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POTENTIAL SUBSTITUTIONS OF TRADITIONAL HYDRAULIC BINDERS IN COLD RECYCLED MIXTURES USING BLAST FURNACE SLAG

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Abstract

Cold recycling techniques are known for decades in pavement engineering as a suitable rehabilitation method mainly for existing asphalt pavements. Traditionally the most common solution is to use bituminous emulsion or foamed bitumen as a binder usually in combination with small amount of cement or lime as active fillers. In some countries cement or hydraulic road binders are preferred instead of bitumen based options since it is believed that hydraulic binders can increase the bearing capacity of cold recycled layer especially for pavements with underestimated structures which were designed ›40 years ago. Based on that the Faculty of Civil Engineering, CTU Prague is for more than 10 years evaluating and developing further alternatives for the cement-based approach of cold recycled mixtures. In the past experience with fly-ashes or activated fly-ash based alternative binders were presented. Presently the focus is concentrating on the potentials of using blast furnace slags which are not generally usable for the cement industry (e.g. because of limited content of glassy compounds which are very typical mainly for granulated blast furnace slags). Air-cooled blast furnace slags were selected and activated by high-speed milling to get a material with latent hydraulic properties. This modified slag was applied in several options to cold recycled mixtures and standard strength and deformation tests were performed, including the determination of resistance to water immersion. Separately pastes based on used treated fine-grained slags were tested and evaluated. Data of the pastes are discussed jointly with the results for experimentally tested cold recycled mixtures.

Keywords: cold recycled mixtures, blast furnace slag, fly-ash, cement substitution, strength properties, reclaimed asphalt

1 Introduction

In the last five years there were several experimental tasks which focused on the potentials of using alternative hydraulic binders which would effectively use existing by-products or wastes. The CTU Prague started firstly with fly-ash binders like DASTIT or SORFIX, which were invented in the Czech Republic and are applicable to hydraulic bon mixtures or concretes. Later it was decided to seek for suitable combinations or effective use of some types of slags including eventually necessary activating agents. The aim was to replace traditional cement where it would be possible and suitable. In case of utilizing alternative hydraulic binders traditional characteristics for the particular mixtures are analyzed – in case of cold recycled mixtures it is indirect tensile strength and resistance to water immersion. In most cases these results are accompanied by testing of cement pastes, which is important to precisely

understand the potentials of cement substitution, especially with respect to the suitable level of substitution.
The cold recycling technology is a well-established technique and there have been presented in the last 20 years many scientific papers, conference contributions and research reports (e.g. [1, 2, 3, 4, 7, 9, 13]) focusing on different aspects of characterizing this technology, manners of carrying out cold recycled pavement layers by using either bituminous binders with cement as well as studying performance related characteristics (e.g. [5, 6, 11, 12]) and advanced test methods. There are also diverse papers where several cement substituting binders are used in these composites (e.g. [8, 10, 14–17]). The reference list would be in reality very spacious and only a review paper cover many pages). At the same time it shall not be forgotten, that in the last 10-15 years some European research projects were realized as well, e.g. SAMARIS, Re-ROAD, CoRePaSol, SCORE etc. They helped to extend the knowledge about cold recycling.
Cold recycling is widely used in the practice for repair works and rehabilitations of pavements. In case of using the in-situ option the construction process can be accelerated ad be made more efficient. The true advantage is the fact that the existing pavement is 100 % reused by this kind of recycling often without the necessity of hauling huge amounts of building materials. It helps also to reduce waste creation and in case there are in the pavement some environmentally problematic materials used in the past, like e.g. tar, they can be safely treated and embedded in the pavement structure again. This helps to avoid not only the creation of dangerous waste but provides also effective protection to air and water pollution.
Since the early use of cold recycled mixtures in the Czech Republic the technological option based on combination of hydraulic binder – usually portland cement – and bituminous binder gained the highest popularity. There were even many road projects where the contractor gave precedence to hydraulic road binder, which must fulfill the criteria of EN 13282-1 or 2. The reason for the mentioned combination of two binders and even preference for solutions with only hydraulic binders is advocated by securing higher strength properties, which helped to increase the bearing capacity of the recycled pavement layer. Of course such approach needs some caution since a stiffer pavement layer can in these cases result in higher susceptibility to cracking. Nevertheless the regular use of cement in cold recycled mixtures has provided interesting potential for substitutes which would be suitable to be used instead of cement.

2 Used materials and cold recycled mix designs

The objective of the more sample experimental study, partly covered by theses [18, 19] was to evaluate suitable substitutions of regularly used cement in cold recycled mixtures by variants of blast furnace slags (BFS) eventually combined or compared with fly-ash based binders. For the preparation of experimental mixtures granular material was used which was formed by combination of granular base material 0/32 mm and reclaimed asphalt RA 0/11 mm with 1:1 ratio or entirely reclaimed asphalt 0/22 mm or site-won asphalt of particle size 0/45 mm and 0/32 mm. Designed cold recycled mixtures contained always slow-setting bituminous emulsion C60B10 and some of the traditional or alternative hydraulic binders as described further. The content of these binders varied in the proposed mix designs. For the tested experimental series the intension was to keep the bituminous emulsion content always the same to avoid too many factors which could influence the resulting mix characteristics.
All compared experimental mixtures (see Tables 2, 3, 4) and gained results for test specimens were compared with corresponding reference mixtures (REF) by laboratory tests as provided by TP 208. Commonly required test were for some mixtures supplemented by determination of stiffness using the repeated indirect tensile stress test (ČSN EN 12697-26, method C) and by determination of resistance to crack propagation according to ČSN EN 12697-44 (not pre-

sented in this paper). These characteristics were usually tested on specimens cured for either 28 days or 56 days. The already mentioned ratio of granular base material and reclaimed asphalt used in one of the test series was selected to provide conditions and especially cold recycled mix composition which will be in terms of mix properties and material composition as close as possible to the conditions of a pavement where it was assumed to be used. In general it is normally not common in the Czech Republic that the cold recycled layer is formed only by a single-kind material and ordinarily there is some ratio of granular base material and site-won asphalt. Of course there are specific exceptions, like the modernization of the key Czech motorway D1, where original cement bond base course was cold recycled. On the other hand the above mentioned rule is well represented by mixed reclaimed pavement material where usually asphalt layers and part of the base layer are treated together. Such material used in this paper originates from a 3rd class road and introduces a good example of common practice.

The composition of reference cold recycled mixtures is presented in Table 1. The alternative cold recycled mixtures with cement substitutions are presented in Tables 2, 3, 4. Grading curves and modified Proctor test result are in more detail presented in [23].

Table 1 Composition of the reference mixtures

Mix constituents [%]	**Mix design**		
	REF 1	**REF 2 (R1)**	**REF 3 (G1)**
Granular base material 0/32 mm	45,05	–	–
Mixed reclaimed pavement material 0/32 mm	–	–	63,1
Reclaimed asphalt 0/11 mm	45,05	–	27,1
Reclaimed asphalt 0/22 mm	–	90,0	–
Water	3,9	3,5	3,8
Bituminous emulsion	3,0	3,5	2,0
Cement CEM II 32,5R	3,0	3,0	4,0

Table 2 Composition of the cold recycled mixtures, series I [18]

Mix constituents [%]	**Mix design**					
	A	**B**	**C**	**D**	**E**	**F**
Granular base material 0/32 mm	44,0	44,1	43,85	43,45	43,85	43,4
Reclaimed asphalt 0/11 mm	44,0	44,1	43,85	43,45	43,85	43,4
Water	4,0	3,8	4,3	5,1	4,3	5,2
Bituminous emulsion	3,0	3,0	3,0	3,0	3,0	3,0
Cement CEM II/ 32,5R	1,0	1,0	1,0	1,0	1,0	–
MS-PT (ladle slag)	4,0	–	–	–	–	–
MS-KVP (air cooled BFS)	–	4,0	–	–	–	–
MS-TG (granulated BFS)	–	–	4,0	–	–	–
MS-TG + DASTIT fly-ash binder (ratio 1:1)	–	–	–	4,0	3,0	4,0

Table 3 Composition of the cold recycled mixtures, series II [19]

Mix constituents [%]	Mix design							
	R2	R3	R4	R5	R6	R7	R8	R9
Reclaimed asphalt 0/22 mm	90	90	90	91	91,5	90	90	90
Water	3,5	3,5	3,5	3,5	3,0	3,5	3,5	3,5
Bituminous emulsion	3,5	3,5	3,5	1,5	3,5	3,5	3,5	3,5
Cement CEM II 32,5R	–	–	–	4,0	2,0	–	–	–
Commercial road binder TB	–	–	–	–	–	–	3,0	–
MS-TG (granulated BFS)	3,0	–	–	–	–	–	–	–
MS-KVP (air cooled BFS)	–	3,0	–	–	–	–	–	–
Milled recycled concrete (D2)	–	–	3,0	–	–	–	–	–
Ternary fly-ash based binder SORFIX	–	–	–	–	–	–	–	3,0
DASTIT fly ash binder with CEM I (ratio 4:1)	–	–	–	–	–	3,0	–	–

Table 4 Composition of the cold recycled mixtures, series III

Mix constituents [%]	Mix design								
	G2	G3	G4	G5	G6	G7	G8	G9	G10
Mixed reclaimed pavement material 0/32 mm	63,1	63,1	63,1	63,7	63,1	63,1	63,1	62,5	63,1
Reclaimed asphalt 0/11 mm	27,1	27,1	27,1	27,5	27,1	27,1	–	26,3	27,1
BFS 0/4 mm	–	–	–	–	–	–	27,1	–	–
Water	3,8	3,8	3,8	3,8	3,8	3,8	3,8	4,2	3,8
Bituminous emulsion	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Cement CEM II 32,5R	–	–	–	3,0	–	–	–	–	–
Cement CEM I 42,5R	–	–	–	–	0,5	0,5	0,5	–	0,5
MP-TTA with CEM I	–	4,0	–	–	–	–	–	5,0	–
MP-TTA with $Ca(OH)_2$	–	–	4,0	–	–	–	–	–	–
MS-KVP : fly-ash from fluidized combustion (1:1)	–	–	–	–	–	–	–	–	3,5
Ternary fly-ash based binder SORFIX	4,0	–	–	–	3,5	–	–	–	–
Fly-ash based binder DASTIT	–	–	–	–	–	3,5	3,5	–	–

The assessed mix variants differ in use of either slag or fly-ash of manifold origin. Combinations were used as well. All these byproducts were firstly treated by high-speed grinding (mechanical chemical activation). In the Czech Republic the BFS sources are limited to Kladno, Třinec and Ostrava. Further option to these locations can be found e.g. in Linz (Austria). Fly-ash based binder DASTIT® is actually produced only in Pilsen as a fully certified product which is mostly used for solidifications of clays, argillaceous rocks and sludge. Utilization in cold recycled mixtures was firstly verified by a trial section on a rural road II/118 near Prague [17]. Another example of fly-ash utilization is ternary binder SORFIX, which is a product of two fly-ash types, which are combined with lime hydrated and chemical additives. Last but not least a commercially available hydraulic road binder TP was used for sake of comparison within the second test series. Similarly high-speed ground recycled concrete of original particle size 0/4 mm was used as well. In this case the material originated from the reconstruction of D2 motorway Brno – Bratislava.

In the case of used BFS the marking MS-PT stays for ladle slag from Třinec, where CaO is found in trace amount. Chemically this slag is dominated by SiO_2 and Fe_2O_3. MS-KVP sample represents stabilized air-cooled blast furnace slag which is stored for decades in the city of Kladno. The material was landfilled on the existing stockpile between the beginning and the 80´ of the last century. The BFS was high-speed milled by the partnering company Lavaris, whereas the determined surface area according to Blaine was 370 m^2/kg. Higher content of free CaO (around 38 %) is a good prerequisite for latent hydraulic activity of this material. It can be expected, that such BFS can be used as partial substitute for traditional cement. This blast furnace slag has again also higher contents of SiO_2 and Al_2O_3. The particle size distribution was within the interval of 0,1–50 μm, whereas the highest count was found for particles between 10 μm and 15 μm. The activity of this slag and other slag-based binder or active fillers is expressed by the efficiency index which was tested according to EN 15167-1 (par. 5.3.2.3). These results, however, are not part of this article, some of the findings can be found e.g. in [22]. The MS-GT sample represents granulated (water cooled) BFS which was ground by high-speed disintegrator and originates in Třinec. The surface area of this sample was only 84 m^2/kg. During further steps of milling (results for these options are not presented in this paper) it was possible to reach a better surface area of 250-300 m^2/kg. Originally very low surface area might be interpretable also by the particle size distribution, as was determined by laser granulometry. Interval of 0,1–250 μm was reached, whereas the highest count was found for particles between 40 μm and 100 μm. This BFS is dominated by SiO_2, CaO (42 %) and MgO. Spectroscopic XRF analyses of the described slags can be found e.g. in [18].

3 Experimental results

Findings obtained from three selected series of cold recycled mixtures, whose design is defined above, are presented in this section. Reclaimed material used in these series was obtained from different locations, and therefore potentials or benefits of it can be observed for some variants, where the same type of alternative hydraulic binder is used. In case of other tested alternative binders, the selection is based on the gradual assessment of inputs like fly ashes from fluidized combustion and blast furnace slags (BFS). In general, the intention is to focus on wastes which are not commonly used in civil engineering (commonly used are e.g. granulated slags used in cement industry, or silica fly-ashes, which traditionally are very well used in concrete production). In many cases, tested fly-ashes and slags have not been used regularly due to concerns of their uncontrolled activity or considerable heterogeneity of such materials. This is, after all, one of the reasons why CTU in Prague has been over a long period supporting the development of high-speed milling technology, which helps to minimize many of these weaknesses in presented wastes or by-products.
In case of series "I" cold recycled mixtures, in the first step variants REF, A, B, C and D were evaluated by indirect tensile strength. The minimum values of indirect tensile strength R_{it} as defined by Technical Specifications TP 208 valid in the Czech Republic were not fulfilled by variant A (0,27 MPa) and variant B (0,30 MPa). The other two variants (C, D) met this minimum requirement without any problems. It should be point out that ladle furnace slag used in variant A has generally lower activity, but on the contrary, as it has been shown in other applications it can improve workability of the mixture. Its composition and especially the relatively large stockpiles, that do not find any reasonable application, could perhaps be used as alternative filler in asphalt mixtures. Variant B is based on blast furnace air-cooled BFS, which works better with an increased amount of a suitable activator or in combination with a suitable type of CaO rich fly-ash, as indicate results of series "III" as well.

Table 5 Volumetric and strength properties of cold recycled mixtures – series I

Variant		REF1	CR-A	CR-B	CR-C	CR-D	CR-E	CR-F
Bulk density (before test)	[g.cm^{-3}]	2,287	2,297	2,299	2,298	2,291	2,288	2,292
Air voids content	[%-vol.]	13,71	13,31	13,28	13,33	13,58	13,71	13,55
Moisture content of fresh mixture	[%-mass]	3,89	3,99	3,79	4,26	5,07	4,33	5,21
Indirect tensile strength, 7 days ($R_{it,7}$)	[MPa]	0,48	0,33	0,30	0,35	0,43	0,35	0,37
Indirect tensile strength, 7+7 days ($R_{it,7+7}$)	[MPa]	0,42	0,27	0,30	0,32	0,43	0,38	0,35
Water susceptibility	[%]	87,3	81,9	101,2	91,1	98,9	106	104,5
Indirect tensile strength, 7 days ($R_{it,28}$)	[MPa]	1,10	0,71	0,62	0,80	0,91	0,83	0,77
Indirect tensile strength, 7 days ($R_{it,56}$)	[MPa]	1,15	0,86	0,81	0,81	1,15	-	-

Furthermore, comparing the results of variants REF and C, the variant C did not reach higher strength. Likewise the variant D reached slightly lower ITS in comparison to reference variant (D = 0,43 MPa vs. REF = 0,48 MPa), but the water susceptibility exceeded in this case the reference mixture. Even the individual indirect tensile strength $R_{it,7+7}$ was higher for variant D (D = 0,43 MPa vs. REF = 0,42 MPa).

In the first phase of testing, the variant D, which contained 1.0 % cement and 4.0 % blended binder of granulated and milled BFS with DASTIT fly-ash based binder, performed best compared to the reference mixture. For this reason, two additional variants of cold recycled mixtures (E, F) were subsequently designed on the basis of variant D. These variants contained the same binder (blend of BFS from the same source and DASTIT), only the amount of blended binder varied. Although these last two mixtures met the requirements of TP 208 for minimum values of indirect tensile strength ($R_{it,\ 7\ min}$ = 0.30 MPa) and water susceptibility (min. 75 %), the results were below the expected values compared to the reference mixture.

If we focus only on water susceptibility (ITSR), the limit was fulfilled for all recycled mixtures with a considerable reserve. The best result was achieved by the variant E (1.0 % cement + 3.0 % MS-GT slag + DASTIT), for which the value of ITSR exceeded 107 %, i.e. the mixture gained additional strength due to the effect of water conditioning, which can be for mixtures with increased amount of hydraulic binder explained by additional hydration and hardening of composite matrix.

Slower, but over time continuing strength increase if BFS-based binders are used corresponds well with the strength development of variant D (see $R_{it,7}$, $R_{it,28}$ and $R_{it,56}$). While in the case of ITS after 7 and 28 days this variant showed still lower strength than reference mixture containing standard portland cement, after 56 days the strength characteristics were equal. It can be assumed that after this time the proposed substitution is fully comparable with the reference mix, while this solution will be more cost effective and at the same time it can be declared as low-emission, since for the production of alternative hydraulic binders a low-energy disintegrator and existing by-products, which are anyway produced by the human activity, are used. On the contrary, the cement cannot be manufactured without emitting higher amounts of CO_2.

The second series of cold recycled mixtures differed in several aspects. Firstly, only reclaimed asphalt with maximum particle size of 22 mm (without use of additional aggregates) was used. Furthermore, the amount of water was same for all mix variants, so the fact that for example fly-ash normally requires a slightly increased content of water to reach optimal humidity, was not reflected. The amount of water was only reduced in case of the variant R6, where the proportion of cement in the mixture was reduced. The effect of increased water consumption is evident from the results of fresh mix moisture – the reference mixture showed the highest value.

In terms of physical properties, the slightly different bulk density is obvious, the variants R1 to R3 represent either a reference mixture with cement or variants with milled BFS as a substitute for the cement. On the contrary, the variants R7 to R9 contained either fly-ash based binders or commercial hydraulic road binder TB according to ČSN EN 13282-1. The density of a fly-ash is generally lower than that of cement or BFS, and this is reflected in the bulk density of cold recycled mixture. However, this aspect does not have any influence on air voids content, whose comparison is problematic for heterogeneous materials like reclaimed asphalt.

Table 6 Volumetric and strength properties of cold recycled mixtures – series II

Variant		**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**
Bulk density	[g.cm^{-3}]	2,249	2,239	2,220	2,175	2,164	2,179	2,151	2,166	2,092
Air voids content	[%-vol.]	10,04	10,46	12,83	13,73	15,00	11,51	13,20	9,97	13,01
Moisture content of fresh mixture	[%-mass]	6,1	5,6	6,0	5,6	5,6	5,9	5,2	4,9	5,7
Water suscept. (ITSR)	[%]	101,6	86,5	95,0	118,0	96,3	117,2	107,2	91,2	125,6

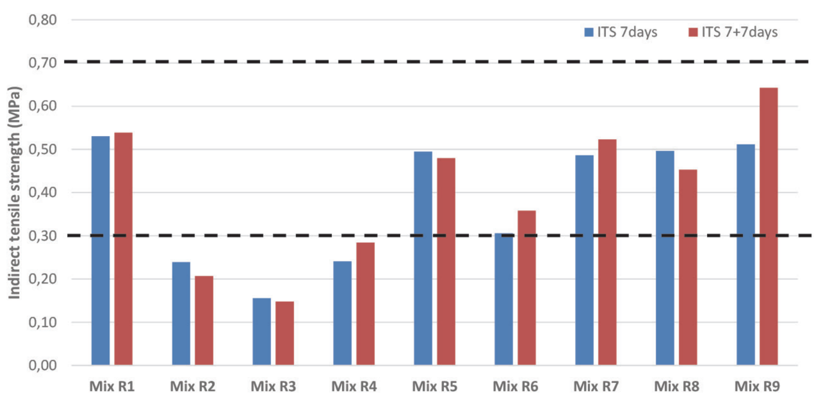

Figure 1 Indirect tensile strength of cold recycled mixtures – series II

The results mentioned above probably caused the differences in strength properties, which are shown in Figure 1. In this series, both variants with milled BFS completely failed. Similarly, the variant R4, where micro-milled recycled concrete was applied, did not reach the minimum required value of $R_{it,7}$. However, it should be emphasized that, on the contrary to series "I", the mixtures with alternative binders did not contain any cement as an activating additive. This obviously plays an important role in the case of latent hydraulic binders, which blast furnace slags undoubtedly are.

To certain extent, the comparison of R1 and R5 is surprising since the latter mixture contained increased amount of cement and reduced amount of bituminous emulsion. This combination does not always necessarily need to lead to better strength results. The variant with a ternary fly-ash based binder SORFIX (R9) clearly achieved the best results. In this case, it is necessary to pay attention to the increase in strength, which occurred after 7 days in water

bath conditioning. The water immersion significantly increased the activation of the fly-ash, which, unlike from slags, had sufficient amount of $Ca(OH)_2$ as an activating additive.
What is necessary to point out, both tested fly-ash binders can work very well as an alternative to hydraulic binders and can effectively substitute cement. The economic impact of price reduction for alternative binders would be at least 20-25 %. A certain disadvantage of these binders is lower bulk density, which partially complicates their usage – it is in these cases necessary to spear such binders in front of the recycler in a thicker layer. This can cause problems with even small wind gusts, when the binder can be blow away in front of the recycler. The solution of this problem could be for example use of binder suspension instead of dry binder spreading.
The third test series was based on the results of previous two. For its performance another type of mixed site-won asphalt was obtained (material resulted from milling 20 cm of an existing asphalt pavement). This material was combined with RA 0/11 mm to adjust particle size distribution of the final mixture. The ratio of the site-won asphalt and RA 0/11 mm was 70:30. It is not possible to make any conclusions from volumetric characteristics. The variants G1 and G5 contained only cement. The variant G10 combined fly-ash from fluidized combustion with blast furnace slag. The remaining mixtures were variations of different types of fly-ash binders. The lightest mixture seems to be the one, which combines chemically very active high speed milled fly-ash from fluidized combustion with lime hydrate (mix G4). Lime hydrate is present in the ternary binder SORFIX (mix G2) as well.

Table 7 Volumetric and strength properties of cold recycled mixtures- series III

Variant		**G1**	**G2**	**G3**	**G4**	**G5**
Bulk density	[g.cm^{-3}]	2,307	2,273	2,254	2,206	2,425
Air voids content	[%-obj.]	12,4	12,4	13,1	14,4	9,8
Moisture content of fresh mixture	[%-hm.]	3,9	4,3	4,5	4,5	3,6
Water susceptibility (ITSR)	[%]	101,5	62,3	103,4	68,0	106,2
Variant		G6	G7	G8	G9	G10
Bulk density	[g.cm^{-3}]	2,330	2,320	2,314	2,247	2,239
Air voids content	[%-obj.]	13,8	14,2	14,4	16,7	14,6
Moisture of fresh mixture	[%-hm.]	3,8	3,6	4,3	3,6	3,6
Water susceptibility (ITSR)	[%]	100,4	98,1	94,9	79,5	102,2

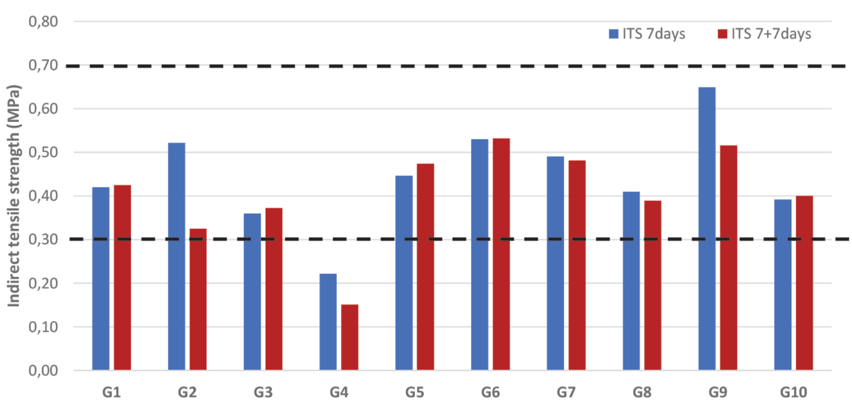

Figure 2 Indirect tensile strength of cold recycled mixtures – series III

The results may thus indicate the effect of slightly different densities of different fly-ash based binders. In terms of air voids content, only mix G5 (reduced cement content if compared to the reference mix) and mix G9 (increased amount of fly-ash based binder "MP-TTA+CEM I") deviate from quite narrow interval of gained results.
From the results of indirect tensile strength (Figure 2), it is obvious that only variant G4, containing fly-ash binder MP-TTA+$Ca(OH)_2$, does not meet the required limits given in TP 208. In all other cases, the limits were exceeded with good comparability of the mixtures. The highest $ITS_{7\ days}$ were achieved by mixtures G2, G6 and G9, i.e. variants where SORFIX binder was applied or 5 % of fly-ash binder MP-TTA+CEM I was used. Interesting is also the comparison of the reference mix and G5. The reference mix design was based on requirements for the rehabilitation of 2nd class road. In this particular case, the comparison shows that higher cement content does necessarily not provide better results. After all, in this comparison, the resistance to water susceptibility (ITSR) is also better for the variant G5.
In terms of water susceptibility, the behaviour of cold recycled mix variants can be assumed as relatively stable, and the water doesn´t have any considerable effects on mix properties. This is a relatively common phenomenon for cold recycled mixtures with hydraulic binders. Only the variant G2 did not meet the requirements of TP 208 and variant G9 showed a significant decrease in strength characteristics. For G2 it can be stated that in comparison with mix G6 it is obvious that in case of Sorfix fly-ash based binder SORFIX it is probably effective to combine it with at least small amount of cement, which subsequently helps to keep water susceptibility of the mixture within required limits.

Table 8 Stiffness modules of cold recycled mixtures

Mix variant	Stiffness modulus @ T(°C) [MPa]			Thermal susceptibility
	0	15	27	S_0/S_{27}
REF 1	12 258	8 056	6 706	1,83
CR – A	7 764	4 449	3 331	2,33
CR – B	6 794	4 874	3 441	1,97
CR – C	9 196	6 834	4 663	1,97
CR – D	11 658	8 447	6 269	1,86
CR – E	12 239	7 849	7 363	1,66
CR – F	10 500	6 326	4 997	2,10
REF – R1	8 684	4 982	3 172	2,74
R2	6 051	2 339	841	7,19
R3	6 445	2 438	985	6,54
R4	4 834	1 989	999	4,84
R5	9 974	8 147	6 193	1,61
R6	5 938	3 886	2 557	2,32
R7	7 424	4 725	3 207	2,31
R8	6 762	4 292	3 204	2,11
R9	6 897	4 708	3 219	2,14

The results of stiffness modulus correlates well with strength properties of mixtures of series "I" and "II". The stiffness modulus was determined at 3 test temperatures (0°C, 15°C and 27°C). Thermal susceptibility was calculated as a ratio of stiffness for the lowest and highest

determined temperature. This characteristic is always significantly lower for cold recycled mixtures than for hot asphalt mixtures.
In case of series “I” it should be emphasized that stiffness of mix D was after 28 days already fully comparable to the reference mixture. It can be even stated that mix E, with a slightly smaller amount of alternative binder, is also well comparable.
The results of mixtures from series “II” are totally opposite and none of the conclusions apply in this case. The highest stiffness values (Table 8) were achieved by the mix R5 designed with higher cement content. This mix variant, due to the reduced content of bituminous emulsion, resulted also in a very low thermal susceptibility. It is apparent that substitution of cement by existing commercial hydraulic road binder (TB) or fly-ash based binder (DASTIT, SORFIX) lead to similar stiffness values. This supports the legitimacy of such kind of substitution in production of cold recycled mixture on site.

4 Conclusions

Following the European-wide effort to reduce energy demand, carbon footprint as well as polluting emissions it would be pity if prospective alternative binders were not be considered as an option. Several secondary resources as by-products of the industrial activities will always exist. These by-products already are represented by a certain amount of embodied energy and there is a carbon-footprint related to their production. There conversion to suitable products normally does not involve in no manner significant increment of energy demand and they can be therefore considered as a “green” solution. Moreover, if we prioritize reasonable recycling of these materials instead of their landfilling, we might reach additional economic added values.
From the realized experimental tests and comparisons of various alternative binders it is possible to conclude that the substitution of traditional cement by fly-ash or BFS based binders is possible and technically even provides justification. It is usually important that the alternative latent hydraulic material is complemented by a suitable activating agent, which can be small portion of cement, hydrated lime etc. Another important aspect without doubts is the influence of particle size the by-products can have. Results presented in this paper have again confirmed the previous findings of the research done at CTU in Prague using high-speed disintegrators for milling, homogenisation and mechanical activation of fly-ash or slag materials. Production costs and energy demand of such process are disproportionally lower that for the traditional cement production. At the same time investment demanding ball mills are not required. In applications, where we are not expecting compression strength for the resulting pavement structures higher than 20-25 MPa, alternative binders or cement substitutes based on fly-ash or slags are a reasonable solution. Nevertheless, the potential will be most probably reachable also for higher strength classes (so far done tests for shotcrete, self compacting concrete or concrete pavement mixtures have indicated such possibility). It is therefore important to stress, that attention is paid to fly-ashes from fluidized combustion and to those BFS, which are not traditionally used for blended cements. If the mentioned potentials would be combined with construction volumes in infrastructural projects the economic leverage of these alternatives could be significant and the contractors could gain inconsiderable cost savings – price for alternative fly-ash or BFS based binders usually do not exceed 55-60 EUR/t (cement price is 75-80 EUR/t), in contrary some solutions can even reach level of max. 45 EUR/t. Carrying out a very simplified comparison for mix variants presented in this paper one can quickly discover the economic benefit of proposed cement substitutions.
The persisting concern in many regions is already the term “slag” or “fly-ash” itself. Many sub-types of these industrial by-products are stigmatized by earlier problematic applications in some construction project or by general distrust just because these materials can contain

higher portions of free CaO and there can be a higher risk of uncontrolled reactions and volume changes. It is nevertheless important to keep in mind that the amount of such fly-ashes or slags in hydraulic bond mixtures or similar composites is quite low which keeps the potential risk in controllable range. Additionally processes like the used high-speed disintegration helps to further avoid some of the problems related to unfavourable reactions.

Remark

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