SUBSTITUTION OF CEMENT BY MICRO-MILLED RECYCLED CONCRETE IN COLD RECYCLED ASPHALT MIXES

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Besides the bituminous binder (foamed bitumen or bituminous emulsion) cement is often added into the cold recycled mixes as well. That is because cement improves moisture susceptibility and provides sufficient strength and stiffness especially during the early stage of mix curing. This article is focused on investigation of the potential of cement substitution by the micro-milled recycled concrete. The waste concrete is simply milled by a high speed mill which causes its mechanical activation. The results of performed measurements show a very positive influence of the micro-milled concrete on moisture susceptibility in the first place. The impact on the strength and stiffness is lower than the influence of cement, however all tested mixes met the requirements for cold recycled mixes with a huge reserve. Besides that, thanks to a slower initial strength increase, the problem with hydraulic cracks origin typical for mixes with cement is eliminated.

KEYWORDS

micro-milled concrete, recycled concrete, mechanical activation, active filler, cold recycled asphalt pavement, moisture susceptibility, cement

1 INTRODUCTION

The positive effect of the idea to substitute cement added into the cold-recycled mixes by pulverized recycled concrete on the environmental and economical matter is obvious. That is the reason why the use of micro-milled materials has been investigated in the laboratory of road structures at CTU in Prague already for almost 2 years. Some results have already been presented, for example in [Cizkova 2015]. The main objective of this research is to find the most convenient mix composition which will provide economic and environmental benefits as well as the sufficient strength and other important material qualities, especially moisture susceptibility.

This paper summarizes the newest results of this research, which has been focused exclusively on added mechanically activated concrete in the previous months. Unlike the research already presented, mixes presented here were designed the way, that they contain lower amount of bituminous binder and therefore they are much cheaper. One of the main objective of this paper is to find out the impact of lower dosage of foamed bitumen on the behavior of a cold-recycled mix containing pulverized concrete. A new area of mixed micro-milled additive (50 % of cement and 50 % of pulverized concrete milled together) was investigated as well.

2 MIX DESIGN

The performed experimental work which creates the body of this paper can be divided into two parts. The first part consists of 8 mixes with varying amount of both - foamed bitumen and pulverized concrete. These mixes (see Tab. 1) contained usually 1% of cement. The second part of the experiment aimed to determine the potential of mixed micro-milled additive consisting of 50 % of cement and 50 % of pulverized concrete which were milled together (see Tab. 2).

For the experimental studies all designed mixes contained the same type of screened reclaimed asphalt material (RAP) with 0/22 mm grading originating from the same source (mix asphalt plant Stredokluky – 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 pavement 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. The bitumen content in RAP was determined to be 5.6 % by mass.

Mix	2F+1C	2F+1C+ 2PC	4F+1C+ 2PC	2F+1C+ 4PC	1F+1C+ 4PC	2F+1C+ 6PC	4F+1C+ 6PC	2F+6PC
RAP 0/22	94.0%	91.5%	89.5%	88.5%	89.0%	85.5%	83.5%	86.5%
Water	3.0%	3.5%	3.5%	4.5%	5.0%	5.5%	5.5%	5.5%
Foamed bitumen	2.0%	2.0%	4.0%	2.0%	1.0%	2.0%	4.0%	2.0%
Cement	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	-
Pulverized concrete	-	2.0%	2.0%	4.0%	4.0%	6.0%	6.0%	6.0%

Table 1. Mixes investigated in the first part of the experiment

Mix	2F+3C	2F+3PC	2F	2F+3CC
RAP 0/22	90.6%	90.5%	94.0%	90.5%
Water	4.4%	4.5%	4.0%	4.5%
Foamed bitumen	2.0%	2.0%	2.0%	2.0%
Cement	3.0%	-	-	-
Pulverized concrete	-	3.0%	-	-
Cement (50%) + Pulverized concrete (50 %) milled together	-	-	-	3.0%

Table 2. Mixes investigated in the second part of the experiment

Nevertheless, this value 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 set 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 by [Valentin 2014]. Because of its heterogeneity, the RAP was assessed repeatedly in terms of its grading and the results are shown in Fig. 1 including the grading envelopes according to the Czech technical specifications [Czech Ministry of Transportation 2009].

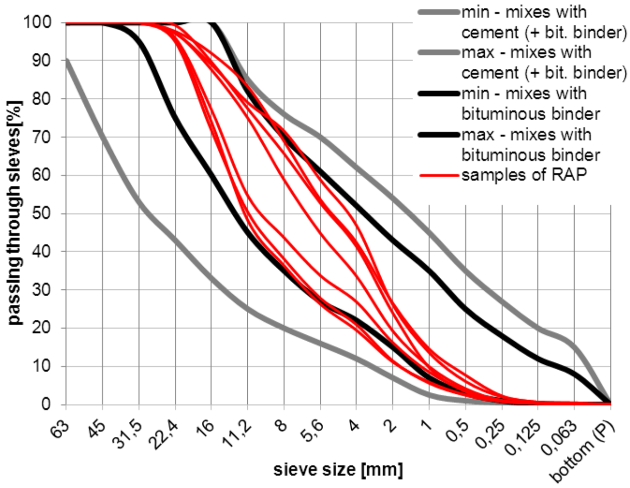

Figure 1. Grading curves of used RAP 0/22 mm (repeated analyses)

The cement added into the mixes in the first part of the experiment was classified as CEM II / B 32.5 R according to [Czech Office for Standards, Metrology and Testing 2012a]. Unfortunately, the same type of cement couldn't be provided for the second part of the experiment. Therefore, the cement classified as CEM II / A-S 42.5 R according to [Czech Office for Standards, Metrology and Testing 2012a]. was used for the second part of the experiment. The optimal moisture content of the cold recycled mix was determined according to [Czech Office for Standards, Metrology and Testing 2011] and reflected already the presence of cement in the final cold recycled mix.

For the production of foamed bitumen standard straight-run bitumen 70/100 was applied according to [Czech Office for Standards, Metrology and Testing 2009]. When preparing the foamed bitumen, there was 3.8 % of water added to the bitumen (according to the procedure recommended for cold recycling technology by [Wirtgen GmbH 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 performed experiment was focused on the application of mechanically activated reclaimed pulverized concrete (PC). Large pieces of concrete reclaimed from a cement concrete pavement of backbone Czech motorway D1 during its reconstruction were crushed to fraction 0/22 in the laboratories at CTU Prague. Consequently, the reclaimed concrete was crushed in an impact crusher to fraction < 1 mm. Intense mechanical activation, or intense grinding in a high-speed mill with repulse disc rotors followed. The mutual perimeter speed of counter-rotating rotors was set to approx. 200-250 m/s. Based on the assumptions, the mode was supposed to guarantee a very high rate of material refinement with acceptable economy (high productivity, reasonable energy consumption, low wear of machinery). Within the proposed mode, only a significant increase in specific surface should have been observed (see Tab. 3).

Sample after mechanical activation	Reclaimed concrete
Density (g/cm^3)	2.670
Specific surface (m^2/kg) according to Blaine	435

Table 3. Basic parameters of finely ground reclaimed concrete

The comparison of results of laser granulometry suggests the conclusion that high-speed grinding achieved a very fine grinding of the input material to prevailing particle size of 0.5 – 50 µm, where the average grain was 18 µm (see Fig. 2).

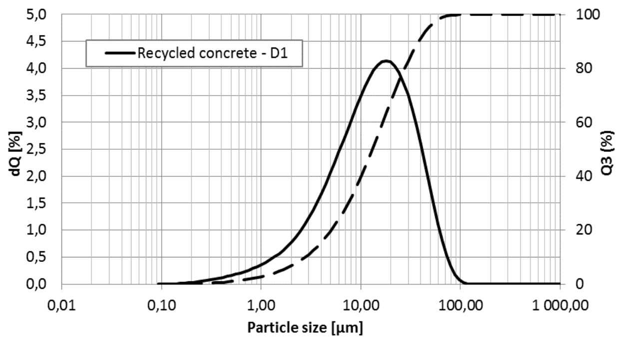

Figure 2. Granular analysis of reclaimed concrete by laser granulometry

Cylindrical specimens with 150±1 mm diameter and 60 mm height compacted by static pressure of 5.0 MPa were prepared according to [Czech Office for Standards, Metrology and Testing 2009]. To simulate the initial moisture content of the mixture after paving and compaction of the fresh mix, specimens were 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. The volumetric parameters and indirect tensile strength of the test specimens were determined according to [Czech Ministry of Transportation 2009]. For all test specimens stiffness modulus data were collected. Repeated indirect tension to cylindrical specimens test (IT-CY) was used according to [Czech Office for Standards, Metrology and Testing 2012b]. Measurement of indirect tensile strength (ITS) and stiffness modulus was performed at 15 °C after 7, 14 and 28 days of specimen curing.

For all the mixes moisture susceptibility was determined with derived indirect tensile strength ratio (ITSR) according to [Czech Ministry of Transportation 2009]. The test specimens that cured for 7 days at laboratory conditions were suspended in water of (20±2) °C for another 7 days and then used for the ITS test. Such prepared specimens were subjected to non-destructive stiffness testing by the IT-CY method prior to ITS testing to determine the effects of water on mix stiffness. The ITSR value is then a ratio of the average ITS value of specimens cured this way and the average ITS value measured in specimens cured just for 7 days in laboratory conditions.

3 DISCUSSION OF RESULTS

The overall results of both parts of the performed experimental work are summarized in Tab. 4. When assessing these results, a very positive outcome appears, namely, the results confirm previous finding of a very good influence of added pulverized concrete on moisture susceptibility of a cold-recycled mix.

As can be seen from Tab. 4 as well, the ratio of stiffness modulus of dry specimens after 7 days of curing and wet specimens treated according to [Czech Ministry of Transportation 2009] is also very high. The significantly worst moisture susceptibility was determined in mix 2F, which doesn't contain any cement or pulverized concrete, just 2 % of foamed bitumen. The highest values of ITS and stiffness were determined in mix 2F+3C as expected. On the other hand, all other tested mixes meet the requirements of [Czech Ministry of Transportation 2009] and moreover, in contrast to mix 2F+3C they don't overcome the upper limit of the ITS value after 7 days, which is set according to [Czech Ministry of Transportation 2009] at 0.7 MPa. That means that adding of milled concrete instead of cement provides sufficient strength and stiffness, very good moisture susceptibility and it doesn't cause the problems with hydraulic crack origin occurring due to too rapid strength increase, which is typical for mixes with higher amount of cement. Together with the economic and environmental benefits and in support of already quite large number of different cold-recycled mixes with pulverized concrete tested, it can be stated, that adding of pulverized concrete is with no doubt very convenient and recommendable. On the other hand, the idea of adding higher amount of pulverized concrete (especially in the mix 2F+6C) doesn't seem convenient. Therefore, the following chapters focus more closely on the differences between tested mixes and searching for the best mix composition.

3.1 *The influence of foamed bitumen content*

When comparing similar mixes, which differ just in the foamed bitumen content, it can be seen that mixes with 2 % of foamed bitumen reach higher results of both measured characteristics than mixes with 1 %. Similarly, higher results were achieved by mixes with 4 % of foamed bitumen than by mixes with 2 %. This phenomenon is clearly visible from Fig. 3 and 4, that depict 3 pairs of mixes differing just in the foamed bitumen content. The mix with higher content of foamed bitumen (depicted with lighter color) achieves higher strength and stiffness in all 3 cases. Also the mixes presented in this paper achieve lower (but still sufficient) values of ITS and stiffness modulus than mixes tested earlier, because those mixes contained higher amount of bituminous binder.

In the past we discovered, that adding of foamed bitumen in higher amount than the optimum leads to a mix which is too flexible. Mixes with more than 2.5 % of foamed bitumen had usually lower strength and stiffness than mixes with lower amount of foamed bitumen [Valentin 2016]. This fact was also one of the motivations for testing mixes with lower amount of foamed bitumen.

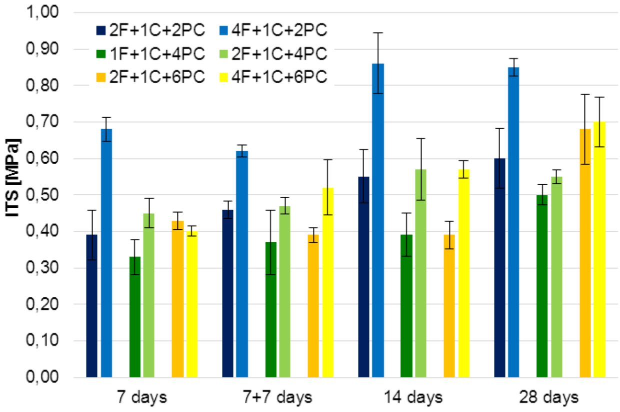

Figure 3. Indirect tensile strength of three pairs of mixes with different foamed bitumen content

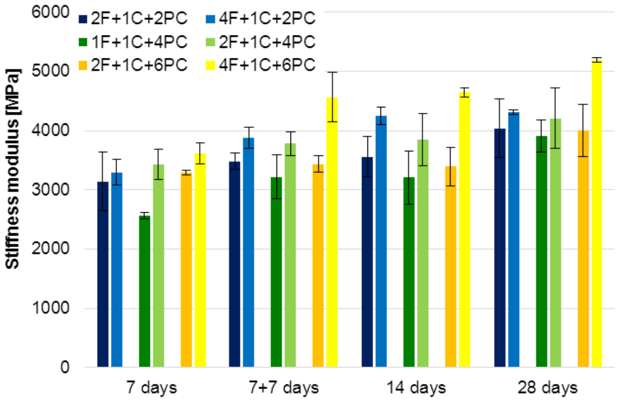

Figure 4. Stiffness modulus of three pairs of mixes with different foamed bitumen content

Mix	Indirect tensile strength [MPa]				ITSR	Stiffness modulus [MPa]				Stiffness modulus(7+7) / Stiffness modulus(7)	Voids content
	7 days	7+7 days	14 days	7 days	7+7 days	14 days	7 days	7+7 days	14 days		
2F+1C	0.50	0.41	0.54	0.62	82%	3177	3315	3685	3886	104%	12.5
2F+1C+2PC	0.39	0.46	0.55	0.60	118%	3139	3482	3557	4038	111%	13.0
4F+1C+2PC	0.68	0.62	0.86	0.85	91%	3294	3875	4246	4307	118%	9.4
2F+1C+4PC	0.45	0.47	0.57	0.55	104%	3421	3777	3851	4205	110%	12.2
1F+1C+4PC	0.33	0.37	0.39	0.50	112%	2564	3216	3208	3907	125%	14.1
2F+1C+6PC	0.43	0.39	0.39	0.68	91%	3290	3434	3396	3995	104%	13.1
4F+1C+6PC	0.40	0.52	0.57	0.70	130%	3610	4564	4643	5191	126%	12.5
2F+6PC	0.30	0.22	0.38	0.52	73%	1590	887	1812	2793	56%	12.8
2F+3C	0.91	0.84	0.88	0.98	92%	5331	5608	5797	5644	105%	11.6
2F+3PC	0.39	0.42	0.54	0.68	108%	1860	1669	2134	2653	90%	12.6
2F	0.43	0.27	0.62	0.67	63%	2011	767	2657	2779	38%	13.6
2F+3CC	0.37	0.50	0.46	0.71	135%	3088	3992	3323	4346	129%	15.0

Table 4. **The overall results of all tested cold-recycled mixes**

The presented finding of better strength and stiffness connected with increasing foamed bitumen amount is therefore in contrast to [Valentin 2016], which can be caused by heterogeneity of the RAP discussed already earlier. Another possible reason for that can be the modification of the grading curve of a cold-recycled mix as a result of adding the finely ground concrete into the mix. The higher content of fine particles can cause the need of higher amount of bituminous binder in order to form „mortar" together, which then coats bigger grains. The optimal foamed bitumen content can therefore move higher.

3.2 *The influence of pulverized concrete content*

Fig. 5 and 6 are focused on the influence of added pulverized concrete. Unfortunately, the influence of added pulverized concrete isn't unambiguous, but the best qualities are achieved usually by the mix 2F+1C+4PC. Despite the positive effect of adding the pulverized concrete into the cold-recycled mix, adding of 6 % of pulverized concrete seems to be already too much and it doesn't bring the desired benefit.

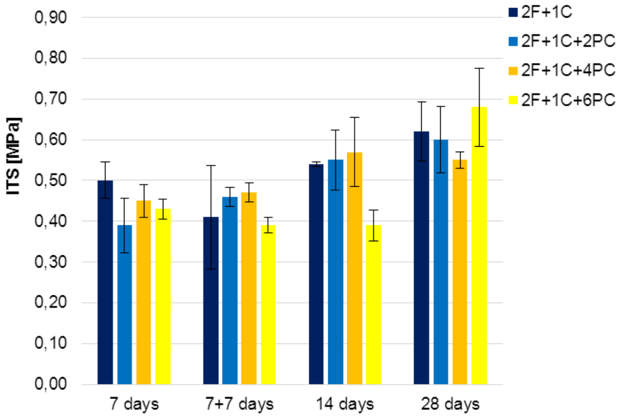

Figure 5. ITS of mixes with different content of pulverized concrete

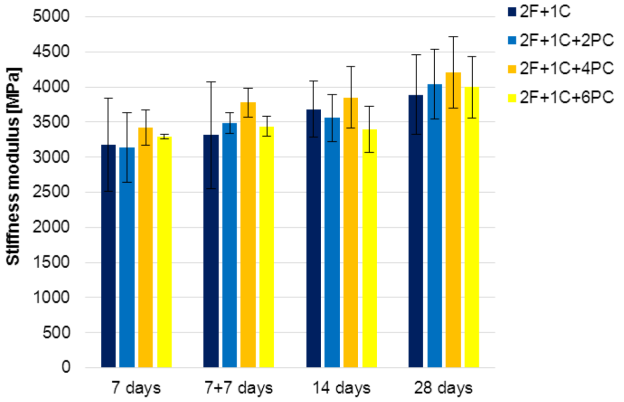

Figure 6. Stiffness modulus of mixes with different content of pulverized concrete

3.3 *The mixed additive (50 % of cement + 50 % of recycled concrete milled together)*

A new idea of milling cement and concrete together instead of just mixing milled concrete with standard cement was investigated as well. It was presumed, that the mechanical activation influencing positively the milled concrete could have a positive effect on cement as well.

Fig. 7 and 8 show that this procedure doesn't bring as good effects as it was expected. In the case of stiffness modulus, the mix with this mixed additive (2F+3CC) achieves slightly higher values than the mix with 3 % of pulverized concrete (2F+3PC) but in the case of ITS, the results are very similar. Considering that the mix 2F+3CC contains 1.5 % of cement and it is therefore more expensive and less environmentally friendly, the positive effect is not big enough.

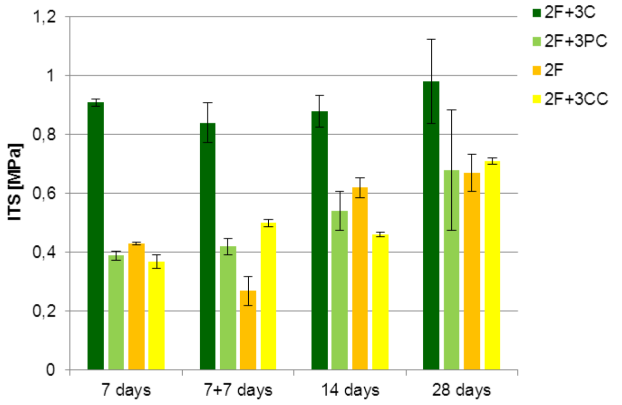

Figure 7. ITS of particular investigated mixes

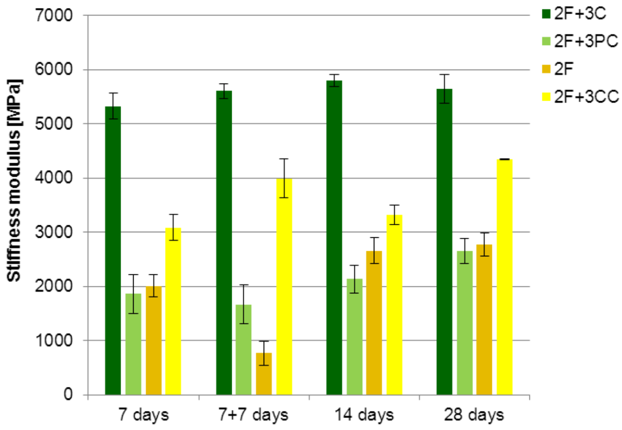

Figure 8. Stiffness modulus of particular investigated mixes

4 CONCLUSION

The substitution of cement by recycled mechanically activated concrete was repeatedly proven to be very beneficial. The pulverized concrete substitutes well the most important role of cement in a cold-recycled mix – providing very good moisture susceptibility. Moreover, although all the mixes with pulverized concrete met the requirements of [Czech Ministry of Transportation 2009] on sufficient strength, the growth of strength isn't too rapid as in mixes with cement and therefore the problem with origin of hydration cracks is eliminated. Together with the economic and environmental benefits the addition of pulverized concrete into the cold-recycled mixes is highly recommendable. Together with the results presented earlier where it was repeatedly proven that mixes with 5 % of pulverized concrete achieve better results than mixes with 3 %, it is recommended to add 4 – 5 % of pulverized concrete into the cold-recycled mixes. Higher content of mechanically activated concrete causes decrease of strength. The production of the mixed additive consisting of 50 % of cement and 50 % of recycled concrete milled together isn't recommendable, because its positive effect is negligible.

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