ALTERNATIVE MICRO-MILLED BINDERS IN COLD RECYCLING TECHNOLOGIES

Jakub ŠEDINA^{1*}, Jan VALENTIN¹, Petr MONDSCHIEIN¹, Jan SUDA¹

Abstract

In addition to bituminous binders (bituminous emulsion, foamed bitumen), hydraulic binders are applied in cold recycling technologies to increase the strength of a final structural layer as well as to increase its resistance to water and frost impacts. This paper deals with the use of energy by-products from fluidized bed coal combustion and mineral waste and their modification into reactive material with the potential of replacing commonly used hydraulic binders. The increase in the reactive potential takes place through a high-speed milling process where the mechanical-chemical activation of the material takes place. This process is associated with the refinement of the material, a higher proportion of micro and nanoparticles, an increased surface area, opening of particles, etc. The material treated exhibits binding properties, and it can be used as an active filler that allows for the partial or complete substitution of hydraulic binders. The experimental part is focused on the application of alternative binders to cold recycling mixtures and their assessment according to valid technical regulations, i.e., an assessment of their indirect tensile strength and water susceptibility as well as compressive strength and resistance to the effects of water and frost.

Address

¹ Department of Road Structures, Faculty of Civil Engineering, Czech Technical University in Prague

* **Corresponding author:** sedinjak@fsv.cvut.cz

Key words

- Cold recycling technologies,
- Hydraulic binders,
- Micro-milling,
- Indirect tensile strength,
- Resistance to water.

1 INTRODUCTION

Cement as a hydraulic binder is a normal part of work in the construction industry, although it is relatively expensive and technologically demanding. Efforts to produce it more efficiently or directly substitute for it with alternative products have been undertaken for many years, whether the idea was to modify cement with slag, fly ash or limestone or to find alternative binders. In this paper, we focus on the processing of waste materials (recycled concrete and energy by-products from fluidized bed combustion) using a high-speed grinding technology. The paper focuses on the application of these materials in road construction technologies, especially in cold recycling technology. The primary purpose is not only the substitution of standard hydraulic binders but also finding new uses

for a relatively large amount of waste material, which will correspond to the current European Union policy and non-waste economic commitments.

2 MATERIALS AND TECHNOLOGIES

Since 2010, research activities at the CTU Road Laboratories in Prague have focused on high-speed milling technology and engaged in the conversion of waste materials into full-fledged alternative binders and fillers. High-speed milling technologies are used to process fluid ash, recycled concrete material, limestone, dust, sludge, and other materials. Partial results can be found, for example, in (Čížková et.al., 2016), (Suda et. al., 2016).

2.1. Mechano-chemical activation of materials

High-speed milling (Faltus et. al., 2016), (Valentin et. al., 2016) is one type of high energy milling that is characterized by a large amount of energy transmitted per unit of treated material. The terms “high-energy” or “high-speed milling” are not precisely defined anywhere in the literature. As with milling in a classical sense, it has all the basic properties, namely, grain refinement, an increase in the specific surface area, opening the grain, etc. Unlike conventional milling, high-speed milling results in certain phenomena (effects) that are not observed in conventional milling. A certain amount of energy is converted by these effects, whereas in conventional milling, this energy is converted into heat without any benefits. These effects for inorganic materials include:

- mechano-chemical (mechanical) activation,
- the formation of higher proportions of micron particles and nanoparticles,
- in some cases, higher efficiency in the use of energy consumed to create new pavement surfaces.

The effect of mechanical-chemical activation utilized by high-speed milling allows for a significantly better utilization of the energy expended for milling materials. This is due to the accumulation of part of it in the form of increased enthalpy of the material. These effects also occur in high-speed milling equipment (disintegrators) (Figure 1), which:

- causes chemical reactions in the solid state of the material during milling (e.g., oxidation or exchange reactions),
- initiates phase changes (not only amorphisation) in different materials,
- creates mechanical alloys of metallic materials in the milling process,
- initiates catalytic reactions in organic and inorganic systems in the milling process.

The use of high-speed milling technology contributes to the homogenization of the binder and acts to prevent the formation of ettringites, thaumasites, and other chemical formations that cause volume changes in the material. We use this technology especially in the processing of fly ash, fluid fly ash, slags and other materials, which have been shown to become swollen in the past.

2.2 DASTIT® Binder

DASTIT® is a dry, inorganic hydraulic binder made by the mechanical-chemical activation of ash from fluid combustion and other additives, depending on the requirements for the final use of such a binder in accordance with the valid Czech national patent. With the use of high speed milling technology, an increase in the internal energy of the material is achieved, which creates active surfaces on the grains of the material while increasing the size of the specific surface (grain refinement) of the materials so that its chemical reactivity considerably increases.

As a result, an alternative hydraulic binder is formed, it can be used alone or together with a filler (e.g., different types of aggregates) and can be used for building and road construction applications (e.g., for soil improvement, the production of vibro-pressed building elements, the bonding of aggregates by hydraulic binders, sludge stabilization, etc.). The binder exhibits very high values of pozzolanity and can also be advantageously used as an active ingredient in concrete (underlying concrete and concrete to produce vibro-pressed products and cement mortars), which in many cases makes it possible (according to the formulas used and property requirements) to save a considerable amount of cement in a concrete mixture (30-70 %). In the case of sludge stabilization, substitution is possible up to 100%. Consequently, the basic mechanical parameters of the concrete remain, and the long-term durability of these products is not limited by the requirement for relatively high relative humidity values. The basic physical parameters of the DASTIT® dry hydraulic binder typically range from a bulk density of approximately 680 - 860 kg / m³, a dry density of approximately 2100 - 2200 kg / m³, and a surface area of approximately 800-900 m²/kg. The DASTIT® type AX2 was prepared from fly ash from the FBC power plant in Poříčí (the Czech Republic); the fine granular ash was removed from electric filters from the Mělník III power plant (the Czech Republic).

2.2.1. Fluid combustion

Fluid combustion technology (FBC) is based on the combustion of a mixture of coal and sorbent, most commonly limestone, in a fluidized layer, which, due to the flow of injected air, furnishes the properties of the liquid. The main advantages over conventional solid combustion are lower combustion temperatures (temperature range

Fig. 1 High-speed mill (left: open rotor annulus for the installation of milling elements)

of 800-900 °C), the ability to effectively regulate power, the higher efficiency of boilers, and the possibility of combining fuel from different sources and different qualities, where the only condition is the same grain size (Basu 2006; Basu 2015; Johnsson, 2007; Oka, 2004). The lower combustion temperature, together with the added desulphurization agent, reduces the emissions of harmful substances discharged into the air and the ecologically unsuitable substances contained in the fly ash. The added limestone (CaCO_3) or dolomite reacts directly in the boiler with sulphur dioxide (SO_2), and the solid product (CaSO_4) is thus part of the ash (see chemical expression 1.2 (Wang et.al., 2009). The resulting product represents a mixture of the ash of the original fuel, an unreacted desulfurizing agent (CaO with any CaCO_3 residues), calcium sulphate, a mixture of ash reaction products with CaO , and unburned fuel. Residual lime is present in the ash in the form of a soft burnt lime that can hydrate further. We also try to use this property when processing the fluidized fly ash into alternative hydraulic binders.

An important factor involved in the quality of binders is the mineralogical composition of the ash, which is directly dependent on the quality and type of materials input, especially on the type and content of the minerals in the combustion coal and the degree of their thermal conversion. One problem can also be the combustion of biomass. Possible problems associated with low characteristic fusible temperatures of ash biofuels were published in (Buryan, 2016; Valentin et.al. 2016). Upon reaching the melting temperature of a given material, in our case, the biomass, physicochemical changes occur in the structure of the ash, i.e., the so-called ash sintering from the biomass and the formation of solid residues of even a few tens of centimetres. Of course, these incrustations have an impact on the material and chemical composition of the fly ash. In practice, we can encounter different qualities and behaviours of by-products not only at individual power plants, but also can encounter varying qualities over time at individual plants as the quality of the sources input and the amount added of biomass or other substances change. One possible way to achieve the homogeneity of by-products is by high-speed milling.

2.3 Micromilled concrete

One of the alternative binders considered was recycled concrete obtained from the reconstruction of the D1 motorway, section 14, the Czech Republic, which was processed by means of high-speed milling for mechanical-chemical activation. The recycled crushed concrete was pre-crushed into 0/32 mm fractions in the CTU Laboratories in Prague. This material was re-crushed by LAVARIS in an impact crusher and processed by high-speed milling technology to initiate chemical changes, refine the processed material, open the grains, increase the specific surface, and achieve some reactivation of the dried cement. Before concrete is applied in the construction industry, "cement pastes" have always been produced, through which the basic characteristics for standard cements in their use in concrete and other composites (Valentin et.al. 2016) are verified. At present, micromilled concrete is used in technologies to produce cement and lime-cement mortars and adhesives or as a mixture for masonry elements. Activated finely milled concrete recycle has also been tested for a long time as a partial or complete substitute for hydraulic binders for road construction, which is also the topic of this paper. The basic physical parameters of the processed concrete recycled from the D1 motorway reached a fineness of milling of 1.5 to 80 μm with an average grain

size of 18 μm ; the bulk density of the material was 2670 kg/m^3 with a specific surface area of 435 m^2/kg .

2.4 Standard binders

For road construction in general and the improvement of materials for pavement base layers, Portland cement lime or compound binders is very often used, with a composition of cement and lime. The choice of binder depends on the material properties and conditions at the construction site, as well as the moisture regime (the water level). With the addition of lime we can immediately achieve an improvement in the material properties. Only during long-term contacts with water can a layer degrade.

In the case of Portland cement for improving mechanical material properties and resistance to frost, in contrast to lime, the hydration of cement is possible under water too, so the moisture regime has a minimal effect on the quality of the resulting layer. Suitable variants include the use of blended binders with a lime effect and hydraulic binders. In the laboratory tests, Portland cement CEM II/B-M (S-22) 32.5 was used. This type of cement is used very often for mixed compositions in pavement base layers. According to the specifications for this cement (it hydrates slowly), it is used in aggressive environments with water and salt.

2.5 Technologies of cold recycling

At the present time, cold recycling is used very often in the rehabilitation of asphalt concrete layers, surfacing and base layers in road construction. RAP material mixes for recycling operations with a hydraulic binder (cement) are frequently used. Cold milling is a process in which a milling machine removes the material to a prescribed cutting depth. Milling machines can be used to eliminate major and minor rutting, bumps, and deteriorated surface material. The reclaimed asphalt pavement and reclaimed aggregate material are combined with either asphalt, generally emulsified asphalt or foamed asphalt, and/or recycling agents, on site or at a central plant.

2.5.1 Qualitative requirements for cold-mix mixtures

Currently, the qualitative requirements for cold-mix mixtures follow Technical Regulations TP 208 when evaluating cold recycling mixes. In our case it is possible to classify mixes with hydraulic binders according to their indirect tensile strength and resistance to water. The mixes can be tested the same way as cement-bounded mixes (Standard ČSN EN 14227-1) according to their compressive strength and resistance to water and frost. We have not exactly precisely the indirect tensile strength and tested their resistance to water or their compressive strength and/or resistance to frost. The qualitative requirements for mixes (and pavement layers) depend on the project manager's decisions.

2.6 Composition of mixes

The design of the composition of the mixes for laboratory tests was based on long-term experience with cold recycling and with micro-milled binders so the amount of micro-milled binder in the mixture was set higher than the amount of the cement. The paper contains the results of the laboratory tests in two variants. In variant 1, the mix composition is asphalt cold-recycling 0/63 mm ("Nouzov" locality); mix composition variant 1 is in Table 1.

Tab. 1 Mix variant 1

Components of the mixture	4C	1C + 4D	Designations
Reclaimed aggregate 0/63 - 1	50.0 %	50.0 %	4C = 4 % cement content 1C + 4D = 1 % cement + 4 % DASTIT
Reclaimed aggregate 0/63 - 2	50.0 %	50.0 %	
Water	4.5 %	5.0 %	
Cement 32.5	4.0 %	1.0 %	
DASTIT	0.0 %	4.0 %	

Tab. 2 Mix variant 2

Components of the mixture	3C	2C + 2MB	1C + 4MB	1C + 4D	Designations
ŠD 0/32	50.0 %	50.0 %	50.0 %	50.0 %	3C = 3 % cement content 2C + 2MB = 2 % cement + 2 % milled concrete 1C + 4MB = 1 % cement + 4 % milled concrete 1C + 4D = 1 % cement + 4 % DASTIT
RAM 0/22	50.0 %	50.0 %	50.0 %	50.0 %	
Water	5.5 %	5.5 %	5.5 %	5.5 %	
Cement	3.0 %	2.0 %	1.0 %	1.0 %	
Micromilled concrete	0.0 %	2.0 %	4.0 %	0.0 %	
DASTIT	0.0 %	0.0 %	0.0 %	4.0 %	

Mix variant 2 contains ŠD 0/32 mm natural crushed stone and reclaimed aggregate material (RAM). The mix design is in Table 2.

3 EVALUATION OF THE RESULTS

The production and curing of the test specimens were conducted according to the TP 208 technical conditions. For testing the specimens resistance to frost, extreme conditions were achieved when the specimens were loaded with 13 freezing cycles, including after 18 hours at the laboratory's temperature in water (20-25 °C) and 6 hours in a freezing box at -20 °C.

The assessment of the possible substitution of standard hydraulic binders by alternative micro-milled binders is a long-term research goal of the CTU Laboratories and their partners. Substitution has a positive effect, particularly on a mix's resistance to water. From Table 3 we can see the effects of the DASTIT micro-milled binder, i.e., the indirect tensile strength increased, and the resistance to water is higher. The mix bounded with the DASTIT micro-milled binder has better parameters than the standard mix, and the micro-milled binder is a valuable substitution for Portland cement.

The results in Table 4 show us the possibility of substituting Portland cement with the DASTIT micro-milled binder. The strength of the mix after 28 days is the same as the standard reference mix. The resistance of the mix to water and frost is a problem, because according to the TP 208 technical regulation, it should be a min. 85 % of strength after 28 days. In the future it will be necessary to correct the mix's com-

Tab. 3 Characteristics, mix variant 1

Mix	R _{it} Indirect tensile strength	ITSR Resistance to water	
	(MPa)	(MPa)	(%)
4C	0.29	0.20	69.3
1C + 4D	0.33	0.26	79.5

position to fulfil the requirements for helping the mix resist the effects of water and frost. After adding the mechanically activated recycled concrete material, the construction mix shows a significant decrease in compressive strength, compared to the standard reference mix. The effects of the strength are only environmental and not economic.

4 CONCLUSION

When processing fluid fly-ash using high-speed milling, the process has repeatedly demonstrated the activation and increased pozzolanicity of the material. At the same time, the formation of ettringite

Fig. 2 Parameters of mix, variant 2

Tab. 4 Characteristics, mix variant 2

Mix	R _c Compressive strength	Resistance to water and frost	
	(MPa)	(MPa)	(%)
3C	3.57	3.52	98.45
2C + 2MB	2.45	2.18	88.92
1C + 4MB	1.92	1.90	99.27
1C + 4D	3.61	3.01	83.22

or thaumasite is eliminated, which results in the degradation of the resulting mixture parameters. The apparent potential for the substitution of the standard hydraulic binders used, particularly in cold recycling mixtures, has been demonstrated, when mixes bonded by binders based on fluid fly ash achieve better parameters than cement-bonded mixtures. There is a faster increase in strength and no considerable decrease in strength due to the effects of water. Therefore, in terms of cold recycling technologies, the new binder has a relatively good potential for practical applications.

In the case of mechanically activated concrete recycled material, we noticed significant decreases in compressive strength compared to

the reference mixture. In this form, when only hydraulic binders are used in cold recycling technology, this material will not find useful applications.

Acknowledgement

The paper was created with the support of the Center for Effective and Sustainable Transport Infrastructure (CESTI) - TE01020168 and with the support of a grant from student grant competition CTU No. SGS17 / 059 / OHK1 / 1T / 11.

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