of the stiffness values, no tendency is possible to detect.

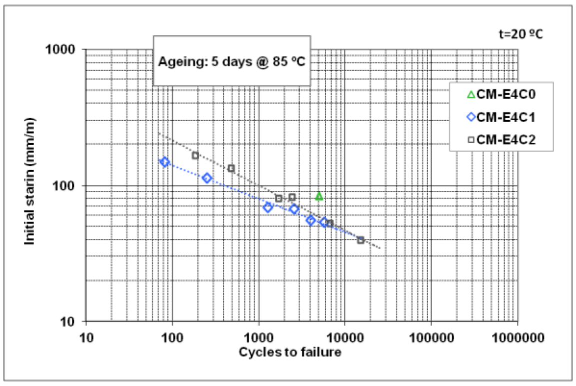
Table 24: Indirect tensile stiffness modulus (E) test results for cold recycled mixes with accelerated laboratory curing and/or ageing procedure

Test applying indirect tension to cylindrical specimens t=20 ºC		Cold recycled mix ID		
		CM-E4C0	**CM-E4C1**	**CM-E4C2**
Curing: 1 day in mould @ 20ºC + 3 days @ 50ºC	ρ_{bdm} (Mg/m^3)	2.087	2.078	2.064
	Vv (%)	14	14	15
	E (MPa)	3,700	3,800	3,700
Aged test specimens: 5 days @ 85ºC (after accelerated lab curing)	ρ_{bdm} (Mg/m^3)	2.143	2,128	2.124
	Vv (%)	11	12	12
	E (MPa)	3,700	3,600	4,000

Figure 50 shows the fatigue test results (repeated indirect tensile tests on cylindrical shaped specimens) obtained for cold recycled mixtures by this partial study. It should be noted that, due to the problems on data acquisition equipment, some of the results on CM-E4C0 test specimens were not possible to obtain (only four results for the fatigue life of specimens after accelerated curing process, and only one in the case of aged test specimens).



(a)



(b)

Figure 50: Fatigue test results for cold recycled mixes: (a) with advanced laboratory curing; (b) aged test specimens

In spite of the variability shown by CM-E4C0 cold recycled mix, it may be concluded from Figure 48a that the slope of the fatigue curve of this mixture (without cement) is lower than the one obtained for the mixtures containing cement (CM-E4C1 and CM-E4C2). For these last two cold recycled mixtures, the fatigue behaviour is quite similar. Analyzing the effect of laboratory accelerated ageing, it seems that the fatigue life of both mixtures with cement is not significantly changed.

4.5 *Problems related to IT-CY stiffness determination of cold recycled mixtures*

4.5.1 Mix design and specimen production

Table 25 summarizes mix design of 4 basic cold recycled mixtures, which were used for performing a large part of the experiments done within CoRePaSol project at CTU in Prague. Key different alternatives of cold recycled mixtures are addressed in this table. There is a mix containing bituminous emulsion and higher content of cement (mix A), mix with foamed bitumen and higher content of cement (mix B), as well as mixes containing solely bituminous emulsion (mix C) or foamed bitumen (mix D). Based on that it is possible to define four main groups of bitumen based cold recycled mixes:

- → BCSM-BE: Bitumen-Cement Stabilized Material – Bitumen Emulsion (mix A)
- → BCSM-FB: Bitumen-Cement Stabilized Material – Foamed Bitumen (mix B)
- → BSM-BE: Bitumen Stabilized Material – Bitumen Emulsion (mix C)
- → BSM-FB: Bitumen Stabilized Material – Foamed Bitumen (mix D)

Some investigated topics required further alternative design of some additional mixes. Composition of those extra mixtures is always defined in the individual chapters presented in this report.

For the experimental studies all designed mixes contained the same type of sorted RAP with 0/22 mm grading or in some cases with 0/11 mm grading originating from the same source (hot mix asphalt plant Středokluky). Nevertheless the homogeneity of RAP was quite poor, which is typical for the Czech circumstances or more generally it is typical for these materials if selective cold milling for each construction site is not done. This fact influenced greatly the test results and complicated setting of any final conclusions with appropriate repeatability of determined data. Figure 51 and 52 show the grading curves of RAP 0-22 mm and 0-11 mm, however, these curves as well as the determined bituminous binder content of 5.6 % for RAP 0/22 and 6.7 % for RAP 0/11 should be considered as just approximate, because the composition of RAP differed even within a single batch not to mention the difference between batches. Because of that it was very important to perform all measurements for each chapter at once. Measuring of some related values later using specimens made from another batch is not recommendable because the RAP composition influences greatly the final mix characteristics, as is discussed in this report.

Table 25: Mix design

	Mix A	Mix B	Mix C	Mix D
Reclaimed asphalt mix	91.0%	90.5%	94.0%	93.5%
Water	2.5%	2.0%	2.5%	2.0%
Bituminous emulsion	3.5%	0.0%	3.5%	0.0%
Foamed bitumen	0.0%	4.5%	0.0%	4.5%
Cement CEM II B32.5R	3.0%	3.0%	0.0%	0.0%

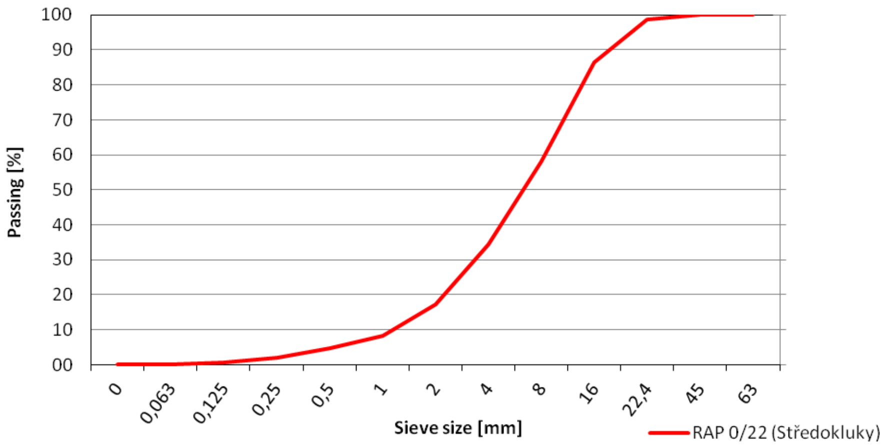


Figure 51: Grading curve of RAP 0/22 mm

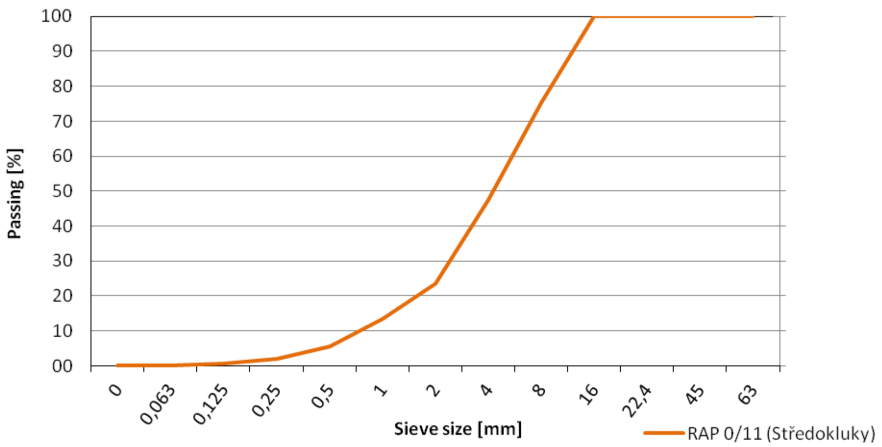


Figure 52: Grading curve of RAP 0-11 mm

The used cement was classified CEM II / B 32.5 according to EN 197-1. The optimal moisture content of the cold recycled mix was determined according to (ČSN EN 13286-2).

Mix A, mix C and other mixes described in the following chapters contained cationic slow-breaking bituminous emulsion C60B7 (according to the designation in EN 13808 valid until 2014) which is commonly used in the Czech Republic. Mix B, mix D and other mixes described in the following chapters as well were based on the foamed bitumen. For the production of foamed bitumen standard pen grade bitumen 70/100 was applied according to EN 12591. When preparing the foamed bitumen, there was 3.8 % of water added to the bitumen (the amount was determined in accordance with the procedure which is recommended for cold recycling technology by Wirtgen Manual 2012). Foamed bitumen was injected into the cold recycled mix under the temperature between 160 °C and 170 °C by means of the Wirtgen WLB10S laboratory equipment. The mix as such was mixed using a twin-shaft compulsory mixing unit Wirtgen WLM 30.

Foamed bitumen is characterized by the expansion ratio ER (ml/g) and the half-life of foam settlement τ½ (seconds). Both parameters are strongly dependent on the kind and origin of the bituminous binder, the amount of the compressed air added and the pressure of the water injected into the hot bitumen. The intensity and efficiency of the foaming effect can be influenced by basic physical conditions such as temperature, moisture and pressure. The optimal amount of the foaming water was set at 3.8 % of bituminous binder in order to achieve maximal expansion ratio (value obtained: 18) and maximum half-life (value obtained: 12 seconds).

The cylindrical specimens usually with 150±1 mm diameter and 60 mm height were prepared by putting the cold recycled mix in cylindrical moulds and compacted by applying pressure of 5.0 MPa. The basic volumetric parameters were determined for the manufactured test specimens, and the indirect tensile strength according to (TP 208) was measured as well. For all test specimens data on stiffness modulus were collected.

Due to the important priority of the civil engineering practice to minimize the duration of laboratory tests, there is an effort to find an appropriate method to accelerate the process of specimens curing. Within the investigation performed during the CoRePaSol project, it was decided that it is possible to divide cold recycled mixes into two groups from the point of view of curing. The first group is formed by mixes with more than 1 % of cement. The curing time of these mixes cannot be significantly shortened, because of the cement hydration process, which is absolutely essential for the final characteristics and behaviour of this type of cold recycled mix. For all mixes containing more than 1 % of cement, the basic period of specimen curing was 14 days. Some specimens were also tested after 7 and 28 days. To simulate the initial moisture content of the mixture after paving and compaction of the fresh mix, specimens were usually stored for the first 24 hours at 90-100% relative humidity and a temperature of (20±2) °C. This was done by keeping the specimens in the mould or by putting them into a suitable plastic bag. Further the specimens were stored at laboratory conditions with 40-70 % relative humidity and a temperature of (20±2) °C for the rest of their curing time.

For mixtures containing 1 % of cement by mass and less, the test specimens were usually subjected to accelerated curing procedure defined e.g. in the project report D1.1. According to this procedure each of such conditioned specimens is stored for first 24 hours at laboratory temperature in a plastic bag, however, after that it is removed from the bag and cured unsealed for additional 72 hours at 50 °C.

4.5.2 Effect of duration of thermal conditioning and specimen dimensions on stiffness modulus

Laboratory specimens (Ø150 mm, height 60 mm) of mix A were compacted by a static pressure of 88.5 kN. The mix design is given in chapter 4.1.1 (3 % cement, 3.5 % bituminous emulsion, RAP 0/22). Half of the specimens were used for drilling cores 100 mm in diameter. That means all measurements were carried out using both specimens of 150 mm (MA1-4) and drilled out specimens of 100 mm (ma5-8). Both groups of specimens were used for investigating stiffness modulus according to repeated indirect tensile stress test (IT-CY) at 15 °C after 14 days of specimen curing in laboratory conditions. The measurement was performed twice, firstly after 3 hours of specimen conditioning, and secondly after a further 4 hours of leaving the specimen at the testing temperature in the climatic box.

As a result of the additional 4 hours of conditioning stiffness modulus values showed an average increase of 10 % irrespective of the specimen size. Specimens with Ø 100 mm even showed slightly higher increase in stiffness modulus values. These results confirm the strong dependence of the stiffness modulus on the testing temperature. Based on these findings there is a recommendation to extend the time of specimen temperature conditioning to 4 ± 1 hour for testing temperatures ≥10 °C.

Despite the negligible delay between the determination of stiffness by using the specimens with 150 mm diameter and 100 mm diameter, the values of stiffness modulus which were gained for specimens with 150 mm diameter were about 20-25 % higher. This can be explained by the boundary conditions resulting from the compaction mould for the diameter 150 mm specimens. For these, the grains of the mix granulates are pressed to the mould and reach differing forced interlock compared to the specimen center. These interlocked regions are removed during specimen coring.

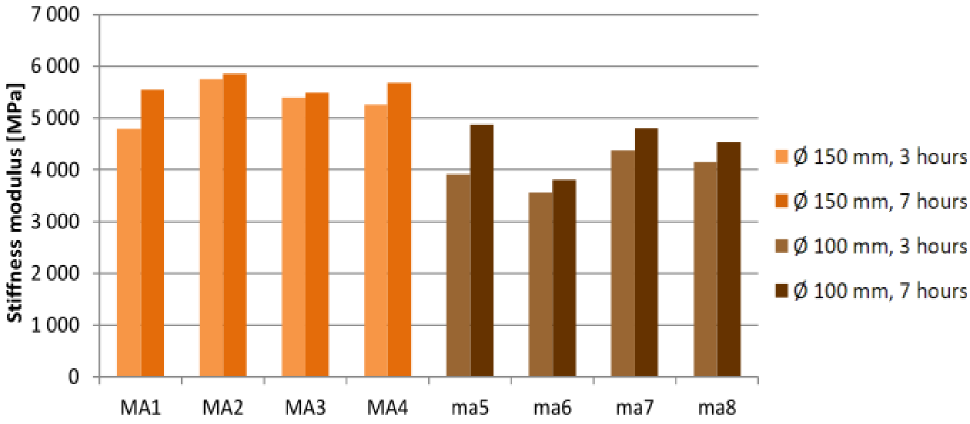


Figure 53: Comparison of specimen diameter impact on stiffness modulus of cold recycled mix

All these specimens were then tested after additional curing at laboratory conditions after eight months. The average increase in stiffness modulus was 16 %. Unfortunately the values of stiffness modulus after 28 days of curing were not measured.

4.5.3 Effect of test specimen height

One of the practical problems of laboratory testing, which occurred within the experiment, consisted in finding the answer for an important question of how does the height of a cylindrical specimen influence the results of the performed tests. The necessity to deal with this issue originated from different requirements on test specimen height for the indirect tensile strength test and stiffness modulus test. As mentioned earlier the stiffness modulus is detected by a non-destructive manner and therefore it is advantageous to use each specimen for detecting both qualities. Firstly the stiffness modulus is measured in NAT apparatus and then the same specimen is destroyed during the destructive indirect tensile strength test. Current Czech technical specifications for cold recycled mixes [15] require for the indirect tensile strength test cylindrical specimens with diameter 150 mm and height 125 ± 2 mm. The use of such specimens for measuring the stiffness modulus is nevertheless impossible due to the limiting size of the frame which is used for fixing specimen during the stiffness modulus test.

The formula for calculation of the indirect tensile strength (1.7) includes also the specimen height and therefore it should be possible to convert a smaller force affecting a smaller area and get the same rate of stress. (Similar arrangements applicable to this relationship should be possible, when comparing values measured on specimens for ITS with diameter of 100 mm and 150 mm).

$$R_{it} = \frac{2.F}{\pi.H.D} \tag{1.7}$$

This assumption was experimentally tested with 56 test specimens compacted from 7 different mix designs with 3.5 % and 4.5 % of foamed bitumen and varying content of cement (see Figure 54 and 55). Only in one case was there a 15 % difference between the specimens with height of 60 mm or 125 mm, which could be caused, e.g., by insufficient temperature conditioning of laboratory specimens. All other average values differ only by a few percent. These measurements proved the possibility of adjusting the specimen height. Due to high amounts of needed laboratory specimens and their demanding production, it was decided to use entirely the specimens of 60 mm height, which can be used for both stiffness modulus test and the indirect tensile strength test.

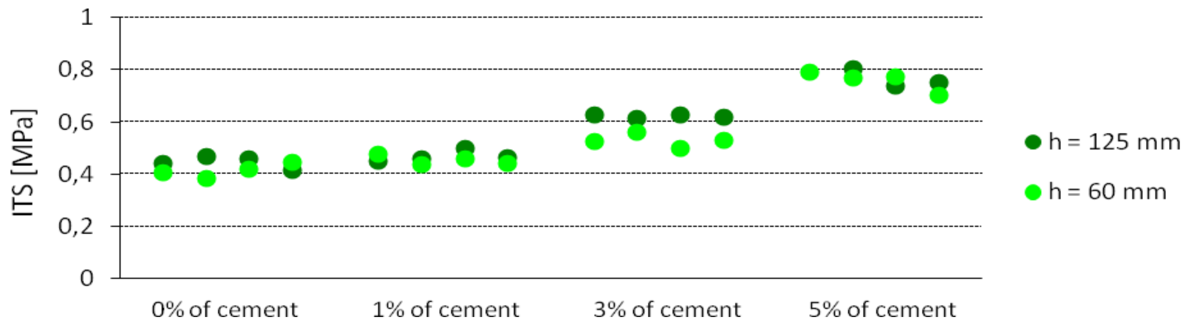


Figure 54: Comparison of indirect tensile strength and the height of test specimen for different mix designs

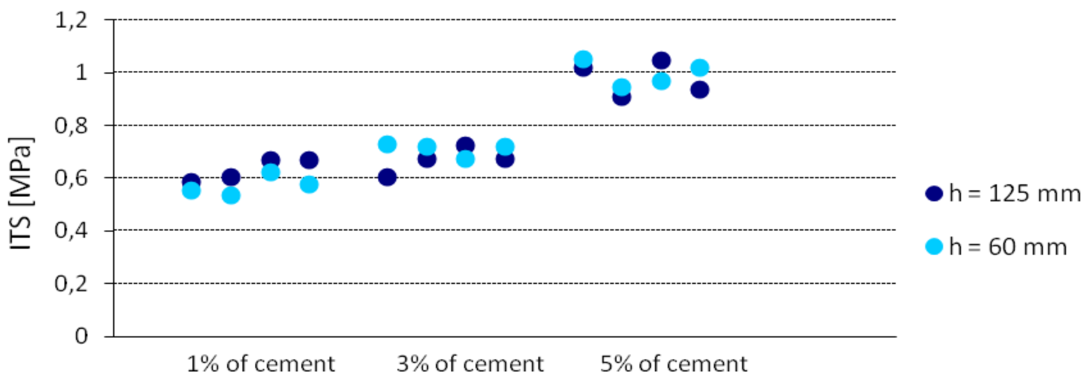


Figure 55: Comparison of indirect tensile strength and the height of test specimen for different mix designs

4.5.4 Effect of voids content on the stiffness modulus

Characteristics of used RAP influence significantly the final properties of the cold recycled mixes. Its heterogeneity complicates also considerably the determination of any limits for the minimum value that these mixtures should achieve. This problem is closely related to the influence of voids on the stiffness modulus, which is described in this sub-chapter.

Within two years of project CoRePaSol duration the stiffness modulus of identical specimens has been repeatedly tested. The specimens produced from the basic mixtures A-D described in chapter 4.1.1 were all compacted and cured in the same way and tested at the same temperature. If using an ideally homogeneous material similar values should be gained for voids content assessments at different times. However, as it can be observed in the Figure 50, measured values of stiffness modulus were rather different. Used laboratory specimens had cylindrical shape (diameter 150 mm, height 60 mm) and they were tested at 15 °C. Those made from mixes containing cement (mixes A and B) were cured for 14 days at laboratory conditions, while specimens from mixes without cement (mixes C and D) were subjected to an accelerated curing procedure (see chapter 4.1.1).

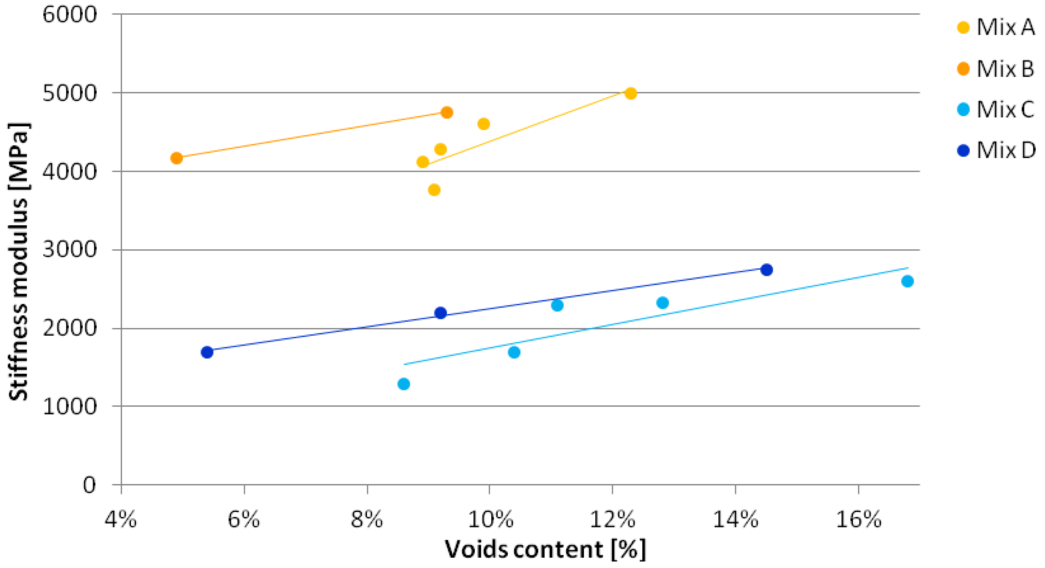


Figure 56: Relationship between stiffness and voids content of selected cold recycled mixes

Depending on the grading curve of used RAP different values of voids content were detected in the specimens produced from identical mixtures. The range of gained voids contents of the cold recycled mixes is quite large compared to the standard hot asphalt mixtures, which are significantly more sensitive to the voids content. Especially for mixtures without cement large scatter of voids content can be observed (mix C – from 8.6 % to 16.8 %, mix D – from 5.4 % to 14.5 %). Mixtures with foamed bitumen (mixes B and D) achieved lower values of voids content than mixtures with bituminous emulsion (A and C), but that was probably affected by the fact that mixtures B and D contained 4.5 % of foamed bitumen, while mixtures A and C contained only 3.5 % of bituminous emulsion. An interesting finding comes up if interspersing the measured values by linear regression function. Figure 56 clearly shows that with increasing voids content the stiffness modulus value increases as well. This fact can be identified by all four types of cold recycled mixtures. This increase shows that for this type of mixtures the coarse skeleton is very important and that it is always necessary to pay appropriate attention to the final grading curve.

5 Conclusions

Following conclusions can be drawn from the stiffness assessment studies presented in this report:

The stiffness modulus of bitumen stabilized materials as well as of other cold recycled mixtures depends on test conditions like applied test temperature and loading speed. This can be explained by viscoelastic material behavior originating from the reclaimed asphalt material (RA/RAP) as well as from the bituminous binder applied.

According to the determination of stiffness for bitumen content variations and cement content variations indicate the differing effects of both types of binders and also their content. The increase in bituminous binder content above an optimum will increase the materials flexibility which however results in a decrease of stiffness. This stiffness decrease will also result in decreasing indirect tensile strength values obtained in deflection-controlled monotonic indirect tensile tests. The strain at specimen failure is still high. It has been clearly shown that mainly for mixes containing foamed bitumen it is not effective to design mixes with more than 3.0 % foamed bitumen content. Similar findings have been found for cold recycled mixes containing bituminous emulsion.

On the other hand the stiffening effect of increased cement content does not increase the indirect tensile strength in the same magnitude as for the stiffness. This results in an increased brittleness and therefore in lower crack resistance at enforced strain loading. This is a typical behavior which can be expected for cement stabilized mixes.

With respect to use of other reclaimed materials than RAP the results has shown large variability. It was even repeatedly proven that the grading combined with voids content have an irreplaceable role in the cold recycled mix and its performance. Therefore the grading envelopes set e.g. in Wirtgen Cold Recycling Manual has to be carefully watched and perhaps even narrowed in order to ensure high mix quality. Similarly the voids content has to be determined and later compared to stiffness or ITS values. Cold recycled mixes are very complex materials and one of their most important characteristics is the suitable grading curve. Therefore, it is more important to look for the quality of the whole mix, instead of the quality of single components and also to care for the appropriate proportions of particular components, which will guarantee the optimal grading curve with good aggregate skeleton. This has been demonstrated e.g. by combining RAP or recycled concrete with some fine grained sand which formed usually an effective mortar. On the other hand comparing mix options with 50 % sand or 25 % sand it is clearly visible that there are some limits. If overrunning them the content of fines has rather negative impact.

In general it can be recommended that if stiffness is determined according to EN 12697-26 by test method IT-CY then for mixes containing at minimum 2 % cement the stiffness after 14 days curing (according to the procedure described e.g. in the Project report D1.1) determined at 15 °C should be at least **3,500 MPa**. Similarly for mixes without cement and bitumen content not exceeding 3 % the stiffness determined after accelerated curing shall be at 15 °C at least **1,000 to 1,500 MPa** (depending on the type of bituminous binder). Comparing use of RAP or recycled concrete no clear final conclusions can be made. In general it seems that mix design containing RAP has slightly higher stiffness values which might be given also by the activity of the bitumen. On the other hand of higher content of bituminous binder would be used in combination with higher content of cement and the recycled concrete would demonstrate a good grading, such mix can easily reach stiffness >4,000 MPa.

More difficult is to find some trends and clearly presentable functionalities if moisture susceptibility is evaluated. Comparing different mixes, it is visible that the binder and its content play a role. Nevertheless it was not possible to identify some dependence which would be true for different sets of mix designs. This again demonstrates a very complex aspect of cold recycled mixes and the necessity to evaluate each design case by case. This might be also influenced by the heterogeneity of the granular material which is used.

If summarizing the additional studies it can be concluded that:

- The stiffness evaluation procedure as specified in EN 13286-43 using indirect tensile strength tests can be applied for cold recycled materials after some necessary modifications.
    - To allow mechanistic pavement design calculations, the stiffness of the mixture shall be evaluated at varied temperature and loading speed conditions to evaluate the viscoelastic behavior of the mixture.
    - To apply stiffness modulus values during mix design, the test conditions like temperature and loading rate has to be specified in detail in order to allow for comparable test results.
- CBR method can be applied as simple evaluation tool for stiffness and/or permanent deformation assessment. Though, the results don't allow for mechanistic pavement design because of non-controlled loading conditions during the test.
- The specimen dimensions have an effect on the stiffness obtained from indirect tensile tests:
    - Specimens of 100 mm diameter cored from the centre of specimens compacted to 150 mm indicated reduced stiffness. This can either be explained by a size effect or by diverse grain interlock at the specimen edges resulting from the boundary to compaction mould.
    - The specimen height has no significant effect on the ITS result. This would enable the preparation of specimens with reduced height which would be advantageous due to improved compactibility in laboratory.
- The stiffness tests have to be conducted at controlled temperature and required conditioning of the test specimens. The temperature conditioning should be long enough for guaranteeing homogeneous temperature in the specimen. A conditioning time of 4 h is even required for test temperature above 10 °C.

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