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CoRePaSol

characterization of advanced cold recycling bitumen stabilized pavement solutions

Report on Durability of cold-recycled mixes: moisture susceptibility

Final report

Deliverable D2.1

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Characterization of Advanced Cold-Recycled Bitumen Stabilized Pavement Solutions

Report on Durability of cold-recycled mixes: moisture susceptibility

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Deliverable D2.1 – moisture susceptibility

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Executive summary

Moisture susceptibility of cold recycled mixes can be determined similarly to hot mix asphalt according to EN 12697-12 or according to national practices, methods or technical specifications developed specially to cold bituminous mixtures (“new” or recycled). For instance, in the Czech Republic, moisture susceptibility of cold bituminous mixtures is traditionally evaluated according to the Czech technical specification TP 208 [1]. Parts of the research described and evaluated in this report are based on this last named procedure. Moisture susceptibility in the case of TP 208 is similarly to the procedure described in EN 12697-12 defined as a ratio of indirect tensile strength (ITS) value for dried and saturated (cured) specimens. In general, the specimens of cold recycled mixes are cured, according to this test procedure, for 7 days in air (dry) at laboratory conditions. Half of the test specimens are then conditioned for an additional 7 days using water saturation. Only dry cured specimens are immediately tested on their ITS after the referred seven days of curing. This method of moisture susceptibility determination has several disadvantages in comparison to the test procedure for hot mix asphalt. The most important one is that when it is applied, values determined on specimens cured for different periods of time are compared. Moreover when using the Czech approach, the determined values of moisture susceptibility exceed in some cases the value of 100 %. Although this may also occur in the case of hot bituminous mixtures evaluated according to EN 12697-12 (see, for instance, the study of Batista *et al.*, 2011) [26] in cold bituminous mixtures this could be more frequent due to differences in tested specimens curing (e.g. “wet” test specimens being 7 days older than “dry” specimens can lead “wet” specimens to a more advanced curing process, thus presenting higher strength than “dry” specimens). Therefore, comparison of the ITS values measured with specimens of the same age seems to be more advantageous, however, the impact on the practical aspects should be also taken into account. Determination of the ITS value of the unsaturated specimens would be carried out after 14 days of specimen curing instead of presently used 7 days, which is inconsistent with the prevailing efforts to minimize the traffic restrictions. An alternative is to produce a larger number of laboratory specimens to get more possible alternatives of the moisture susceptibility ratio. In other countries, moisture susceptibility tests are performed on test specimens of the same age. This is the case of France, where the Duriez test (unconfined compression test on Duriez test specimens conditioned with/without immersion) is usually applied in order to investigate the resistance of mixtures against water immersion, in accordance with the French standard NF P 98-251-4. In this case, the test requires both group of test specimens to be tested at 14 days, but in different conditions: while the group of “dry” specimens is kept stored for 14 days in air (in a standardized manner) prior to testing, the group of “wet” specimens is firstly conditioned for 7 days in air, and submersed in water for further 7 days. As in the case of the previously described method, also some disadvantages are associated with the Duriez method, being one of them the relatively long duration needed for it. Another example comes from southern European countries such as Portugal and Spain, where a shorter time and higher temperatures for curing (3 days at 50 ºC) are used, prior to assess specimens’ moisture susceptibility. Therefore, it is clear that in many other countries where cold recycling technology is carried out, other approaches for moisture susceptibility determination can be found, as had already been stated in CoRePaSol project report D1.1.

The key objective of the presented report was a more detailed assessment and comparison of moisture susceptibility determining methods. Alongside the 7 + 7 method defined in the Czech specifications TP 208 [1], the procedure used in European countries for hot mix asphalt testing was also evaluated. This procedure is used in all countries, which are jointly governed by harmonized European specifications, particularly by EN 12697-12 [2]. The conducted research was also supplemented by the test method for moisture susceptibility determination described in the American specification AASHTO T283 [3]. The indirect tensile strength and stiffness modulus values were measured for both – cold recycled mixes stabilized only by bituminous binder (bituminous emulsion or foamed bitumen), and mixes containing combination of bituminous and hydraulic binder (cement + bituminous emulsion and cement + foamed bitumen)..

1 Introduction

Moisture susceptibility is considered to be one of the most important characteristics of a road base or binder course if asphalt mixes are used in the pavement structure. That is because the individual pavement courses are constantly exposed to water, which is present in the pavement structure in all states (liquid, solid – ice, gaseous – water vapour).

The main problem of the water presence in the pavement structure is that it weakens the adhesion between aggregate particles and bitumen, potentially leading to the occurrence of aggregate stripping. This can lead to various forms of distress, such as rutting and fatigue cracking or pothole formation at later stages. Another effect that this process may cause is the binder extrusion on the pavement surface, which reduces then the pavement skid resistance. Mentioned consequences of the deteriorated moisture susceptibility can be very serious, and therefore many research projects all around the world are devoted to the field of HMA moisture susceptibility. Major international conferences focusing exclusively on this topic took place during last years as well (e.g. Workshops on Moisture Damage, held at Delft University of Technology in 2005 and at Texas A & M University in 2007).

Moisture susceptibility research of mixes with higher content of RAP or research focused fully on cold recycled mixes is significantly newer and therefore less developed, even in terms of available research findings and recommendations. In this field several research projects have been conducted, but the results to date have not yet brought any consistent conclusions.

2 Moisture susceptibility – literature search

2.1 Moisture susceptibility of mixes containing RAP

Efforts of many scientific papers to compare the moisture susceptibility of traditional HMA and asphalt mixes containing RAP remain incomplete. It is still not possible to determine unambiguously the influence of a recycled material on moisture susceptibility. Kennedy, Roberts and Lee [4] found out that the asphalt mix with RAP withstands the water effect better than the asphalt mix containing just virgin aggregate. This finding is quite logical when considering the fact that the bituminous binder may create a thicker film around the mineral particles of RAP and some weakened spots can be remedied as well. Similarly Aurangzeb et al. [5] proved that the addition of up to 50 % of RAP into the asphalt mix gives equal or even better resistance to the moisture effect than the mix from virgin materials. On the other hand e.g. Hu et al. [6] claimed that already addition of 30 % of RAP causes significant decrease of the resistance against moisture effects and therefore such mix design can induce large number of pavement distress.

Very interesting findings in this field are summarized in the work of Poulikakos et al. [7], which is focused on the comparison of both mix types in terms of macro and micro scale. Using the Dynamic Vapour Sorption method (DVS) it was proven that a mix containing 40 % of RAP is significantly more sensitive to the effect of water than a mix containing virgin materials, that absorbed distinctively less water and it also reached the saturation much faster. Further, investigations using the atomic force microscope (AFM) showed that there was a change of surface properties of the bitumen film coating the aggregate particles before and after immersion in water. However, in this part of the performed research no higher moisture susceptibility was observed. This was supported by same investigations of moisture susceptibility in macro-scale using standard laboratory specimens.

In terms of the cold recycled mixes used for base courses, moisture susceptibility is a crucial characteristic which can usually be identified as a source of distress. According to the South African technical specification TG2 [8] (Asphalt Academy 2002), this characteristic is critical especially for mixtures with foamed bitumen, due to the typical way of coating the aggregate particles by the bituminous binder – the coating is just partial and fully present for small particles. Bituminous foam coats the fine particles, which form a compact mortar, which then provides a spot agglutination of larger/coarser particles.

Iwański and Chomicz-Kowalska [9] investigated the influence of the bituminous binder content (bituminous emulsion and foamed bitumen) on the moisture susceptibility using the TSR method. They verified experimentally that in the examined range of bituminous binder content (2 %, 2.5 %, 3 % and 3.5 %) a significant effect on moisture susceptibility can be identified. The more bituminous binder the mix contained, the lower the moisture susceptibility (higher ITS ratio) was. Mixes with foamed bitumen showed better moisture susceptibility than mixes with bituminous emulsion.

2.2 Chemical bond between aggregate and bitumen

Water sensitivity is closely connected to the adhesion characteristics, i.e. to the strength of bitumen-aggregate bond. In this bond the bituminous binder molecules orientate themselves according to the ions at the aggregate surface. Its strength depends on chemical properties of used materials, particularly on their surface tension. Bituminous binders of higher viscosity generally comprise larger amount of asphaltenes, large polar molecules which can form better adhesive electrical voltage due to their polarity. Another factor which affects the adhesive properties of the bituminous binder is the content of sulfoxides, carboxylic acids, phenols etc. In terms of the used aggregate, better bond with bituminous binder forms aggregate types with an alkaline surface. Suitable is also the content of iron, magnesium and calcium, while detrimental is the content of sodium and potassium, which cause acidic surfaces.

Replacement of bitumen molecules by water molecules, which results in aggregate stripping, is caused by the fact that the dipolar water molecules are more polar than the molecules of bitumen. Due to that they tend more to satisfy the energy need at the aggregate surface. Particularly serious is this problem when using hydrophilic aggregate i.e. aggregate which attracts water.

For measuring the quality of the bitumen-aggregate bond hence for determining the effect of moisture on the strength of this bond, e.g. the BBS (Bitumen Bond Strength Test) is used, Moraes et al. [10]. Canestrari et al. [11] suggested a modification of this test for assessment of the bond between the bituminous binder and RAP. When investigating this topic it was found that the bond between bituminous binder and RAP is stronger than the bond between bituminous binder and virgin aggregate. Moreover the failure occurred in the layer of the bituminous binder, not in the contact of the bituminous binder and RAP. Furthermore the reduction in adhesive properties caused by effect of water presence was more striking when using the virgin aggregate than in the mix with RAP.

2.3 Voids content and other factors influencing the moisture susceptibility

There are many factors which influence the moisture susceptibility, but the most important one is without any doubt the voids content. This was confirmed e.g. by research from Lu and Harvey [12] conducted in California on 63 cores, which identified essential affecting factors as voids content, pavement structure, amount of rainfall and age of the pavement. On the other hand as a factor with insignificant effect the repeated loading by road traffic can be considered, which can cause accumulation of the pore pressure and if the water has any possibility to escape, it can extrude the bituminous binder from the aggregate surface.

Other less serious affecting factors are weather conditions during the paving, which can lead to poor compaction and hence the greater voids content or permeability. Further similar factor is the climate prevailing at the construction site. The last factor worth mentioning is the aggregate porosity, because if too porous aggregate is used, a large amount of bituminous binder gets right into the pores. Due to that there is not enough bituminous binder left for forming a film around individual particles, which also reduces the moisture susceptibility.

Within the research of voids content effect on moisture susceptibility Masad et al. [13] defined, that for each mix type there is a so-called pessimum, i.e. a sort of critical value of the voids content for which the moisture susceptibility is the worst. If the mix has very low voids content, it is nearly impermeable for water. On the other hand when the mix achieves high value of voids content the water is easily drained away. This corresponds to the partition of HMA, where mixes with voids content <3 % are identified as impermeable, whereas mixes with voids content >8 % are considered to be well-drained. D'Angelo and Anderson [14] proved experimentally that the value of pessimum most often varies between 5-10 % by volume, i.e. in the range of voids content values of standard HMA mixes.

In case of cold recycled mixes the approach is not as clear as for HMAs. For example Czech specifications TP 208 define the value of required voids content only for cold recycled mixes with bituminous binder (bituminous emulsion or foamed bitumen) to be in the range of 6-14 %-vol. There are no limits established for hydraulically bound mixtures or for mixes containing combination of hydraulic and bituminous binder.

As a conclusion of this part of the report it is worth mentioning, that in terms of the impact of voids on moisture susceptibility the important aspect is not just the final value of voids content, but also the structure and connectivity of voids (Arámbula et al., [15]), tortuosity of voids [16] and their distribution – a mix with the same value of voids content may contain either a larger number of smaller voids or lower number of large voids (Masad et al., [13]).

2.4 Methods used for determination of moisture susceptibility

Considerable expansion of the cold recycling technology is dating back to the 80s and 90s of the 20th century. Development of methods for testing the moisture susceptibility of these mixes is therefore approximately 70-80 years shorter than the development of testing methods for HMA mixes. This makes methods and knowledge from the field of HMA mixes a valuable resource on which it is possible to build the research in the field of cold recycled mixes.

Determination of the moisture susceptibility of HMA mixes is closely related to the determination of binder to aggregate adhesion. Testing of these characteristics is carried out either with freshly coated mix or with laboratory prepared specimens. The main disadvantage of some test methods is a considerable degree of subjectivity, such as e.g. when applying the boiling water test (ASTM D 3625), the static immersion test (AASHTO T 182), rotating bottle test (EN 11697-11), or the method used for determination of adhesion in the Czech Republic (CSN 73 6161) – short term water immersion of bitumen coated aggregate 8-16 mm. These tests are based on visual assessment of the extent of aggregate coating by bituminous binder.

Another widely used group of methods consists of tests based on the principle of comparing the properties of specimens exposed to water and specimens cured at laboratory conditions. The most commonly used methods or procedures of this group of tests are the Lottman and Modified Lottman test (AASHTO T 283), the TSR method (TG2) and the Tunnicliffe and Root test method (NCHRP 274). On the principles of these methods test procedure used for HMA mixes according to EN 12697-12, as well as the test procedure for cold recycled mixes according to TP 208 are based. For determination of the moisture susceptibility some other laboratory tests can be used as well, such as e.g. the original wheel tracking test in small test device during which the tested specimen is immersed in water with a temperature between 25 and 70 °C.

On the other hand there are also laboratory devices developed specifically for the purpose of moisture susceptibility assessment, such as e.g. MIST (Moisture Induced Sensitivity Tester). This device simulates the effects of pore pressure, which can be generated in the saturated pavement due to the traffic loading (by pushing the water into the voids by the tires of passing vehicles and at the same time by pulling water from the road when the wheels roll away from its surface). During this test the tested specimen is placed in water at constant temperature, while the cyclic loading caused by compressed air makes the water to be pressed repeatedly into the specimen and subsequently withdrawn from it. Another example of a laboratory device developed for measuring moisture susceptibility is the Dynamic Asphalt Stripping Machine (DASM) used e.g. in Malaysia. This device simulates the dynamic effect of water by using the simulation of rain by specially installed shower.

All methods used for determining the moisture susceptibility do not measure the impact of individual factors, but rather seek to quantify the ability of the mix to resist the failure resulting from the effect of water presence. These methods provide just imprecise comparative results and they cannot be used for predicting the degree of distress caused by moisture. Another problem of these tests is the bad repeatability and reproducibility, and especially the strong dependence of the results on some factors (e.g. even very small deflections in the voids content result in significant impact on the moisture susceptibility). In the experimental part of this report, the specimens were subjected to three procedures for determining the moisture susceptibility, which are described in the following parts of this report.

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. At the same time for standard asphalt mix the test specimens are compacted differently. The first set of laboratory specimens is saturated with water in a vacuum chamber similarly to the method according to EN – 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 %.

3 Experimental study and results

3.1 Moisture susceptibility: Czech study

3.1.1 Mix design of cold recycled mixes used for the moisture susceptibility testing

All experiments described in this partial study were performed by using cylindrical specimens with diameter of (100±1) mm and in few cases also (150±1) mm and the height of approximately 60 mm. Test specimens were produced from seven different cold recycled mix designs as is shown in Table 1.

Table 1: Mix design for used cold recycled mixes

	Mix A	Mix B	Mix C	Mix D	Mix K	Mix S	Mix W
Reclaimed asphalt mix	91.0%	90.5%	94.0%	93.5%	95.5%	95.0%	94.0%
Water	2.5%	2.0%	2.5%	2.0%	2.0%	2.0%	2.5%
Bituminous emulsion	3.5%	0.0%	3.5%	0.0%	0.0%	0.0%	2.5%
Foamed bitumen	0.0%	4.5%	0.0%	4.5%	2.5%	2.0%	0.0%
Cement CEM II B32.5	3.0%	3.0%	0.0%	0.0%	0.0%	1.0%	1.0%

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 as reported also in other studies or reports within CoRePaSol project. This is typical not only for Czech circumstances but more generally for this type of recycled materials if selective cold milling for each construction layer is not done. The used cement was classified CEM II / B 32.5 according to EN 197-1 [17]. The optimal moisture content of the cold recycled mix was determined according to EN 13286-2 [18].

Mix A, mix C and mix W contained a cationic slow-breaking bituminous emulsion C60B8 which is commonly used in the Czech Republic. Mixes B, D, K and S were based on the foamed bitumen. For the production of foamed bitumen standard pen grade bitumen 70/100 was applied according to EN 12591 [19]. When preparing the foamed bitumen 3.8 % of water was added to the bitumen (the amount was determined in accordance with the procedure which is recommended for cold recycling technology by Wirtgen Manual 2012 [20]). Foamed bitumen was injected into the cold recycled mix at 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. Compaction has been done by static compression applying 5 MPa as described e.g. in the report D1.1 or D1.2. Volumetric properties of the investigated mixes are shown in Table 2.

Table 2: Volumetric qualities of the investigated mixes

Cold recycled mix	Bulk density (g.cm^{-3})		Maximum density (g.cm^{-3})		Voids content (%)	
	RAP 0/11	**RAP 0/22**	**RAP 0/11**	**RAP 0/22**	**RAP 0/11**	**RAP 0/22**
Mix A	2.154	2.220	2.449	2.377	12.1%	6.6%
Mix B	2.147	2.155	2.419	2.295	11.3%	6.1%
Mix C	2.098	2.203	2.444	2.412	14.2%	8.7%
Mix D	2.151	2.119	2.378	2.237	9.6%	5.3%
Cold recycled mix	Bulk density (g.cm^{-3})		Maximum density (g.cm^{-3})		Voids content (%)	
	Ø 100 mm	**Ø 150 mm**	**Ø 100 mm**	**Ø 150 mm**	**Ø 100 mm**	**Ø 150 mm**
Mix K	2.020	2.150	2.440	2.371	17.2%	9.3%
Mix S	2.032	2.123	2.460	2.366	17.4%	10.3%
Mix W	2.108	2.154	2.388	2.389	11.8%	9.8%

3.1.2 Applied specimen curing procedure

For all mixtures containing more than 1 % of cement the basic duration of specimen curing was 14 days. To simulate the initial moisture content of the mixture after paving and compaction of fresh mix specimens were stored for the first 24 hours at 90-100 % relative humidity and temperature of (20±2) °C. This was done by keeping the specimens in the moulds or by putting them into a suitable plastic bag and keeping sealed. Further the specimens were stored at laboratory conditions with 40-70 % relative humidity and at a temperature of (20±2) °C for the rest of their curing period. This procedure was performed for all mixes which contained more than 1 % of cement, because the cement hydration process is absolutely essential for the final properties of this type of cold recycled mixes. The curing time cannot be therefore significantly shortened.

For mixtures containing ≤ 1 % of cement, 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 sealed for first 24 hours at laboratory temperature in a plastic bag, however, after that it is removed and cured unsealed for additional 72 hours at 50 °C.

3.1.3 Moisture susceptibility of the tested mixes

The main objective of this part of the executed experiments was to compare three methods for setting the moisture susceptibility of the cold recycled mixtures. These methods which are described in chapter 2.4 were compared one to another and to the reference values gained by evaluating the characteristics of specimens cured at laboratory conditions. For assessment of these methods the indirect tensile strength test was chosen, which was carried out at 15 ° C by using cylindrical specimens with a constant load rate of 50 mm / min. In parallel, all tested specimens were used for the determination of stiffness modulus, which was performed by a non-destructive method according to the repeated indirect tensile stress test (IT-CY) in compliance with EN 12697-26 at 15 °C.

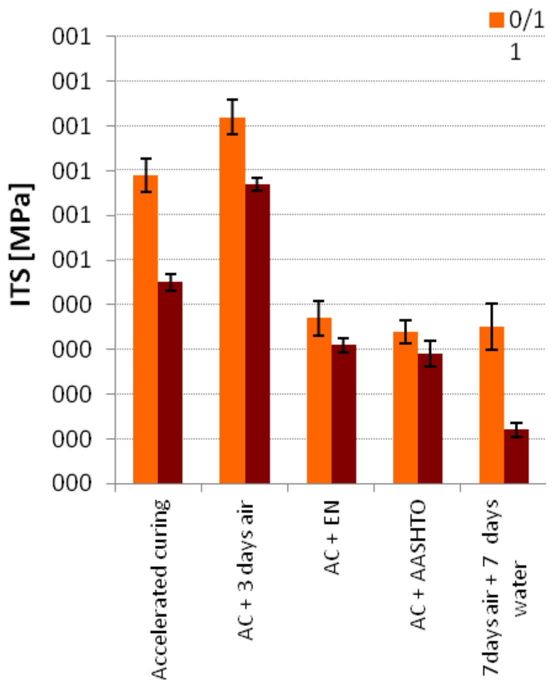
Cold recycled mixes with 0 % of cement

As a result of applying the accelerated curing procedure the testing of mixes without cement (mixtures C and D) was performed with specimens of different age. In case of specimens treated according to TP 208, the comparability with other methods remains questionable and gained results are the most conservative.

Table 3: Curing procedures for mixes without cement

Moisture susceptibility procedures		Days of curing
3 days air storing	Accelerated curing + 3 days in air	7 days
EN 12697-12	Accelerated curing + water saturation under pressure (6.7±0.3) kPa and 3 days in water in 40 °C	7 days
AASHTO T283	Accelerated curing + 1 freezing cycle according to AASHTO	6 days
TP 208	7 days in air + 7 days in water	14 days

When comparing the influence of the used RAP it is obvious that for both mixtures sorted material with a maximum particle size of 11 mm achieves higher indirect tensile strength and stiffness. The most significant difference depending on the RAP grading was measured by the specimens, which were cured in laboratory conditions. Higher values of mixes with 0/11 mm RAP were probably caused by higher voids content and better interaction between the grains.



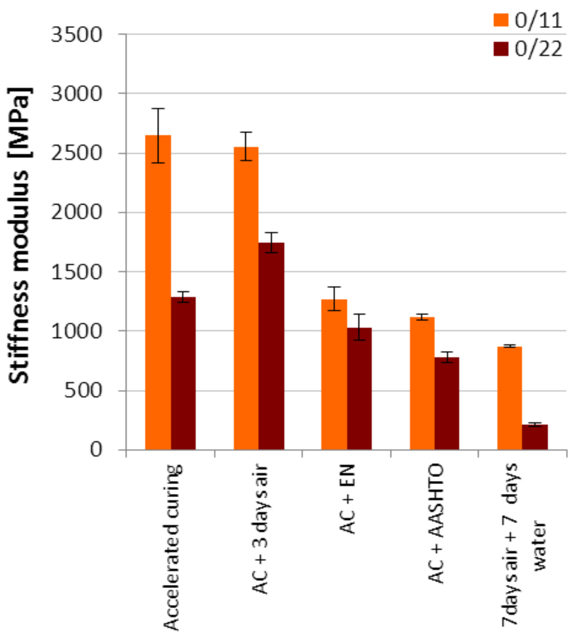


Figure 1 and 2: Determined values of ITS and Stiffness modulus – mix C

Another finding that can be pointed out is that among the performed comparisons there was not any significant difference between the mixes with bituminous emulsion and mixes containing the foamed bitumen. It is possible that two facts mutually compensated itself – in case of mix with bituminous emulsion (mix C) the residual content of bituminous binder was lower than in the mix with foamed bitumen (mix D), but on the other hand bituminous foam contained in mix D created a compact bituminous mortar, which led only to the spot bonding of the remaining grains. In other words the imperfect coating was probably compensated by higher bitumen content in the cold recycled mix.

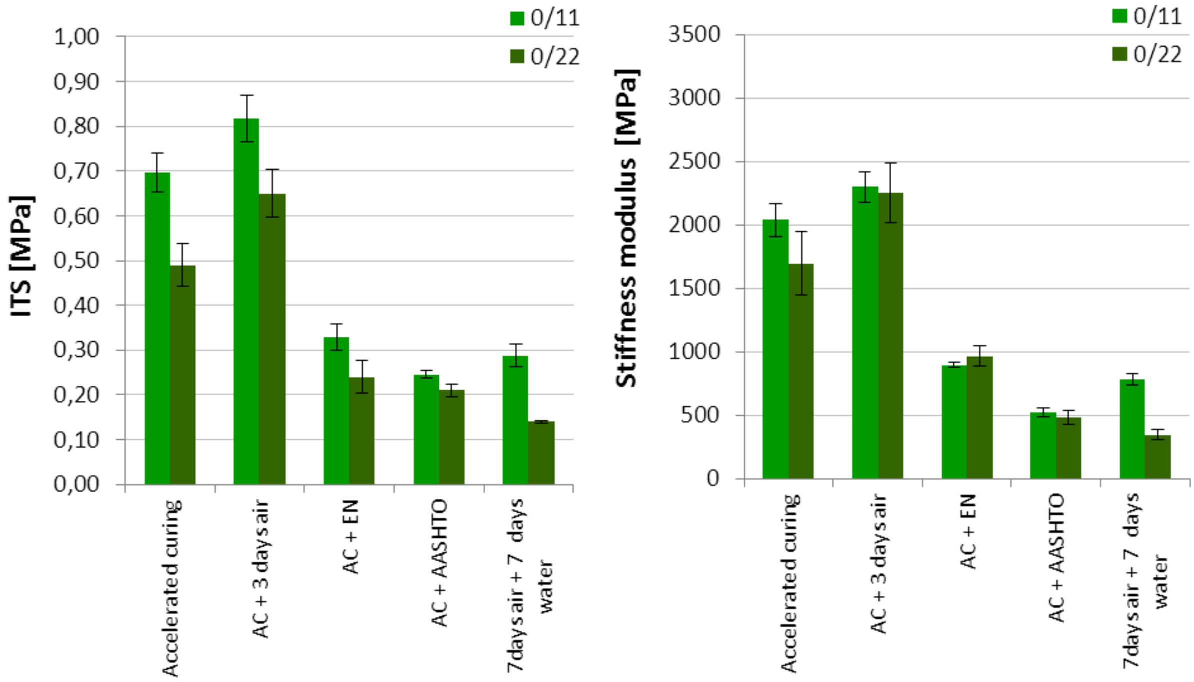


Figure 3 and 4: Determined values of ITS and Stiffness modulus – mix D

Determined values showed that any curing of test specimens in water results in poorer values of measured characteristics. For both mixtures the ITS and stiffness modulus values of the specimens cured according to AASHTO were on average about 10-30 % lower than values of specimens cured according to the method specified in EN. The lowest values were caused by the longest immersion of tested specimens in water according to the methodology defined in TP 208. Generally better indirect tensile strength and stiffness were unambiguously observed for mixes containing the RAP with 0/11 mm grading.

<u>**Cold recycled mixes with 3 % of cement**</u>

The second group of assessed mixes corresponds much better to the common circumstances prevailing in the Czech Republic. All specimens made from mixes containing >1 % of cement (mix A and B) were tested after 14 days of their curing at laboratory conditions. This period was chosen in project CoRePaSol as probably the most appropriate and still acceptable in terms of current common practice. The amount of bitumen remains similar as in case of mixes C and D. The amount of cement was identical in both cases.

Even in case of mixes with cement immersion of test specimens in water provides negative effects. However the differences between various methods are not as significant as for mixes without cement. The lowest values of ITS and stiffness modulus were achieved by test specimens which were cured according to the modified procedure given in AASHTO T283. These values were in some cases even lower than the values determined for specimens cured according to TP 208. Values of test specimens for mix A containing RAP with 0/22 mm grading divert from the tendency which occurred by all other tested specimens, which is probably caused by the material heterogeneity. Measurements of both mix types confirmed that the coarser RAP leads to slightly lower values of indirect tensile strength and stiffness modulus.

Table 4 – Curing procedures for mixes with cement

Moisture susceptibility procedures	
14 days air storing	14 days air curing
EN 12697-12	11 days air curing + water saturation under pressure (6.7±0.3) kPa and 3 days in water at 40 °C
AASHTO T283	12 days air curing + 1 freezing cycle according to modified procedure of AASHTO T283
TP 208	7 days in air + 7 days in water

Decrease of strength characteristics and stiffness modulus which is caused by the presence of water may be in case of these mixes lower due to the fact that during the first fourteen days the hydration process and gradual hardening of cement takes its place if there is sufficient moisture content. Water, which is brought into the mix within the saturation, is partly used by cement which can gradually achieve higher strength. This compensates the negative effect, which causes the water in a cold recycled mix (or generally in an asphalt mix) which contains just bituminous binder. The influence of cement is also confirmed by determined values of stiffness modulus, which confirm earlier findings gained at CTU in Prague during the last 6-8 years.

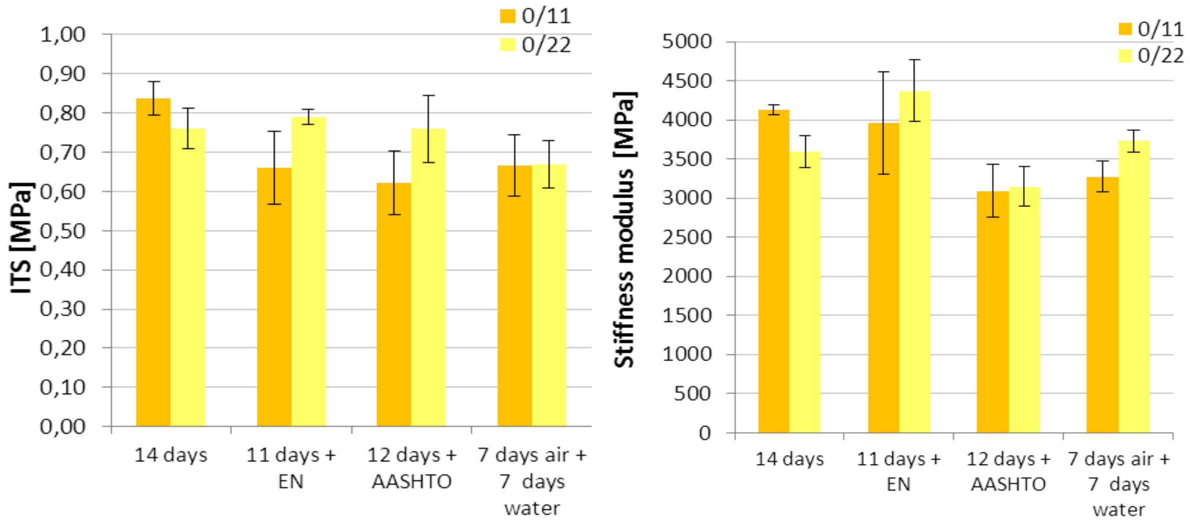
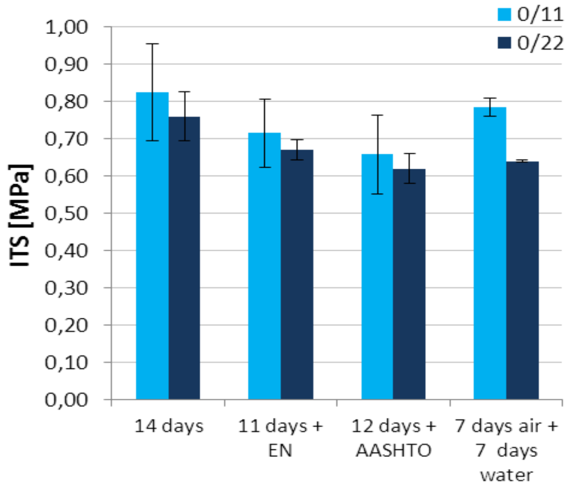


Figure 5 and 6: Determined values of ITS and Stiffness modulus – mix A



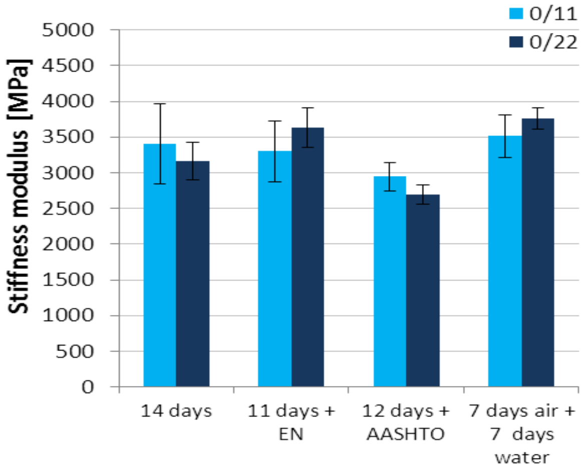
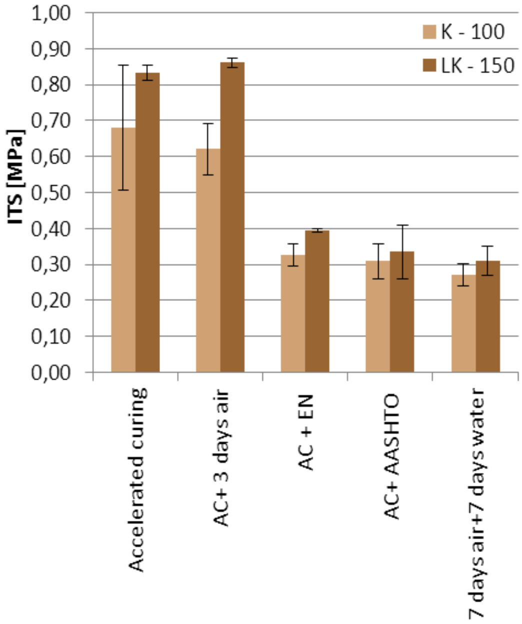


Figure 7 and 8: Determined values of ITS and stiffness modulus – mix B

<u>**Cold recycled mixes with lower content of bituminous binder**</u>

Last of the partial research studies focused on moisture susceptibility and its investigation for cold recycled mixes with lower content of bituminous binder representing both, bituminous emulsion or foamed bitumen. The mix design of mixes K, S and W is summarized in Table 1. These mixes contain 2.0-2.5 % foamed bitumen (S and K) or 2.5 % emulsion (W) and 0 % or 1 % of cement and therefore the same specimen curing procedure as for mixes C and D was applied. As a result of the accelerated curing procedure, the tested specimens were not cured for the same time until their testing. Considering the fact that the ITS and stiffness modulus values depend significantly more on the hydraulic binder content, it is possible to place this group of cold recycled mixes as an option between previously tested mixes without cement (C and D) and mixes with 3 % of cement (A and B). This is also proved by the determined values, which basically fell into the interval limited on both ends by values gained for mixes A-D.



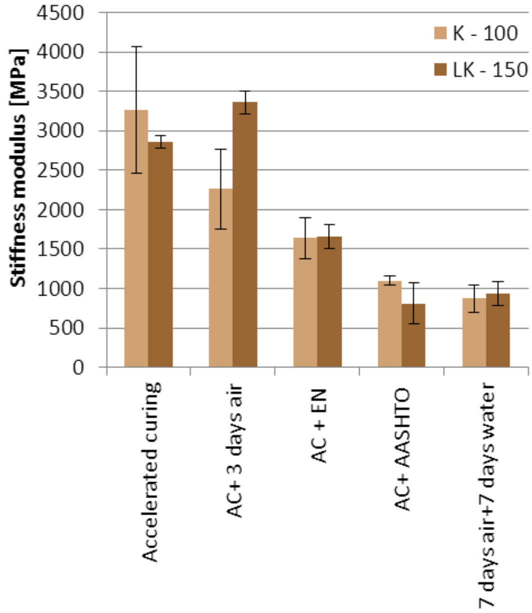


Figure 9 and 10: Determined values of ITS and stiffness modulus – mix K

The determined values are summarized in Figures 9-14. It is necessary to emphasize that in figures shown in this part of the report the pairs of columns do not show results of the same cold recycled mix, since they contain RAP of different batches and with slightly different grading. Additionally, they represent measurements performed on specimens with different diameter (two cylindrical specimen diameters were compared). All measurements of this partial study were conducted for mixes containing RAP with 0/22 mm grading, however, the tests were actually conducted twice, namely for specimens with diameter of 100 mm and 150 mm.

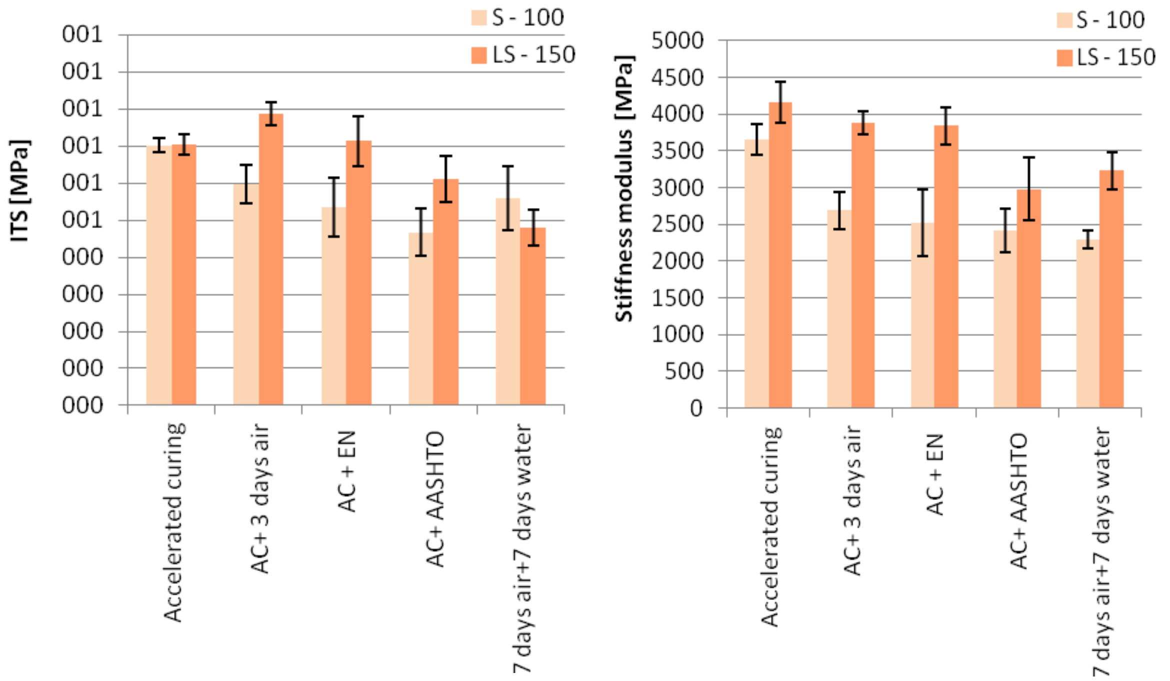


Figure 11 and 12: Determined values of ITS and stiffness modulus – mix S

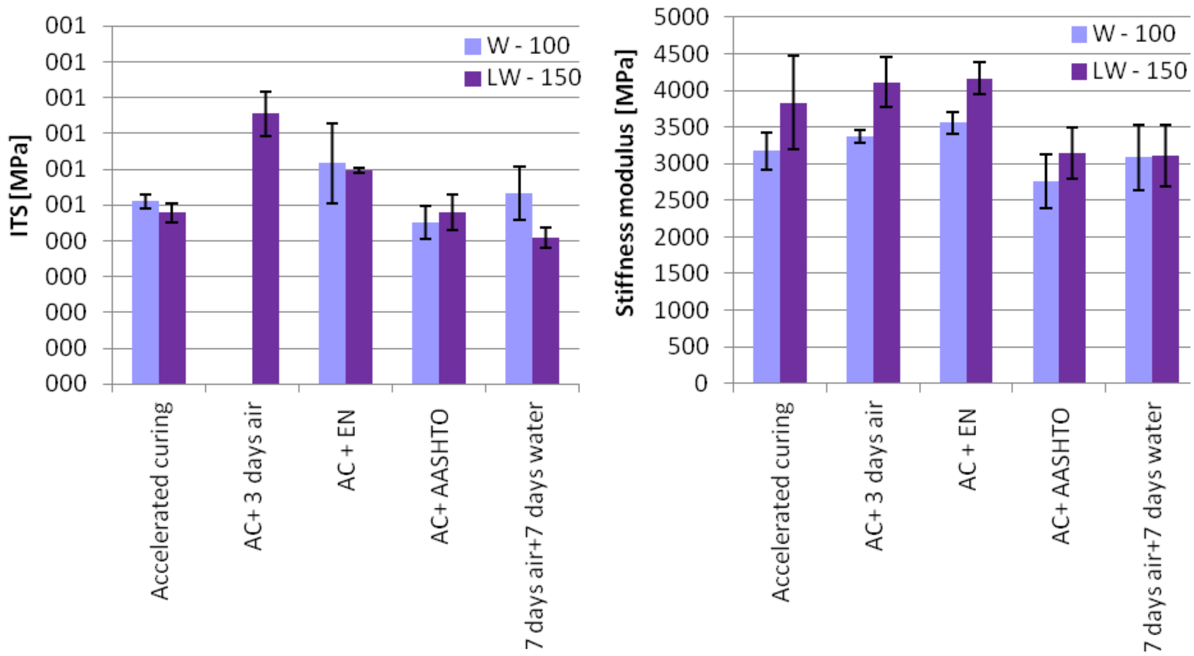


Figure 13 and 14: Determined values of ITS and stiffness modulus – mix W

Determined values complete well the findings summarized in previous chapters. For mix K, which similarly to mix C and D did not contain any cement, it is possible to observe again a significant difference between the ITS and stiffness modulus values for test specimens cured at dry conditions for the whole curing period and for specimens, where conditions of one of the tested moisture susceptibility test method were applied. For mixes S and W, which contained 1 % of cement, the gained values were more similar. This trend approximates the trends observed in mixes with 3 % of cement. For all three mixes the lowest ITS and stiffness modulus values were achieved by specimens that were cured according to the Czech procedures given in TP 208 and according to the modified American AASHTO test procedure. In terms of specimen size effect on the moisture susceptibility, it is not possible to establish any consistent conclusions yet.

3.1.4 Conclusions

The objective of this report was to investigate the effect of a suitable testing procedure used for determining the moisture susceptibility of cold recycled mixes. Because of the fact that research in the area of this material behavior characterization is still less developed for cold recycled mixes, procedures used commonly for hot mix asphalt were included and investigated alongside the procedure prescribed in the Czech specifications TP 208. The additional selected test procedures were the method described in EN 12697-12 and the modified procedure according to American technical specification AASHTO T283. The most important findings resulting from the investigation of seven different mixes with various combinations of bituminous and hydraulic binder content, and all of that performed with two types of reclaimed asphalt material with different grading, can be summarized as follows.

For all examined mixes higher values of ITS and stiffness modulus were gained for mixes, containing RAP with 0/11 mm grading, compared to mixes containing coarser RAP with 0/22 mm grading. Mixes containing RAP 0/11 mm grading which achieved higher values of measured characteristics had also higher voids content values, which complies with other findings described in the CoRePaSol report D2.1. Furthermore, it is possible to claim that trends which can be observed in measured values of the indirect tensile strength correspond to the trends detected in the stiffness modulus. From the results of performed measurements it is not possible to formulate a completely reliable conclusion in terms of the influence of used bituminous binder (foamed bitumen, bituminous emulsion) on moisture susceptibility. Specimen damage caused by presence of water was especially significant for mixes without cement, where the lowest values were measured when applying the assessment procedure according to TP 208, according to which the test specimens were immersed for 7 days, which is considerably longer than the other two methods.

For mixtures containing cement, the differences between values measured in specimens cured at laboratory conditions, and specimens cured according to one of the three investigated procedures, were significantly smaller. The lowest values were achieved by specimens, which were subjected to a modified procedure according to the American test method given in AASHTO T 283.

3.2 Moisture susceptibility: Irish study

3.2.1 Selected materials

For this investigation material was obtained from an Irish road site where cold recycling was used. Figure 15 shows the grading of the combined surface and granular material obtained from the site. The grading was created by taking in account recycling depth of 300mm where material ratio surface to granular material is 1:2. The Wirtgen cold mix grading envelope (Wirtgen, 1998) was used as a guide in analysing the material grading mix.

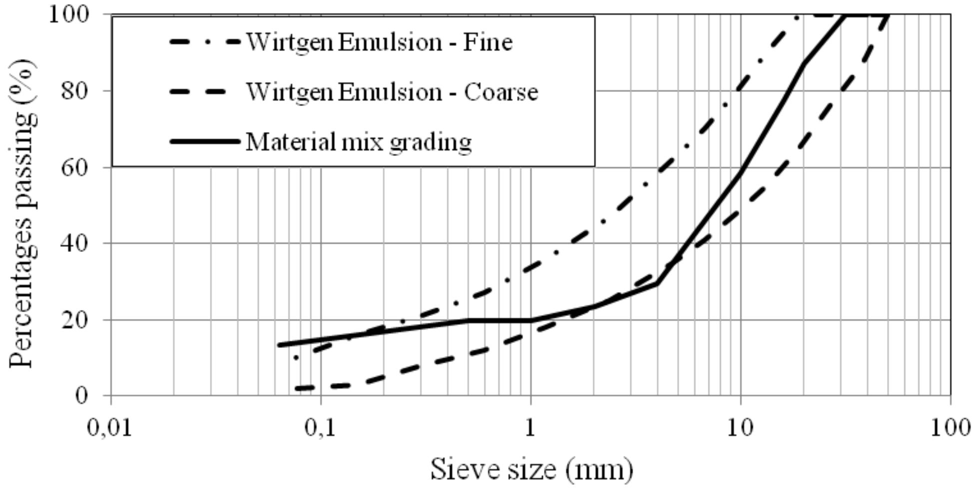


Figure 15: Material Mix Grading

The optimum moisture content of the material was obtained using a procedure based on the standard soils Proctor test, BS 1377- 4: 1990. The moisture content was gradually increased within samples of this material and the corresponding density measured. The results for the test are presented in Figure 16, which shows the dry density - moisture content relationship. From the graph we can conclude that optimum moisture content for the material mix is around 4 %. This moisture content was adopted for the material mix designs from all of the five pits as it is just on the dry side of optimum as recommended in the IAN.

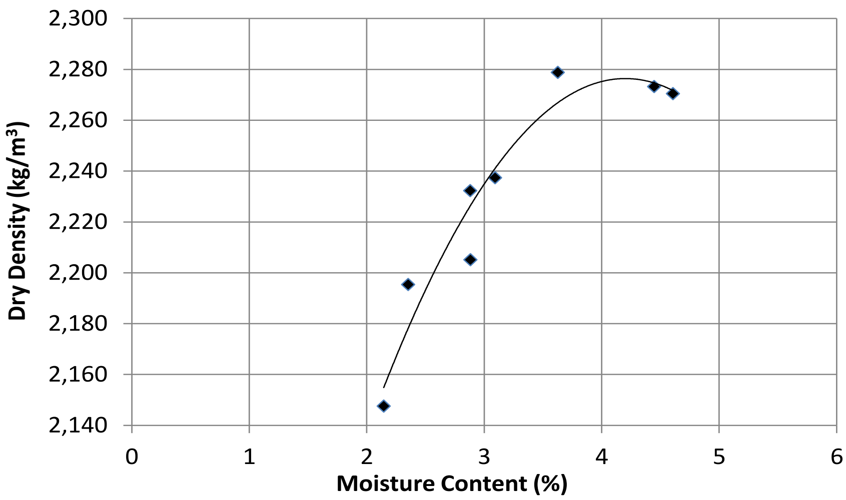


Figure 16: Determination of Optimum Moisture Content

3.2.2 Description of the study

Three emulsion mixes were designed, summarises the mix designs. The material mix designs are classified in the IAN (NRA, 2011) as Quick Viscoelastic Mixes (QVE) as 3% of cement was included in their design. The mixes were designed both with 3% cement included and also without any cement included. Additional, stiffness and dry strength tests were performed on mixtures containing 1.5 % cement.

Table 5: Mix Designs density tests results

Mix	Mix type	Mix Constituents (%)					
		Surface Material	Granular Material	Cement	Water/ Moisture	Binder	Emulsion
A	Emulsion Mix without cement	33.3	66.7	0	4	2.2	3.5
B	Emulsion Mix with cement	32.8	65.7	1.5	4	2.2	3.5
C	Emulsion Mix with cement	32.3	64.7	3	4	2.2	3.5

Note:
1. All percentages contents are by mass,
2. The emulsion used in the mix is the Irish Tar and Bitumen Suppliers Ltd. product: 'Fuarflex', of the binder specification C60B4.
3. The amount of added water in cold recycled mix with bituminous emulsion was adjusted per mount of water in the
4. emulsion and moisture content of the surface and granular material.
5. The amount of added water in cold recycled mixes with foamed bitumen was adjusted per mount of moisture content of the surface and granular material.

Mixing Procedure

A cold emulsion mixing procedure was used for the study. The mixes were mixed using a Wirtgen foam material mixer at speed of no more than 30 rev/min. The reason for the slow speed is that at higher mixing speeds the emulsion breaks down and the binder separates from the water, thus inhibiting adequate coating of the aggregates.

The following steps were taken during the mixing procedure:

i. dry aggregates are pre-mixed for about 1 minute;
ii. half of the water is added into the mix;
iii. the emulsion is gradually added to the mix;
iv. the remaining water is added to the mixture.

Compaction Procedure

All of the specimens were compacted in accordance with IS EN 12697-31:2007. A Coopers Technology gyratory compactor was used to compact the test specimens. Figure 17 illustrates the kneading motion used in the compaction process, whereby a simultaneous static compression and shearing force, resulting from the rotation of the top surface of the mould, is used to compact the mixture.

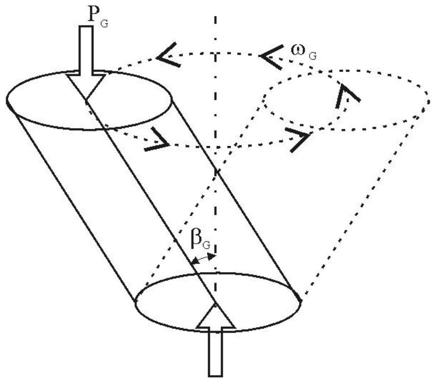


Figure 17: Basic gyratory compaction concept with insert of Coopers Technology gyratory compactor (P_G=compaction pressure (0.6MPa), β_G =gyratory angle (1.25°), ω_G=angular velocity (30 gyrations/minute).

The static compaction pressure was set at 0.6MPa with an angular velocity of 30 gyrations per minute and the gyratory angle set at 1.25°. A set number of gyrations were used as the compaction control target, in this case 100 gyrations. For this study the cylindrical test specimens were compacted to the target dimensions of 150mm in diameter and 75mm in height. Slotted moulds were used in the compaction process in order to allow for the drainage of the excess moisture and thus better compaction. The same weight of material, 3kg, was placed into the mould for all of the specimens. Six specimens of each mix were produced, in total 30 specimens. After compaction, test specimens were left in the mould to cure for 24 hours. The test specimens were then extruded, and their dimension and weights were recorded. The specimens were then ready for curing.

3.2.3 Testing

For this study water sensitivity tests were conducted to IS EN 12697-12: 2008. After the 28 day curing period at 40 °C, the set of six specimens were then divided into two subsets of three specimens. The first set was stored in a temperature control chamber at 20 °C. The second set was placed under distilled water and subjected to a vacuum of 6.7kPa for 30 minutes, and then left submerged in water for another 30minutes at atmospheric pressure. After this, the wet conditioned set of specimens was placed into a water bath at 40°C for 72 hours. Both sets of test specimens were then conditioned at a test temperature of 25°C for three hours prior to testing. The dry set was conditioned in a temperature controlled air chamber, and the wet set conditioned in a temperature controlled water bath.

A control testing system was employed to complete the Indirect Tensile Strength Test (ITS) in accordance with EN 12697-23: 2003. The ITS test is conducted by applying a vertical compressive strip load to a cylindrical specimen. The load is distributed over the thickness of the specimen through two loading strips at the top and bottom of the test specimen.

The critical stresses and strains within the indirect tensile specimen are computed using following analytical formulation based on linear elastic theory:

$$\sigma_{xy}(\max) = \frac{2P}{\pi dt} \quad (1)$$

where P = Load (N); d = diameter (mm) and t = thickness/height (mm).

Using equation 1, the maximum tensile strengths of both wet and dry conditioned test specimens were calculated and an indirect tensile strength ratio was calculated for each.

3.2.4 Results

The water sensitivity tests and indirect tensile strength tests were performed at two different temperatures, a standard test temperature of 25 °C and lower temperature of 15 °C. Table 6 shows the water sensitivity test results. The results show a very good ITSR values for both mixes at all test temperatures slightly higher at 15°C test temperature for mix ‘C’ (mix containing 3% cement). For the mix without cement ITSR values were very close. However, ITS values are much higher at lower test temperature. This was expected, as at lower temperature bituminous material will experience more brittle like behaviour. This was confirmed by the additional ITS test on the mix A and B (mix A = 0 % cement and mix B = 1.5 % cement), see Table 7. The results also illustrate the influence of the curing time period and cement on the mix strength. Where the increase in the curing time period and cement resulted in the improvement in the material strength, which is in agreement with the ITSM test results.

Table 6: Moisture susceptibility (ITS and ITSR) test results

Mix	Mix type	Curing Method	Test temperature (°C)	ITS (MPa)	ITSR (%)
A	Emulsion Mix without cement	3 days at 50°C	25	$0.28_{(wet)}$	80
				$0.35_{(dry)}$	
			15	$0.58_{(wet)}$	79
				$0.74_{(dry)}$	
C	Emulsion Mix with 3% cement	14 days at 20°C	25	$0.47_{(wet)}$	85
				$0.65_{(dry)}$	
			15	$0.83_{(wet)}$	88
				$0.94_{(dry)}$	

Table 7: ITS test results

Mix	Mix type	Curing Method	Test temperature (°C)	$ITS_{(dry)}$ (MPa)
A	Emulsion Mix without cement	7 days at 20°C	25	0.24
			15	0.52
		14 days at 20°C	25	0.31
			15	0.61
B	Emulsion Mix with 1.5% cement	7 days at 20°C	25	0.33
			15	0.63
		14 days at 20°C	25	0.41
			15	0.74

3.2.5 Conclusions

From the results presented above it can be seen that the mixtures with and without cement showed good ITSR values (79% to 88%). It was also noted that the ITS results showed increase in material strength with:

- increase of curing period (7 – 14 days);
- decrease of the test temperature (25 °C to 15 °C);
- inclusion of cement in the cold recycled mix.

3.3 Moisture susceptibility: Portugal study

3.3.1 Materials and mix designs

Main objective of this partial study was the evaluation of the effect of low content of cement on moisture susceptibility of cold recycled mixes with bituminous emulsion in combination with ageing. 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 18.

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 of the cement content on performance related properties of cold recycled mixtures, such as stiffness modulus, resistance to fatigue and to permanent deformation and moisture susceptibility, 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 8 shows the compositions that were adopted for these mixtures.

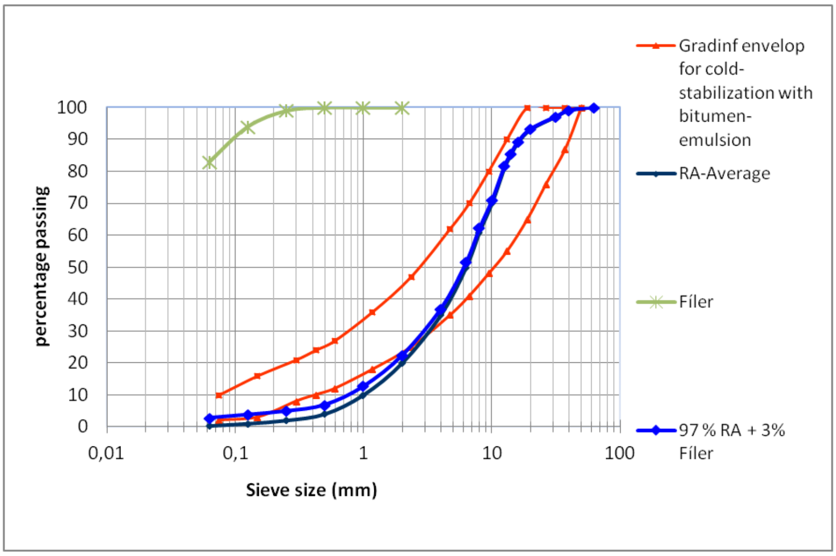


Figure 18: RA, filler and final granulate material grading curves

Table 8: 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 9.

Table 9: 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.

3.3.2 Effect of ageing on the moisture susceptibility of cold recycled mixtures

In order to evaluate the effect of ageing on the moisture susceptibility of cold recycled mixes without or with a small content of cement, cold recycled mixtures CM-E4C0 and CM-E4C1 were produced, and compacted by applying a compressive load of about 7.5 MPa (static compaction). Furthermore, all test specimens were cured by accelerated curing procedure (1 day in the mould at room temperature + 3 days in air – unsealed – @ 50 ºC). The adopted accelerated ageing procedure consisted on conditioning cured test specimens in the oven at 85 °C for 5 days. Afterwards, the moisture susceptibility was determined, based on the method described in EN 12697-12 (method A: ITT), at a temperature of 15 ºC (Table 10 and Figure 19).

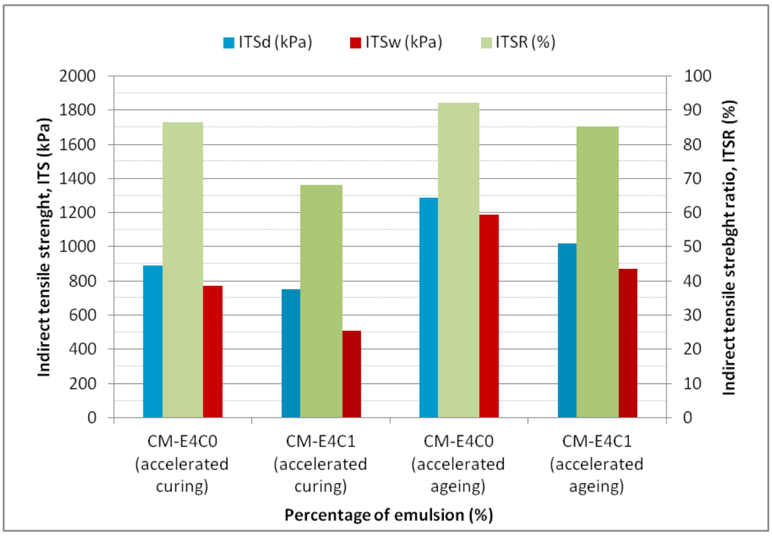


Figure 19: Water sensitivity of cold recycled mixes aged or not

Table 10: Moisture susceptibility test results for cold recycled mixes after accelerated curing and laboratory ageing

Moisture susceptibility based on the indirect tensile strength (@ 15 ºC) ratio		Cold recycled mix ID	
		CM-E4C0	CM-E4C1
Curing: 1 day in mould @ 20ºC + 3 days @ 50ºC	ρ_{bdm} (Mg/m^3)	2,165	2,117
	Vv (%)	11	13
	ITS_d (kPa)	890	750
	ITS_w (kPa)	770	510
	ITSR (%)	87	68
Aged test specimens: 5 days @ 85ºC (after accelerated lab curing)	ρ_{bdm} (Mg/m^3)	2,113	2,066
	Vv (%)	13	15
	ITS_d (kPa)	1290	1020
	ITS_w (kPa)	1190	870
	ITSR (%)	92	85

It may be concluded that in both addressed cold recycled mixtures, ageing has a positive influence, not only on the increased ITS values, but also because of improved ITSR (in this case, mainly for CM E4C1). The obtained results also show that mixtures without bitumen have, for the same age, better resistance to water immersion. It must be, however, noted that the same trend may not occur for other performance related properties. For instance, wheel tracking tests carried out on the same mixtures (CM-E4C0 & CM-E4C1) at early ages (curing for 7 days at room temperature) pointed out that the mixture with cement (1 %) would have a better resistance to permanent deformation than the one without cement.

3.4 Moisture susceptibility: German study

3.4.1 Design and materials

The mix granulate used in this study was sampled at the asphalt plant in Rhünda (Germany) and represents milled reclaimed asphalt. The grading of this material is plotted in Figure 20. The bitumen content of the asphalt granulate was evaluated by standard bitumen recovery procedure to be 5.4 %.

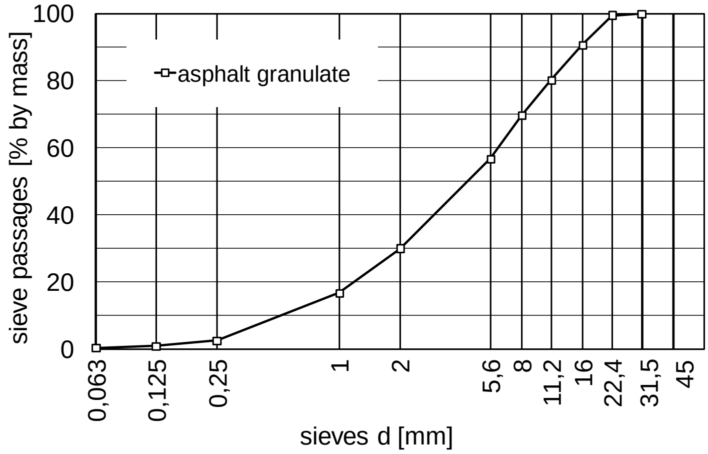


Figure 20: Grading of particle size for reclaimed asphalt

In order to raise the content of fines in the reclaimed asphalt, 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 mixture options designed and tested.

From the mix granulate cold recycling mixtures were prepared in a pug-mill mixer by applying the binder contents as summarised in table 11. Details to the mix design can be obtained in CoRePaSol Report D2.1 "Ageing".

Table 11: Variation of bitumen emulsion and cement according to the IDT-stiffness study

Sample name	Content of bitumen emulsion (residual bitumen) C 60 B1 – BEM	Content of cement CEM I	Content of reclaimed asphalt	Content of limestone filler
I	2,0 (1.2) %	0.0	95 %	5 %
II	3.5 (2.1) %	0.0	95 %	5 %
III	3.5 (2.1) %	1.5 %	95 %	5 %

After the mix preparation, the specimens were compacted by double-plunger static compaction. For 3 minutes a force of 50 kN was held constant. After compaction, the specimens were demoulded after one day. The specimens of mix options I and II were cured in a heating chamber for additional 3 days at 50 °C. The specimens from mix option III were cured for 11 days at room conditions in order to allow the cement to hydrate.

3.4.2 Testing

For this study moisture susceptibility tests were conducted according to EN 12697-12: 2008. After the curing procedures as described earlier, the specimens were separated into two sets. The specimens of the first set were stored for three days at room conditions. The specimens of the second set were water saturated by applying a vacuum of 6.7 kPa for 30 minutes and afterwards stored for 3 days immersed in water of a temperature of 40 °C.

Before conducting the indirect tensile test the specimens of both sets were conditioned for at least 3h by storing at test temperature of 5 °C and 15 °C which were applied for comparison. After temperature conditioning each specimen was transferred to the test frame and the indirect tensile strength test was conducted according to EN 12697-23.

3.4.3 Results

The results obtained in the indirect tensile strength tests for two different temperatures on the dry and water saturated conditioned specimens are summarized in table 12.

Table 12: Moisture susceptibility (ITS and ITSR) test results

Mix	Mix type	Curing Method	Test temperature (°C)	ITS (MPa)	ITSR (%)
I	2 % Emulsion Mix without cement	3 days at 50°C	15	$0.14_{(wet)}$	36
				$0.39_{(dry)}$	
			5	$0.22_{(wet)}$	32
				$0.68_{(dry)}$	
II	3.5 % Emulsion Mix without cement	3 days at 50°C	15	$0.31_{(wet)}$	41
				$0.76_{(dry)}$	
			5	$0.59_{(wet)}$	44
				$1.34_{(dry)}$	
III	3.5 % Emulsion Mix with 1.5 % cement	14 days at 20°C	15	$0.63_{(wet)}$	76
				$0.83_{(dry)}$	
			5	$0.95_{(wet)}$	81
				$1.17_{(dry)}$	

3.4.4 Conclusions

From the results presented in this study following conclusions can be drawn:

- For the two emulsion stabilized cold recycled mixtures without cement, comparably low ITSR values are obtained. These mixtures show high sensitivity regarding excessive moisture.
- The addition of 1.5 % of cement will improve the moisture resistance considerably.
- The test temperature has a minor influence on the resulting ITSR value. However the strength results obtained at 5 °C are significant higher compared to the strength obtained at 15 °C.

4 Discussion of comparability study

For various options of cold recycled mixtures the moisture susceptibility was measured by indirect tensile strength tests. The tests were conducted at four laboratories what allows some comparative assessment regarding comparability of the results obtained. For the following evaluation, all test results obtained at IDT test temperature of 15 °C are summarized for test specimens that were conditioned according to two different procedures for evaluating the moisture susceptibility according to EN 12697-12:

- Dry conditioning.
- Water conditioning at 40 °C for 3 days after vacuum saturation.

Then following properties (material/mix characteristics) were varied between the mixtures and can be named:

- Mix granulate composition (as indicated by % of RA in the mix granulate).
- Bituminous emulsion content.
- Cement content.
- Compaction procedure (static, gyratory).
- Curing procedure (as indicated by temperature and duration).

Table 13: Synthesis of water susceptibility study results

Study	Sample	Mix granulate	Bitumen emulsion content	Cement content	Compaction	Curing	ITS_{dry}	ITS_{wet}	ITSR [%]
CZ	A	100	3.5	3.0	Static	11d20	0,75	0,78	104
	C	100	3.5	0,0		3d50	0,65	0,3	46
	W	100	2.5	1,0		3d50	0,75	0,6	80
IR	A	33	3.5	0	Gyratory	28d40	0,74	0,58	78
	C	33	3.5	3.0		28d40	0,93	0,83	89
GER	I	95	2,0	0	Static	3d50	0,39	0,14	36
	II	95	3,5	0		3d50	0,76	0,31	41
	III	95	3,5	1,5		11d20	0,83	0,63	76
PT	CME4C0	100	3.8	0	Static	3d50	0,89	0,77	87
	CME4C1	100	3.8	1.0		3d50	0,75	0,51	68

When discussing the results summarised in table 13, the individually applied mix designs and specimen compaction and curing procedures have to be considered. Additionally it is necessary to pay attention to the used reclaimed asphalt since it was repeatedly proven that there is a crucial problem with its homogeneity. And even if same grading would be applied and similar binder content added the moisture susceptibility and strength properties would be still influenced by the RA grading and bitumen content. Another aspect which might be closely connected to the comparison shown in the table is the void content for cold recycled mixes prepared in the 4 different studies. This will have again an impact on resulting ITSR values and is dependent on the type of used RA material. For the bituminous emulsion it is expected that the properties were similar and the emulsions used by different studies were based on 70/100 bitumen. This component of the cold recycled mix will not influence the resulting comparability of moisture susceptibility.

5 Conclusions

At the conclusion of this report, it would be important and of preference to stress that moisture susceptibility is a crucial characteristic also for cold recycled mixes and it deserves a proper attention. Quite essential would be continuous research of the voids content influence, because, as mentioned earlier, the voids content is one of the most influential factors. Due to current pavement construction practice in the area of cold recycled mixes, the voids content is significantly varying, which is caused by the considerable heterogeneity of RAP, is nevertheless influenced also by what is recycled (only asphalt layers or combination of an asphalt layer and e.g. base unbound material). Additionally the grading envelope limits for cold recycled mixes have another effect on voids content and therefore on moisture susceptibility. It has been found earlier in CoRePaSol project that in some countries the grading envelope is relatively broad. The fact of the heterogeneity issue makes formulating of any conclusions extremely difficult and foremost it limits extending of the RAP use to a greater extension.

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