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# Stiffness characterization of cold recycled mixtures

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**Abstract**

One of the objectives within the European research project CoRePaSol (supported within the CEDR Transnational Program) was to summarize assessment and research of stiffness modulus of cold recycled mixes determined according to repeated indirect tensile stress test (IT-CY). In most cases the stiffness modulus values were 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 the standard cold recycled mixes, thus mixes whose aggregate skeleton is formed entirely 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). Later also combinations with other types of recyclable materials were done and tested. 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 change of these characteristics, effect of testing temperature or the influence of fines addition on the stiffness modulus value. This paper therefore brings some summarization of the gained experience.


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*Keywords:* Stiffness modulus; indirect tensile strength; cold recycled asphalt mix; RAP; recycled conrete; influence of binder content

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## 1. Mix design and specimen production

Mix designs of four basic cold recycled mixtures, which were used for performing a large part of the experiments done within CoRePaSol project at CTU in Prague and presented in this paper are summarized in Table 1. 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).

For the experimental studies almost all designed mixes contained the same type of screened reclaimed asphalt material (RAP) with 0/22 mm grading originating from the same source (hot mix asphalt plant Středokluky – see Fig. 1). 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 makes final conclusions more difficult. The bitumen content was determined to be 5.6% by mass. Nevertheless this value should be considered as just approximate because the composition of RAP differed even within a single batch. Because of that it was very important to perform all measurements for each sub-study 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.

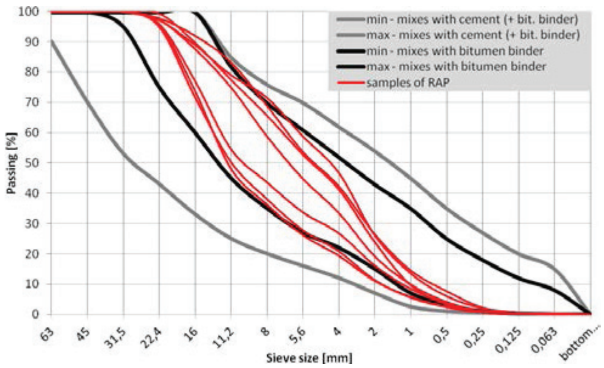


Fig. 1. Grading curves of used RAP 0/22 mm (location Středokluky, repeated analyses).

Part of the mixes described in the following chapters contained cationic slow-breaking bituminous emulsion C60B7 (according to the designation in [EN 13808:2013]) which is commonly used in the Czech Republic. Other mixes were based on the foamed bitumen using standard straight-run bitumen 70/100 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 using the Wirtgen WLB10S laboratory equipment. For mixing twin-shaft compulsory mixer Wirtgen WLM 30 was used.

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. Unless otherwise stated, the measurements of ITS and stiffness modulus was performed at 15 °C.

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.

For mixtures containing 1% of cement by mass and less, the test specimens were usually subjected to accelerated curing procedure. 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.

## 2. Influence of bituminous / hydraulic binder content

The stiffness modulus and indirect tensile strength (ITS) values were determined after 14 days of specimen curing. Tested cylindrical specimens had diameter 150 mm and height 60 mm.

### *2.1. Cold recycled mixes with foamed bitumen*

Table 1 shows the matrix of binder combinations contained in the investigated mixes. The results of performed measurements are depicted in Figure 2 and 3. 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 more significant impact on both characteristics than higher content of foamed bitumen. From all the examined variants the highest values of stiffness 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).

Table 1. 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 |

The optimal amount of foamed bitumen in terms of the highest stiffness (and also the ITS) values appears between 2.0% and 2.5%. On the contrary higher content of foamed bitumen leads to lower stiffness modulus.

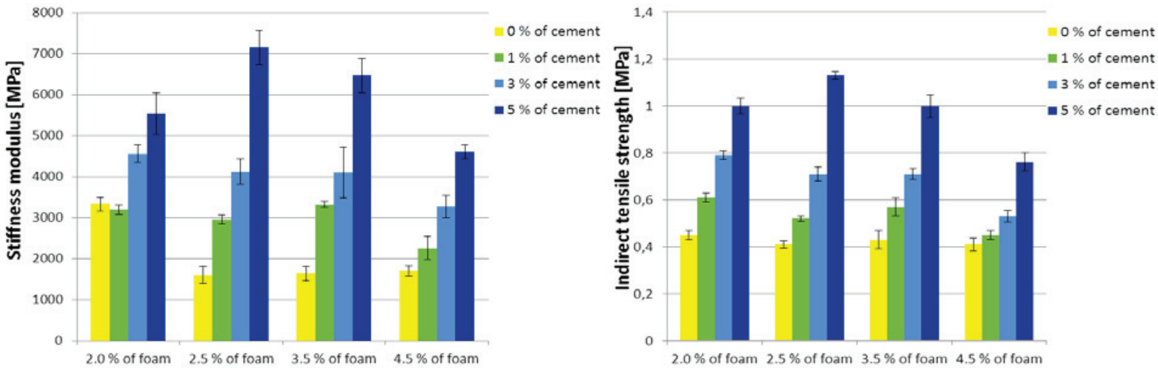


Fig. 2 (a) stiffness and (b) ITS of cold recycled mixes with different content of foamed bitumen (with standard deviation error bars).

Results shown in Fig. 2 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.

*2.2. Cold recycled mixes with bituminous emulsion*

Investigated mixes contained 2.5%, 3%, 3.5% or 4.5% bituminous emulsion and between 0% and 3% cement. The average measured values of stiffness modulus and indirect tensile strength are summarized in Fig. 3. 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.

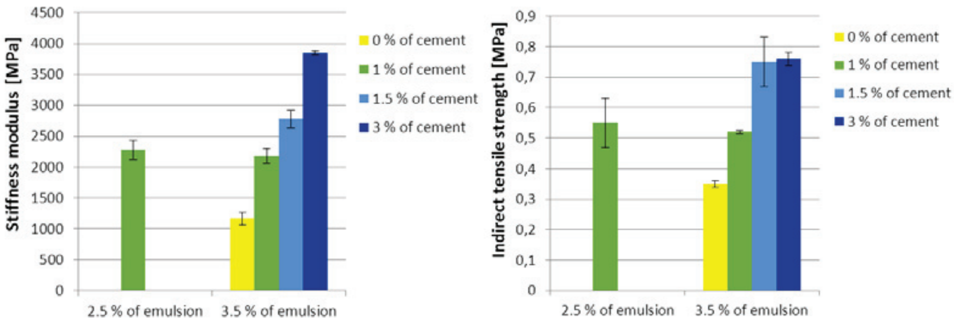


Fig. 3 (a) stiffness and (b) ITS of cold recycled mixes with different content of bituminous emulsion (with standard deviation error bars).

Based on presented results a comparison of impact of bituminous emulsion content was additionally done by testing cold recycled mixes without cement, which contained varying amount of bituminous emulsion (2.5%, 3%, 3.5% and 4.5%). These specimens were cured according to the accelerated curing method described earlier in this paper, 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. This part of the 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 (see Fig. 4).

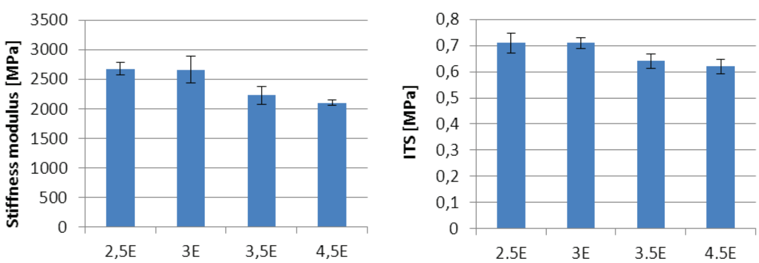


Fig. 4 (a) stiffness and (b) ITS of cold recycled mixes with different content of bituminous emulsion (with standard deviation error bars).

## 3. 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 2.

Table 2. 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% |

Fig. 5 and Fig. 6 show successive increase in both characteristics during the first 28 days of test specimens curing. The extent of characteristic increment in relation to the added hydraulic binder is illustrated as well.

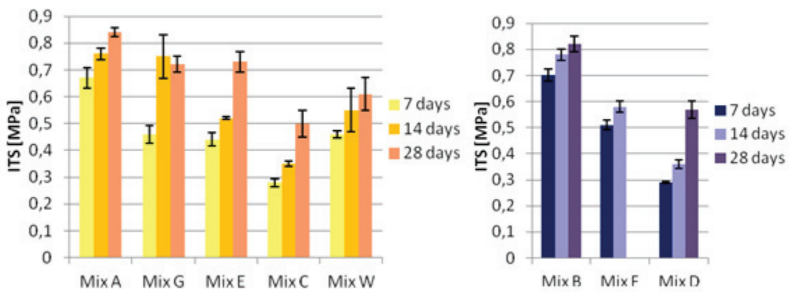


Fig. 5. Indirect tensile strength of mixes (a) with bituminous emulsion (b) with foamed bitumen (with standard deviation error bars).

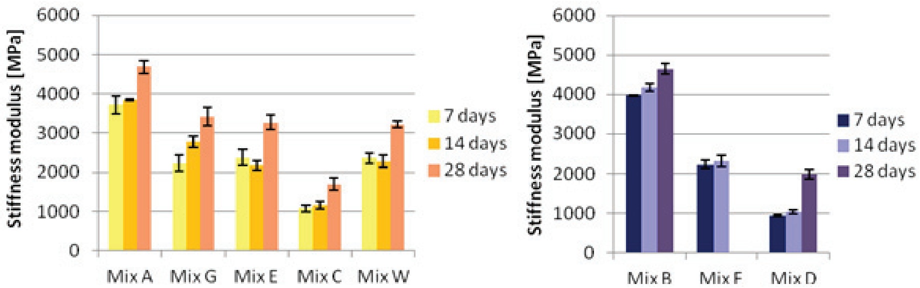


Fig. 6. Stiffness modulus of mixes (a) with bituminous emulsion (b) with foamed bitumen (with standard deviation error bars).

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 4 increase of both characteristics is always faster for cold recycled mixes with higher content of hydraulic binder. The table summarizes 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.

There is a significant difference in values gained after 7 days specimen curing in mixes with and without cement. This difference then gradually decreases as can be seen in Fig. 6. Further, 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 assessments done within the project CoRePaSol.

## 4. Effect of fine grained aggregate and fines, effect of testing temperature

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 Table 3.

### *4.1. 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.

Table 3. 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 |

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.

Fig. 7 and Fig. 8 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 selected 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 regions of continental Europe.

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.

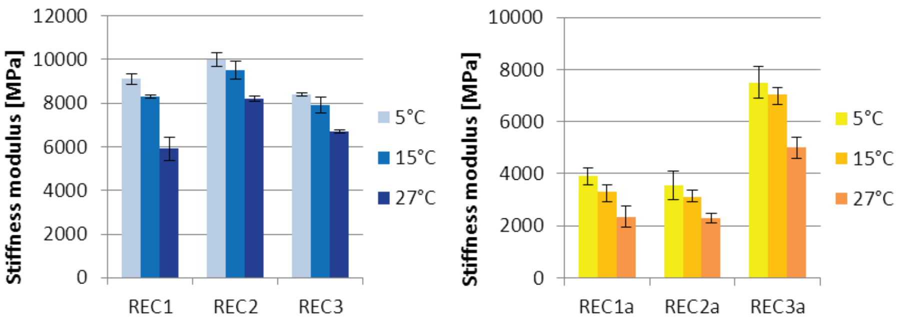


Fig. 7. Stiffness of cold recycled mixes (a) containing waste filler (b) containing fine grained aggregates (with standard deviation error bars).

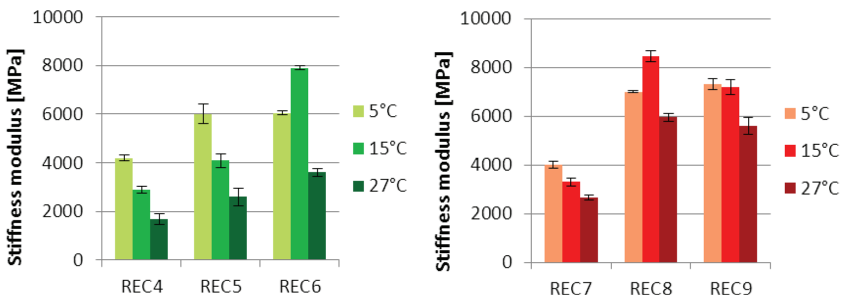


Fig. 8 (a) and (b) stiffness modulus of cold recycled mixes containing fine grained aggregates (with standard deviation error bars).

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 IT-CY test procedure determined for 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.

### *4.2. Effect of waste filler content*

Another aim 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 similar composition to mixtures REC1a – REC3a, 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 mm grading.

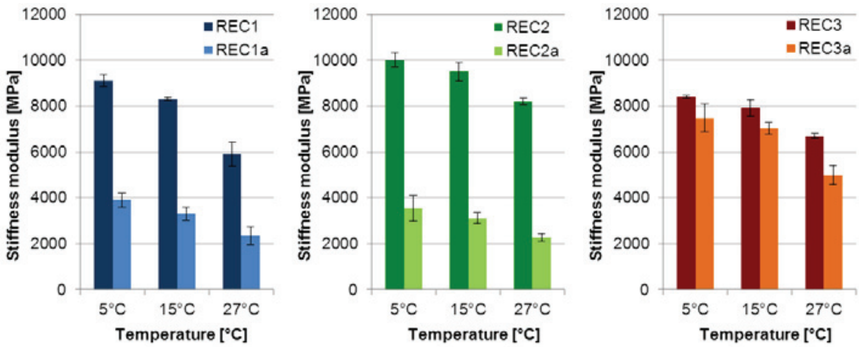


Fig. 9 (a) (b) (c) Stiffness modulus of cold recycled mixes containing waste filler or fine grained aggregates (with standard deviation error bars).

Fig. 9 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 chart, but this fact only confirms the positive effect of waste filler. Both presented mixes contain 20% of fine aggregate / waste filler, whereas mixture REC3a contains additional 10% of waste filler, and therefore the measured stiffness demonstrate high values for mixtures REC1 – REC3. Moreover the mix REC3 contains about 0.5% less cement than mix REC3a, which contributes to smaller difference between them.

## 5. Mixes with recycled concrete, recycled gravel/sand and pulverized concrete – case study Czech Republic

### *5.1. Mix design*

The research of the CoRePaSol project was also complemented by investigation of mixes with different composition of the granular element. Mix design of 11 mixes containing some alternatives to classical RAP such as recycled concrete or recycled gravel/sand are shown in Table 4. 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 (lot 14). The recycled gravel/sand comes also from this construction site, from its unbound base course.

Table 4: Composition of designed and tested mixtures.

| Mix type | Mix BA | Mix BC | Mix OA | Mix 3O | Mix 5O |
|---|---|---|---|---|---|
| RAP 0/22 | 45.5% | 47.0% | 45.5% | 89.5% | 87.5% |
| Recycled concrete 0/22 | 45.5% | 47.0% | 45.5% | 0.0% | 0.0% |
| Bituminous emulsion | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% |
| Cement / pulverized concrete | 3.0% / 0.0% | 0.0% / 0.0% | 0.0% / 3.0% | 0.0% / 3.0% | 0.0% / 5.0% |

| 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% |
| Bituminous emulsion | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% |
| Cement / pulverized concrete | 3.0% / 0.0% | 1.0% / 0.0% | 1.0% / 0.0% | 0.0% / 5.0% | 3.0% / 0.0% | 0.0% / 0.0% |

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. The accelerated curing was not applied on these specimens. They were just cured at laboratory conditions for 7, 14 and 28 days (first 24 hours in a plastic bag).

### *5.2. Discussion of results*

Determined voids content of these mixes 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. The resulting values of stiffness modulus and indirect tensile strength are summarized in Fig. 10. 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 these specimens achieved lower bulk density.

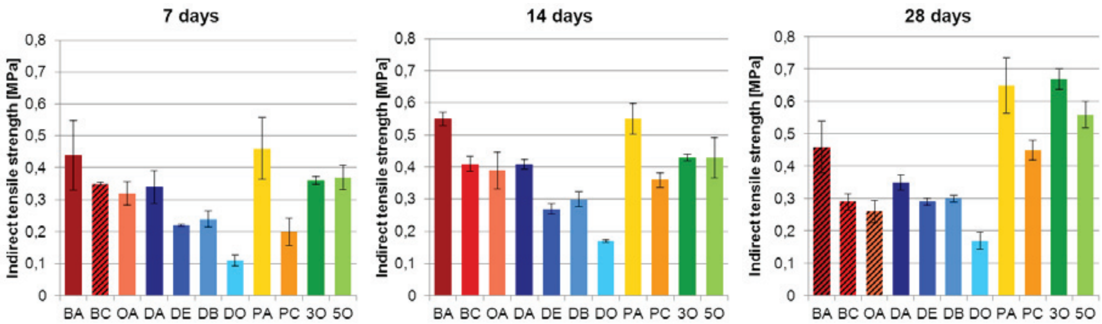


Fig. 10. Indirect tensile strength after (a) 7 days, (b) 14 days and (c) 28 days of curing (with standard deviation error bars).

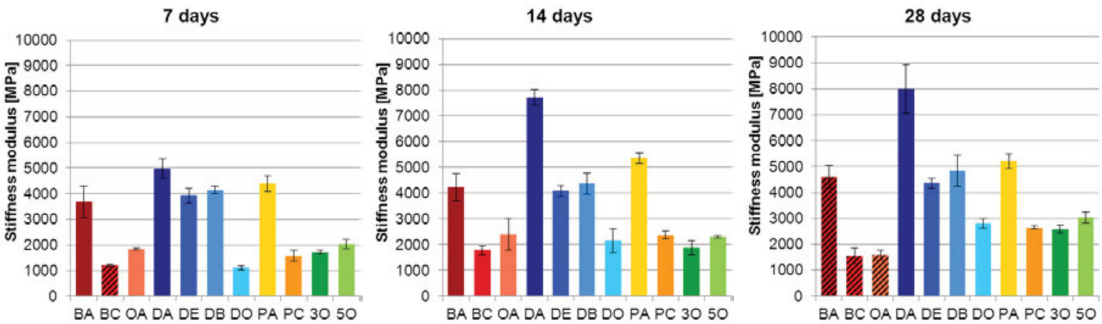


Fig. 11. Stiffness modulus after (a) 7 days, (b) 14 days and (c) 28 days of curing (with standard deviation error bars).

The main finding, clearly visible from the figures, is a large difference among the trend of stiffness modulus and the 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.

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 gained findings are totally different. The highest values were achieved by mixes without RAP, thus mixes with recycled concrete and recyclable gravel/sand.

When comparing the results of mixes with ≤1% of cement (BC, DE, DB, PC) the unambiguous negative effect of RAP absence on ITS values can be seen. 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.

## 6. Conclusion

To summarize two years of work into one contribution is quite difficult. To sum up just the most important findings into few concluding sentences – that is a challenge. Nevertheless it can be stated:

- Optimal foam bitumen content seems to be between 2.0% and 2.5%, higher content of foamed bitumen leads to lower stiffness modulus and ITS. Similarly for bituminous emulsion optimal content is 2.5-3.0%.
- Increased bitumen content will improve the material flexibility which however results in a decrease of stiffness.
- Using additional cement has more significant impact on both characteristics than higher content of foamed bitumen. With increasing cement content ITS and stiffness are increasing as well, but the positive effect of cement has also negative impact – it results in an increased brittleness.
- There is a significant difference in stiffness values gained after 7 days of specimen curing in mixes with cement and without cement. This difference then gradually decreases.
- Addition of cement has markedly bigger positive influence on stiffness values than on ITS values
- Adding fine aggregate seems to be quite advantageous; waste filler causes even more significant increase of investigated characteristics and can partly substitute cement.
- Concerning the mixes including alternatives to standard RAP – recycled concrete and/or recycled gravel/sand – it can be stated, that these mixes show very different trends in stiffness compared to ITS trends. Content of RAP is necessary for high ITS, but highest stiffness was achieved by mixes without RAP.
- Influence of the aggregate skeleton appears to be much more important than the amount of pulverized concrete added. The pulverized concrete has very good effect on stiffness but it caused similar or lower values of ITS.

## Acknowledgements

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