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Fly-ashes from fluid combustion as an alternative binder for cold recycling and stabilized base courses in pavement structures

Jan Suda[1], Jan Valentin[2], Miloš Faltus[3]

[1] *Czech Technical University in Prague, Faculty of Civil Engineering, Department of road structures, email: jan.suda@fsv.cvut.cz*

[2] *Czech Technical University in Prague, Faculty of Civil Engineering, Department of road structures, email: jan.valentin@fsv.cvut.cz*

[3] *Technical University in Ostrava, Faculty for mining and geology, Institute of mining engineering and safety, email: geologicus@seznam.cz*

Abstract

In road construction sector in the present the focus is laid on technologies and techniques, which allow decreasing energy demand necessary for production. At the same time attention is paid to decreasing construction costs related to new structures or pavement rehabilitation works. In the Czech Republic in this connection the development during last ten years was oriented in increased extend on cold in-place recycling techniques. Certain positive potential of this group of techniques is the possibility to use energetic by-products in a form of alternative binders or fillers. These by-products, coming from coal combustion, have a relatively broad range of possible applications especially like alternative substitutes of normally used hydraulic binders (cement, lime) in cold recycling mixes. Within the experimental activities of Faculty of Civil Engineering CTU in Prague usually used cement was replaced by fly-ashes or inorganic loose binder obtained by mechanical activation of fly-ash coming from fluid combustion. With respect to limited knowledge of behavior and properties of mixes if an alternative solution is used, it is necessary to specify correctly newly designed mixes. For assessed mixes basic volumetric properties, as well as strength and deformation characteristics were determined. Within the evaluation of particular performance characteristics the influence of different aggregate grading on strength properties was assessed as well. From the expected use leaching tests were done for selected mixes as well as combined water and frost susceptibility tested. So far gained results are presented in the paper.

Keywords: Fly-ash from fluid combustion, mechanical activation, cold recycling techniques, indirect tensile strength, stiffness, water sensitivity, leaching, diffusive test

1 Introduction

In the research done in road construction increased focus on environmental aspects and the protection of the environment are more and more visible. This is closely related to the necessity to limit consumption of natural non-renewable resources, to decrease amount of waste material disposed on land-fills and at the same time to identify suitable techniques which would help to reduce the energy demand during construction of transport networks. In case of waste there is a European wide target to reach for construction and demolition waste a level of their recyclability about 70 % until 2020. Similar criteria can be found or it would be wise to promote them also for other waste materials [1].

Simultaneously some other initiatives and programs originated within the EU during last few years (especially as part of the activities done by the European centre for advanced studies), which focused on defining and describing suitable end-of-waste criteria. Such criteria will have in economic terms an important impact on easier use of such materials in further production chains and for various applications. One of the areas which gain an increased attention is represented by so called mineral waste materials. In this group also fly-ashes and solid reactive products based on calcium from desulphurized flue gasses can be included in. From this point of view the research activities and experimental testing based on searching for new solution with alternative fine graded mineral materials and performed by the Faculty of Civil Engineering CTU in Prague aim on reflecting these aspects.

Despite of R&D activities in the area of fly-ash utilization as an alternative binder or geopolymer especially for concrete, the possibilities to exploit bigger amounts of this material are limited. Various results can be found also in the research quite successfully realized presently also in the Czech Republic. The smaller applicable amounts of fly- ashes are determined by the mix composition and expected function of the fly-ash in mixes like concrete, usually having a role of a binder. Following the situation of fly-ash producers these trends cannot significantly solve the persisting problem of land-filling large amounts of this energetic by-product. So far gained results of ongoing research presented and discussed in this paper therefore aim on the possibility use fly-ash as an alternative binder in cold recycling mixes as well as on the possibility to substitute or supply part of the RAP material by fine-graded (filler) particles. Although it is realistically possible to use effectively only 10-15 % by mass of such material, this level represents an indispensable portion of utilizing especially more problematic fly-ashes from soft coal combustion and power production. In this area the Czech Republic shares front brackets in a worldwide comparison, especially in terms of per capita production.

Key energy source in the Czech Republic are still solid fuels, especially soft coal. In CZ about 69 % of coal exploitation (soft and lignite) is used for electricity production. Heat power plants produced in the year 2000 in the Czech Republic about 9.1 million tones of solid products (for comparison solid products from coal combustion reached in EU15 in the same period about 59 mil. tones). From this amount about 600 thsd. tones (comparing to 1,121 thsd. tones in EU15) is represented by fly-ash from fluid combustion. The total amount of fly-ashes increased in 2011 up to 11 million tones of solid products coming from the yearly coal combustion [6, 7]. Some of these solid combustion residua can be considered as good-quality by-products which differ in grading, chemical and mineralogical composition, as well as in properties and potential applications.

In the Czech Republic several heat power plants and generation plants can be found which use fluid combustion caldrons already approximately since 1996. These facilities have a combustion effectiveness of 85 to 88 %. The caldrons performance is based on the principle of coal combustion at temperatures between 850 and 950°C in a circulating fluid layer which is composed by milled coal, desulphurization additive (lime stone) and additive for stabilization of fluid layer (inert sand). The fluid layer is formed by a dispersive system, which is created by gas flow in required amount in the bed of particles loose below the fluid furnace grate. During the dissociating process the SO_2 released from the coal relate to $CaSO_4$ what has quite important environmental benefit. If it would be to the contrary, large amounts of SO_2 emissions would be released to the air causing significant pollution. Lower combustion temperature also reduces the generation of NO_x emissions. Resulting product can be defined as a mix of ash from the original fuel, untreated desulphurizing agent (CaO with eventual residua of $CaCO_3$), calcium sulphate ($CaSO_4$) and products of reaction between ash matters and CaO, as well as non-burnt fuel. With respect to the combustion temperature which is in case of fluid processes lower than in case of granular combustion technique, the untreated CaO is presented in form of so called softly calcined lime (about 30 %). Fluid combustion fly-ashes contain relatively higher amount of SO_3 (7-18 %), which can cause in the binder formation of ettringite. For fluid combustion fly-ashes absence of hot melt is typical as well. [2]. Important are as well chemical compounds containing Al. In fly-ashes form granular combustion (> 950°C) usually aluminum is mostly fixed in mullite, which is unable for any reaction during different types of high-speed milling. By contract in fly-ashes from fluid combustion the aluminum seems to be present in roentgen-amorphous conglomerates (probably in metakaolinit). Therefore the hydration reaction is much faster comparing to regular pozzolanic reaction.

Fluid combustion fly-ash contains relatively high content of pozzolanic active components, which potentially allow use this material in civil engineering for several applications. For this reason it is possible to develop suitable approaches how exploit this by-product for preparation of structural binders and increase the raw material basis. To get a highly effective modified binder it is necessary to apply physical (mechanical) activation of this material. Fluid combustion fly-ash with content of SiO_2 + Al_2O_3 larger than 50 % by mass is milled up to the maximum particle size 200 μm using a high-speed disintegrator equipped with a set of 6 rotors moving in opposite direction with radial velocity > 160 $m.s^{-1}$. Material milled by this process is on its own reactive and it is not necessary to use another additive for stimulating hydration processes. Newly originated loose inorganic binder is called Dastit®, patented in the Czech Republic. Potential benefits of physical activation are savings in form of reduced energy demand necessary for production of traditional hydraulic binders.

2 Range of experimental research

Within the experimental activities done in the research of alternative cold recycling mixes used in road construction several sets of mixes with variable content of fluid combustion fly-ash and Dastit® have been designed and tested. Fly-ash and Dastit® have a role as hydraulic binder substitutes or filler agents. At the same time a set of laboratory tests has been defined to allow the impact assessment of these alternative binders/fillers on the mix behavior. The experimental cold recycling mixes have been prepared according to the principles defined in the specifications of Ministry of Transportation in the Czech Republic (TP208). For the mix design sorted reclaimed asphalt material (RAP) of grading 0/11 and 0/22 from mixing plant Běchovice of PSVS (Porr) company has been used. For this material grading analysis has been done before and after extraction to get exact information about the content of odd particle sizes and the bitumen content. In RAP 0/11 bitumen content of 7.3 % has been found, in the coarser RAP 0/22 the content was lower, reaching 6.2 %.

As binders cationic bituminous emulsion of class C60B7 has been selected. It is a standard product used for cold recycling techniques in the Czech Republic. Similarly usual Portland slag cement CEM I/B- S32.5R has been used for most of the experimental mixes. For the comparison of alternative additives Dastit® and fluid combustion fly-ashes from ČEZ power plant Ledvice (filter fly-ash) and Počerady (bottom fly-ash) have been selected and applied in the mix designs. The most interesting aspect about these fly-ashes is with respect to their chemical chemistry very high content of SiO_2 + Al_2O_3 (> 70 %) and lover content of unbound CaO (< 9 %). These findings lead from the beginning to the expectation of similar behavior like known for cement.

Composition of odd mixes is shown in Table 1. Test specimens have been prepared by the modified procedure described in technical specifications TP208, [5]. For each mix at minimum 16-30 cylindrical specimens have been prepared and for each mix bulk densities of specimens, moisture of fresh produced mix, air voids content and permeability of the mix has been determined.

In the next step standardized tests required by the technical standards and TP208 have been executed. In the technical requirements for cold recycling mixes with bituminous emulsion and cement it is prescribed to perform indirect tensile strength test (ITS) at the temperature of 15°C after 7 days air curing and then after 14 days combined curing, i.e. 7 days air-curing and 7 days water curing. From these values the water sensitivity is afterwards calculated, which is used in the practice as one of the key quality criteria. In case of the done research broader range of assessment has been selected and besides described characteristics and parameters also ITS after 14 and 28 days air curing have been included. Results of strength characteristics on specimens with combined curing in water and on air have been subsequently compared to 7 and 14 days strength values for assessing the impact of water sensitivity according to TP208 and for determination of modified indicator ITSR* which is normally set and evaluated in case of hot asphalt mixes. In case of this ratio the temperature conditioning 72 hours in water at 40°C has not been done and specimens cured 7 days on air and 7 days in water have been just compared to specimens cured 14 days on air. Further evaluated characteristic was the stiffness modulus gained from non-destructive indirect tensile stress test at 5, 15 and 27°C after different curing periods. Specimens cured 14 and 28 days on air and 14 days of combined curing condition were tested.

To receive correct identification of selected materials used for newly designed experimental mixes basic chemical analyses of elements represented in these materials have been done. These analyses at the same time serve as a reference information base for assessment of leaching of hazardous substances in water leach of experimental mixes. Chemical analysis have been carried out in cooperation with the Geological Institute of the Academy of Sciences of the Czech Republic (AV ČR) for fundamental analysis of elements represented in the used materials and partly as a basis for future description of potential leaching effects. Particularly selected samples of waste granular material, by-products, and reclaimed materials the use of which is being considered or expected in pavement structures, or where such construction applications already exist, has been selected for the analyses done. The set of tested materials involves waste filler from aggregate production, fly ashes and reclaimed asphalt material.

In connection to the list of technical standards governing the leaching methods for various types of mineral materials different analytical procedures are used [8]. None of the methods governed by any standard concerned has been used; a modified procedure was preferred and applied based on analytical spectroscopy method. For this test procedure samples were analysed with IRIS Intrepid II XPS spectrometer (ICP-EOS) manufactured by Thermo Electron Corporation, using axial plasma view and cyclone type nebulizer. The standard operational conditions were used (plasma power 1150 W, nebulizer pressure 25.0 psi, auxiliary gas flux 1.0 ml/min, sample uptake 2.40 ml/min). For the analytical purposes wavelengths recommended by manufacturer for each element were used, as is published in the instrument manual as well. The calibration curves were constructed using four points (blank and multi-element standards in 1% supra-pure nitric acid) covering full range of the concentrations measured. Concentration of macroelements and microelements were calibrated and measured in separate experiments. Each sample was analysed three times. Quality control was ensured inserting QC sample into analytical run after each ten unknown sample.

For analytical purposes and as a basis for future leaching tests, the total elements contents in the solid samples were measured, after total decomposition of the solid samples in nitric acid/hydrofluoric acid/perchloric acid mixture. In this way the solid samples went into acidic solutions, in which elements concentrations were measured by ICP EOS. The concentrations of basic elements (macroelements) were estimated as well as the trace elements (microelements) by ICP EOS technique. ICP EOS stands for the spectroscopic analytical technique optical emission spectroscopy with inductively coupled plasma. Among others, the macroelements Al, Ca, Fe, K, Mg, Mn, Na, P, S, Si and the microelements As, B, Ba, Be, Cd, Co, Cr, Cu, Li, Mo, Ni, Sr, Ti, Zn were analysed.

For the future alternative leaching tests distilled water (pH value ~6.5) and aqueous solution of acetic acid (pH value ~ 4.5) will be used as leaching agents. Acetic acid was chosen to approximate the effect of leaching by acidic rain water. Similar testing procedure and environment can be found, e.g. in [9]. Analytical experiments were performed on samples of the materials pulverised and homogenised, fraction of grain size < 0.1 mm was used. Even if such testing sample preparation is not usual in the standardised leaching test methods for granular materials, the pulverisation has been decided for the total inorganic analysis and only for samples, where the largest particle was >500 µm. Sample weight 1-5 g and 100 ml of the leaching solution was used. Weighted samples were covered with the leaching solution and agitated on an overhead shaker for 2 h at room temperature. Leachates were then filtered over 0.45 µm filter and analysed. No leaching solution exchange was performed in the course of the test. Thus, the test can be characterised as a short-time procedure without dynamic character, i.e. without leaching solution exchange.

3 ASSESSMENT OF VOLUMETRIC AND MECHANICAL PROPERTIES

For the determination of properties of cold recycling mixes initially standard tests according to TP208 have been done. As described already in the previous text bulk density, air void content and moisture of produced mix, see Table 3. The bulk density has been determined by the SSD method (procedure with saturated dry surface) [4] and according to dimensions (height and diameter). All results of SSD method were in average about 3 % higher than bulk densities gained by the second method. In case of air voids content interesting trend has been observed, when the void content relatively linearly increased with fly-ash content in the mix. This has been abated also in variants with different cement and/or bituminous emulsion content. In case of Dastit® the situation was different, especially in case of lower content of this alternative binder in the mix and the voids content of the mix decreased and increased again with higher content of the material (see Table 2). Optimum moisture content has been determined by modified Proctor Standard test. For mixes with fluid combustion fly-ashes also permeability according to ČSN CEN ISO/TS 17892-11 has been determined. The values of filtration coefficient decreased with fly-ash content in the mix and the values were in the interval of 10^{-6} - 10^{-9} m/s at testing temperature of 10°C.

From the results of strength characteristics, which are summarized in Table 3, it is possible for assessed mixes to induce that fluid combustion fly-ash content in the mix is increased the indirect tensile strength decreases. Opposite trend is occurred if Dastit® has been used. In this case the strength characteristics steeply increase with higher content of the binder in the mix. The largest strength increase has been reached during the first seven days of curing. This means that during this period the vastest quantity of hydration processes is in progress and the shrinkage of the mix can be mostly negative affected. The aspect of modified ITSR* indicator and the ratio of indirect tensile strength decrease shows that ITSR* leads to worse values. Based on this finding it would be suitable to complement the criterion of strength decrease parameter in the existing technical specifications TP 208 by a minimum value for indirect tensile strength after 14 days curing. If RAP material of 0/22 grading is used the indirect tensile strength values decreased in average about 18 % comparing to mixes with 0/11 RAP.

The stiffness modules of cold recycling mixes assessed by the cyclic tensile stress method (IT-CY according to CSN EN 12697-26) are an important deformation characteristic. Stiffness is used together with the Poisson value for designing structural pavement layers in the Czech Republic. The stiffness modulus was determined on cylindrical specimens in the NAT (Nottingham Asphalt Tester) apparatus [3]. The respective performance of the testing has been done according to the setup described e.g. in [2]. From the received results it is visible, that increased filter fly-ash content the stiffness and ITMR ratio is significantly decreased. At the same time the thermal susceptibility is worsened as well. Opposite trend arose in cases where the alternative binder Dastit® and gliding bar fly-ash have been used. In these cases experimental mixes show abrupt increase in stiffness values and the water and thermal susceptibility gains smaller values. Further if analyzing mix REC P03 the significant importance of cement can be demonstrated. This mix shows relatively high stiffness modulus values and a good ITMR ratio. At the same time mixes with sufficient cement content are less thermal susceptible (see Table 4 and Figure 2).

Quite interesting are in general results of water susceptibility if this characteristic is assessed by comparing stiffness modules and setting the ITMR ratio comparing to modified indicator of indirect tensile strength ratio (ITSR*) and the indicator of indirect tensile strength decrease according to TP 208 specifications. Again like in the case of indirect tensile strength, also for stiffness modules there is an average decrease in values about 23 % if RAP grading 0/22 is used.

Further for selected experimental mixes the resistance to frost and water has been analyzed. This is an important performance characteristic especially from the viewpoint of practical application of these mixes in regions like the Czech Republic where winter seasons should be considered as one factor as well. Selected mixes have undergone several frost-thaw cycles according to the procedure described in specifications TP 112. The key determined parameter was the coefficient of decrease for stiffness modulus and indirect tensile strength. Limiting value for the decrease was set within the experimental testing at the level of 0.7. From the gained results (see Tab 3 and 4) it is visible, that with increased content of fluid combustion fly-ash and Dastit® the mix stability decreases. Nevertheless mixes with different content of alternative binder Dastit® are in all cases satisfactory and fulfilling the set minimum value. In case of mixes with fly-ash different situation can be seen. The trend of decreased stability is relatively significant and this can limit use of these mixes in base pavement courses.

3.1 Chemical analyses of macro- and micro-elements

In the cases of the waste filler from the Svrčovec quarry and the reclaimed asphalt material from the Běchovice mixing plant dump, two separate samples were taken from different places of the stock piles during 2008. For fly-ashes a small sample has been selected from a laboratory bulk of more than 60 kg used for mix designs and further testing. For the alternative binder Dastit a sample of about 20 kg has been milled. It is also necessary to state that it was impossible to carry out a general analysis of macro-elements for the crumb rubber sample due to the nature of the material. Subsequently, the leaching tests were limited to one of the three waste filler from traditional aggregate production.

The results of performed measurements are summarized in the tables 5 and 6. The concentrations of particular elements are normalized by the unit mg/g per sample. Due to this normalization easy and well understandable comparison of odd macro- and microelements is possible. It is possible to transform the normalized amounts into relative expression showing that besides the analyzed elements the material usually contains also some other.

For the macro-elements aluminium, calcium and partly silicon seems to have the highest concentration. The elements are represented in form of chemical compounds in crystalline or amorphous phases. Aluminium represented in Dastit and in both fly-ash samples is a puzzle because the source material burnt was soft coal and lime-stone used as catalyst. Only in case of Hodonin sample the energy producer is trying to modify the burn process by including also an alternative solid fuel. The content of calcium can be easily explained by the burning process as already stated previously. This explanation might be used for sulphur as well. Silicon is represented in one of the RAP materials and in waste filler from Těškov quarry. This can be explained by the source mineral materials.

From the micro-elements analysis following conclusions can be made. Increased content of hazardous/toxic micro-elements (observed) was found in total sample analyses as part of analyzed material:

- both fly-ashes – cadmium,
- reclaimed asphalt material 0/11 – barium,
- waste filler Těškov, waste filler Markovice, Dastit (only Co) – nickel, cobalt.

In this context, it should be emphasized that in the case of beryllium (Be) and cadmium (Cd) the elements in question are highly poisonous and toxic and are distributed mainly in dust. Highly effective allergens can be mentioned with respect to nickel (Ni) and cobalt (Co); last but not least, barium (Ba) is a well known and generally classified toxic heavy metal.

- Significantly different content of titanium in Dastit cannot be explained easily there might be an important amorphous compound rich on this element. The reason for that might probably be in the source material of soft coal.
- In terms of total analysis reclaimed asphalt material can be described as a material rich on arsenic. During the respective leaching test of RAP samples it was however found, that arsenic is released rather from brown coal multi-dust sample. In this connection it is necessary to emphasize, that in term of total extracted content of particular elements an important role will play the type of bond between such element and the analyzed material.
- Beside the elements shown in table 2, for Dastit and both fly-ash samples also zirconium has been detected in amount of 0.08-0.34 mg/g.

3.2 Diffusion test

As important assessment for possible use of cold recycling mixes containing energetic by-products and/or different types of waste material in base courses of pavement structure it is necessary also consider environmental aspects of this technology. Therefore it is important to perform suitable leaching test and determine potential hazardous substances which can be released from the final structural layer to the environment (especially ground water). In the laboratory the leaching can be simulated by monolithic diffusive test based on the procedure described in EA NEN 7375:2004. By this procedure long-term influence of water incidence on a product or material is observed. Chemical (content of analytes in the leach) and mechanical (ratio of loosen solid particles) impacts are assessed. The test is done statically with any water circulation to avoid influence on natural diffusion and any distortion of sample surface. The total result is shown as determined leached content per are after 64 days (see table 7). The whole sample (usually a cylindrical or cubic specimen) is placed in leaching fluid (demineralised water with neutral pH). Leachates are extracted after 6, 24, 54, 96, 168, 336, 816 and 1,536 hours and analysed on concentration of selected elements or compounds.

Because in the Czech Republic no limits for leaching of chemical elements and compounds are not defined for pavement structures, required criteria given in the regulation on building materials set in Dutch VROM (Ministry of housing, planning and environment) have been used. Received findings have been compared with limits for pavement sub-base and with limits for pavement surface and sidewalks (Building Materials Decree BMD, 64 days). Results were compared with the amendment of Landfill Regulation for England and Wales No. 1640endorsed in 2005 for waste put on regulated landfills – leaching after 64 days).

From the results it is visible, that for mixes with fly-ash from fluid combustion there are increased contents of sulphates and arsenic. The highest concentration of sulphates has been found in cold recycling mix, where fly-ash from Hodonin location has been applied (probably caused by the combined solid fuel used, i.e. not only soft coal). The highest arsenic content can be found in experimental mix with Dastit, nevertheless generally this element can be found in most of the man-made products used today. For all samples it was typical, that the water pH was alkaline reaching values between 8.0 and 11.0. The ph values rose up during the first 14 days of testing and then usually slightly decreased.

4 Summary

Gained results so far have shown, that there is a potential to utilize energetic by-products in form of alternative binders. Nevertheless it cannot be expected, that bigger effect will be reached if coarse grained RAP material will be used. From the above discussed findings and results following statements can be made. If the amount of alternative binder Dastit® is increased all assessed characteristics improved significantly. In this connection it is possible to argue, that mechanical modification of fluid combustion fly-ash allows completely substitute the hydraulic binder used in cold recycling mixes. This is the main difference to the application of non-modified fly-ash used as a by-product without any treatments. In this second case it is possible to use such material for partial binder substitution or as a substitute of fine-graded particles often missed in sufficient amount in the RAP. As a suitable content of Dastit® in the cold recycling mix it can be recommended to use not more than 10 % by mass with respect to outstanding increase of hydration heat during the first seven days of curing. This could eventually affect the shrinkage processes in the mix if higher contents are used. In case of fly-ashes form fluid combustion the recommended maximum content in a cold recycling mix might not exceed 7-8 % by mass and always has to be combined with lower cement content. With respect to further potential utilization of new cold recycling mixes in different structural pavement layers it is necessary further to monitor and to describe correctly performance-based parameters of such mixes as well as environmental aspects like leaching and other types of pollution.

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Table 1. Composition of experimental mixes

Mix design	REC REF	REC P01	REC P02	REC P03	REC P04	REC P05	REC P06	REC P07	REC P08
Water	4.5%	4.5%	5.0 %	5.5%	5.5%	5.0%	5.0%	5.0%	5.5%
Cement CEM II/B - S32,5R	3.0%	-	-	1.0%	-	-	-	1.0%	1.0%
Bituminous emulsion C60B7	3.5%	3.5%	3.5 %	2.5%	3.5%	3.5%	3.5%	2.5%	2.5%
Fly-ash (Ledvice)	-	3.0%	7.5 %	10.0%	-	-	-	-	-
Bottom-ash (Počerady)	-	-	-	-	-	-	-	10.0%	15.0%
DASTIT®	-	-	-	-	3.0%	7.5%	10.0%	-	-
Reclaimed asphalt material 0/11	89.0%	89.0%	84.0 %	81.0%	88.0%	84.0%	81.5%	81.5%	76.5%

Table 2. Fundamental characteristic of assessed cold recycling mixes

Characteristic	REC REF	REC P01	REC P02	REC P03	REC P04	REC P05	REC P06	REC P07	REC P08
Bulk density (g/cm^3); dimension	2.121	2.124	2.065	2.064	2.033	2.078	2.083	1.987	1.936
Bulk density (g/cm^3); SSD	2.189	2.159	2.098	2.097	2.088	2.118	2.127	2.032	1.981
Voids content (%-hm.)	10.0	10.2	12.6	12.3	8.5	9.8	10.0	16.0	17.8

Table 3. Indirect tensile strength results

Mix	Indirect tensile strength [MPa]				ITSR*	Decrease of ITS	Frost susceptibility
	7 air	14 air	7 air + 7 water	28 air			
REC REF	0.45	0.84	0.56	0.91	0.68	1.24	0.91
REC P01	0.71	1.05	0.78	0.82	0.74	1.10	-
REC P02	0.51	0.58	0.43	0.82	0.74	0.84	0.88
REC P03	0.4	0.55	0.41	0.63	0.74	1.02	0.60
REC P04	0.66	0.63	0.54	0.65	0.86	0.82	-
REC P05	1.14	1.18	1.37	1.42	1.16	1.20	0.88
REC P06	1.23	1.19	0.97	1.63	0.82	0.79	0.81
REC P07	0.49	0.51	0.42	0.66	0.82	0.86	-
REC P08	0.41	0.49	0.40	0.55	0.82	0.98	-

Table 5. Total sample analysis – macro-elements

Element	Al	As	Ca	Fe	K	Mg	Mn	Na	P	S	Si
Sample	**Total content (mg) of element per 1 g of sample**										
crumb rubber <1 mm	-	-	-	-	-	-	-	-	-	-	-
waste filler Těškov	19.88	0.07	51.76	41.43	4.26	10.47	0.73	7.91	0.54	2.22	59.50
sorted RAP material 0/11	55.01	0.10	56.06	31.02	17.61	12.6	0.66	21.84	0.35	2.82	72.47
sorted RAP material 0/11	3.24	<	4.88	7.17	1.61	1.36	0.01	2.56	<	0.33	0.30
Dastit	105.95	-	166.36	40.39	1.55	9.88	0.96	8.20	1.58	32.29	0.51
Fly ash Ledvice (fluid comb.)	104.35	-	200.87	25.22	0.98	9.24	0.32	4.7	0.54	41.74	1.11

Fly ash Hodonín (fluid comb.)	108.33	-	141.67	36.11	1.80	9.44	0.43	5.11	0.54	29.64	0.35

“<” stays for below the detection limit, generally < 0.020 ppm.

Table 6. Total sample analysis – micro-elements

Element	B	Ba	Be	Cd	Co	Cr	Cu	Li	Mo	Ni	Sr	Ti	Zn
Sample	**Total content (mg) of element per 1 g of sample**												
crumb rubber <1 mm	-	-	-	-	-	-	-	-	-	-	-	-	-
waste filler Těškov	2.32	0.03	<	0.007	0.05	0.27	0.08	0.01	<	0.17	0.05	5.55	0.07
brown coal multi-dust								0.06	0.001	0.02	0.05	5.50	0.04
sorted RAP 0/11	1.89	0.30	0.0004	0.006	<	0.03	0.02	0.03	0.002	0.05	0.11	1.73	0.06
sorted RAP 0/11	0.84	1.3	0.0009	0.001	0.0008	0.002	<	0.04	0.0005	0.008	0.02	0.20	0.02
Dastit	-	0.41	0	0.01	0.07	0.11	0.19	0.24	0.008	0.05	0.54	18.4	0.10
Fly ash Ledvice (fl. comb.)	-	0.28	0	0.01	0.03	0.12	0.05	0.11	0.01	0.08	0.30	7.50	0.05
Fly ash Hodonín (fl. comb.)	-	0.31	0	0.01	0.02	0.13	0.13	0.12	0.01	0.07	0.29	5.42	0.30

Table 7. Leaching values of cold recycling mixes (cylindrical specimens)

Assessed element or compound in the leachate		**REC REF**	**REC P06 (10 % Dastit)**	**REC P07 (10 % - bottom ash Počerady)**	**REC H (fly ash Hodonín)**	BMD 64 days U1a	BMD 64 days U2 1b	Land-filled waste (leaching after 64 days
Chlorides	[mg/m^2]	2 809,8	2 552,9	2 444,0	2, 516.1	-	-	10,000
Sulphates	[mg/m^2]	2 390	71 397	73 264	126,308	27,000	80,000	10,000
Arsenic	[mg/m^2]	0,45	8,712	1,468	2.48	41	140	1.3
Cadmium	[mg/m^2]	0,09	0,086	0,09	0.085	1.1	3.8	0.2
Chromium	[mg/m^2]	0,6	0,6	1,56	0.6	140	480	5.0
Copper	[mg/m^2]	4,3	4	5,035	3.6	51	170	45.0
Mercury	[mg/m^2]	0,03	0,03	0,02	0.02	0.4	1,4	0.1
Nickel	[mg/m^2]	0,9	0,9	0,858	0.8	50	170	6.0
Lead	[mg/m^2]	0,2	0,31	0,277	0.3	120	400	6.0
Zinc	[mg/m^2]	8,3	5,2	5,95	6.1	200	670	30.0
pH	-	8,9 - 10,5	8,4 - 10,4	8,1 - 10,5	8.9 – 11.2	-	-	-
Weight loss	[g/m^2]	0,1096	0,2857	0,3217	0.5715	-	-	-