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PROCESSING AND RECYCLING OF AGGREGATE RESIDUES AFTER ORE EXTRACTION FOR STABILIZATION OF MINED AREAS

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Abstract. The article focuses on the treatment and recycling of aggregate. It also addresses the issue of treatments effects on mine tailings, fly ash and acid mine water on the measured parameters of concrete with load-bearing and backfilling paste with non-load-bearing function. Four different mixes were developed, and standard tests were performed on them. These mixtures were made with different types of mine tailing's fillers with varying degrees of treatment. Mineralogical and chemical tests were carried out on the treated aggregates, with sieve analysis and their subsequent adjustment for suitable aggregate gradation curve in concrete. Strength and volumetric weight tests were carried out on hardened samples at 28, 56 and 90 days. The results of the determined functional specimens showed that it is possible to develop an almost completely waste-free technology using recycled aggregate and fly ash from the ore mining and energy industries and its subsequent processing and use for backfilling of mine deposits with load bearing and non-load bearing function concrete.

Keywords: Mined residues, mine tailings, mechanical properties, filling and static requirements.

1. Introduction

The mining industry is divided into two major categories, metallic and non-metallic, based on the ore extracted. Both industries lead to the generation of large quantities of solid industrial wastes from mine expansions [1]. A large amount of sub waste generated from the processing of metallic ores in the separation of valuable minerals, this waste is called tailings [2, 3]. The generation of large quantities of tailings adversely affects the environment, including air, water, and soil [4, 5]. Consequently, a large area of surface land is required for the appropriate storage and management of this waste. An effective solution is the underground disposal of these industrial wastes (tailings, fly ash, mud, etc.) generated from mining and related activities in the form of mine backfill [6–8]. The spaces created after ore extraction in underground mines can be filled with a specific waste material referred to as backfill mix of cement and mined aggregate, fly ash, in a consistency that can be well pumped and transported.

Backfill material can be divided into two major categories, the first being unconsolidated backfill without static function and the second being backfill with cement and static function [4–6]. Unconsolidated backfill, waste is added without any binder. While in cemented backfill, a hydraulic binder is added, usually this binder is Portland cemen, which is added to the solid waste material to provide a background for the mechanical properties of the paste or concrete [7, 8]. One form of cemented backfill used in underground mines is a paste with well-defined mechanical properties [3–7].

Mine fill mixtures should be homogeneous, mobile, suitable for transport by pumping over distances of hundreds of meters, and workable for a minimum of 120 minutes. After curing, they should ideally reach a strength of at least 4 MPa after 90 days; however, a strength of about half 0.1 MPa may be acceptable in conditions without static function. The aim is to completely minimize the binder component, which should only have the function of ensuring the cohesion of the cured composite. One way to achieve this is use of fluidized power plant fly ash, which is not used at all to produce conventional concretes. In this case, even total replacements of conventional cements as binders are realistic options. Fluidized fly ash from "Ledvice" was used as a binder for number of samples in this article.

Backfill mixture for stabilization of old mining sites. The important requirement here is not ultimate strength but low hydration heat development and workability. The residue after separation of heavy and light recoverable components from the "Zlaté Hory" landfill was used to create the mixture without static function. The residue after separation of heavy and light recoverable components from the "Cínovec" deposit was used to form the second mixture with static function. An important requirement is ultimate strength and low hydration heat development.

The implementation of the achieved theoretical basis will be carried out according to the developed complex design of the treatment plant technology for the "Zlaté Hory" underground mine with obtaining the residual material from the treatment in a further usable form. The results are summarized in the TREND FW project report 01010061-1-2022.

	Label	CEM I 42,5 R	Fluidized Ash	Fly Ash	Aggregates "Cínovec"	Water [l]	Plasticizing additive [l]
1	"Cínovec" C 25/30	300	100	200	1 260	400	10
2	"Cínovec" filling	50	33	66	1 720	480	3

Table 1. The main concrete and filling recipe in [kg].

	Label	CEM I 42,5 R	Fluidized Ash	Fly Ash	Aggregates "Cínovec"	Water [l]	Plasticizing additive [l]
3	ZH CEM	50	33	66	1 720	460	3

Table 2. Composition of mixtures with "Zlaté Hory" aggregate without static function in [kg].

	Label	Modified fluidized ash (SOR)	Aggregates "Zlaté Hory"	Water [l]	Plasticizing additive [l]
4	ZH SOR	150	1 720	460	3

Table 3. Composition of mixtures with modified fluidized ash without static function in [kg].

2. Material and methods

Based on the results of the laboratory tests, a formulation for a foundation with a static function that uses aggregate from mine "Cínovec" was selected for validation in a mining environment. A mixture of fluidized and conventional fly ash supplemented with Portland cement was selected as the binder. At the same time, a mixture based on aggregate from mine "Zlaté Hory" with a filling function without static requirements was also proposed. The main concrete recipe in [kg] is given in Table 1 and the recipes of the base mortar cast mixes in Tables 2 and 3.

For each sample, four samples of 20 liters of mixture were produced. At the same time. control cubes were formed for storage under laboratory conditions. The sample storage conditions were set to a stable temperature of 7 °C ± 1 °C. Strength checking and mine water sampling for pH measurements were carried out 90 and 180 days after mixing also with Schmidt reflection hardness test. The resulting pH of the sampled mine water, as determined by a digital pH meter, was 4.8. The water was therefore slightly acidic. In the case of structural concrete, the following laboratory tests were carried out:

- concrete mix design,
- determination of basic technological tests on fresh and hardened mixes (water coefficient, settlement, fresh concrete temperature, bulk density, flexural and compressive tensile strength.

In the case of the development of aggregate mixture cement cemented, the following tests were carried out:

- Design of the gradation curve of the resulting aggregate mixture,
- design of the composition of the mixture,
- Proctor test,
- determination of basic technological tests – bulk density, compressive strength.

The following laboratory tests were carried out for the aggregates from "Cínovec" within this sub-stage:

- sieve analysis of aggregate with percentage of fine particles,
- design of the composition of cast mixtures, subsequent testing of the resulting recipes,
- determination of basic technological tests on fresh and hardened mixtures (water coefficient, spillage, bulk density, flexural and compressive tensile strength)

The XRD analysis on samples was performed using a Panalytical Empyrean diffractometer. The reflection Bragg-Brentano para focusing geometry device is equipped with a Cu anode ($\lambda = 1.54184$ Å) and programable divergence slits a PIXcel3D detector with 255 active channels. The X-ray generator settings were 45 kV and 40 mA. The measured range was 5–80° with a step size of 0.013° and 38 s per step. Each sample was measured four times, and the scans were next simply summed. The total measurement time for each sample was 60 min. The Panalytical HighScore 3 plus software was used to identify the individual phases.

3. Results and discussion

There is no relevant standard available for foundation materials, however, the concrete standard ČSN EN 206 can be used and to verify the parameters of the samples, the following tests were carried out: To perform the strength tests, the recipes of mortar mixes for individual types of fillers and mining wastewater from the extraction of tailings were designed and compared with a reference recipe prepared in proportions corresponding to the standard mortar according to the

Label		**1. "Cínovec" C 25/30**	**2. "Cínovec" filling**	**3. ZH CEM**	**4. ZH SOR**
Consistency by spilling [cm]	[days]	24.5	25.4	26	26
Volumetric mass [kg m^{-3}]		1 830	1 360	11 390	11 390
Compressive cubic strength [MPa]	28	18.7	0.3	0.1	0.1
Schmidt reflection [-]/ strength [MPa]		Not determined	Not determined	Not determined	Not determined
Volumetric mass [kg m^{-3}]		1 800	1 350	1 380	1 380
Compressive cubic strength [MPa]	90	21.1	0.4	0.1	0.1
Schmidt reflection [-]/ strength [MPa]		22/ 15 ± 4	Indefinable	Indefinable	Indefinable
Volumetric mass [kg m^{-3}]		1 780	1 330	1 360	1 360
Compressive cubic strength [MPa]	180	21.9	0.7	0.3	0.3
Schmidt reflection [-]/ strength [MPa]		26 / 19 ± 4	17 / <10 MPa	16 / <10 MPa	16 / <10 MPa

TABLE 4. Properties of concrete and mortar cast mixes.

Label	**Properties**	**Unit**	**Measured Value**
Aggregate "Cínovec" 0/2 mm	Volume weight of aggregate grains	[Mg m^{-3}]	2.69
	Volumetric weight of grains after drying in the oven	[Mg m^{-3}]	2.65
	Volumetric weight of water-saturated and surface-dried grains	[Mg m^{-3}]	2.66
	Absorption after immersion in water for 24 hours WA24	[%]	0.47

TABLE 5. Determination of bulk density and water absorption of aggregates "Cínovec".

fresh mortar consistency test using a shaking table according to ČSN EN 1015-3. Volumetric weight of fresh mortar according to ČSN EN 1015-10 (722400), and Flexural tensile strength and compressive strength at curing times of 28, 90 and 180 days according to ČSN EN 1015-11 (722400), determination of flexural and compressive strength of hardened mortars. Properties of concrete and mortar cast mixes made of aggregates from "Cínovec" and "Zlaté Hory" are in the Table 4.

Due to the requirement for flowability of the mixes, the consistency of fresh mortar was chosen to have more than 240 mm spillage. To achieve a 240 mm spillage, more water and had to be added to the mixes due to wetting of the separated aggregate and more fine filler to ensure the correct consistency of the mixture. A sieve analysis was carried out on the tin aggregate with results at Figure 1. To determine the volumetric weights and absorption rates according to the relevant standard. ČSN EN 933-1: Testing of geometric properties of aggregates – Part 1: Determination of grain size – Sieve analysis. And ČSN EN 1097-6: Testing of mechanical and physical properties of aggregates – Part 6: Determination of bulk density of grains and water absorption, Chapter 9 with results in the Table 5.

Mineralogical analysis shown in Figure 2 shows that the proportion of heavy components (pyrite and chalcopyrite) after separation is low. The gravity separation of the heavy component was quite effective. The light component: concentrate separation ratio was determined after processing of 1 000 kg. The deposit was composed of 56 % quartz, 16.5 % muscovite, 14.6 % albite and 12.6 % chamosite. A chemical analysis was also performed on the sample, which can be found in Table 6.

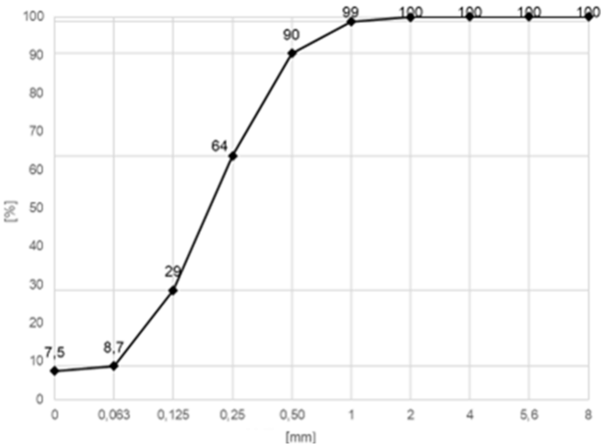

FIGURE 1. Result of sieve analysis of aggregate from mine "Cínovec" fraction 0/2 mm.

Loss on drying (105 °C)	%	0.27
Sulphides	mg/kg dry	23.3
Calcium oxide	% dry	3.53
Magnesium oxide	% dry	2.26
Potassium oxide	% dry	2.13
Aluminium oxide	% dry	10.5
Silicon dioxide	% dry	67.8
Iron oxide	% dry	7.03
Sodium oxide	% dry	0.937
Zinc	% dry	0.206
Zinc oxide	% dry	0.257

TABLE 6. Results of the chemical analysis of the "Zlaté Hory" landfill.

Despite the low strength in backfill mixes without static function, the amount and type of binder was chosen in both cases to be sufficient to ensure the

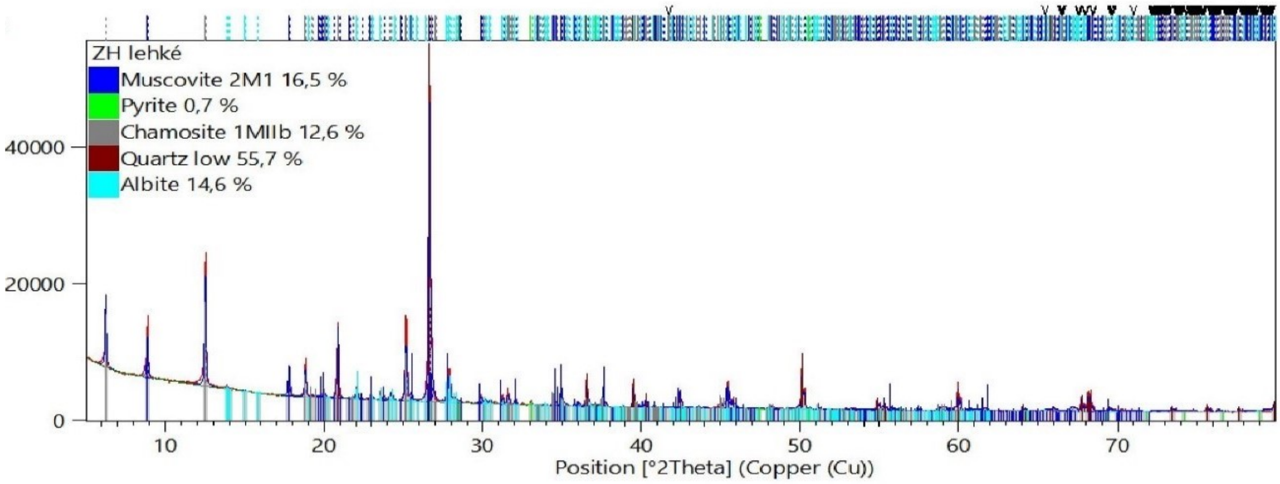

Figure 2. Mineralogical analysis from mine "Zlaté Hory".

Properties	ZH SOR	Declared property of the backfill mixture	"Cínovec" C 25/30	Declared property of the concrete mix
Spillage ČSN EN 1015-3	250/255 mm	> 240 mm	240/245 mm	> 230 mm
Bulk mass ČSN EN 12390-7				
- 28 days	1 390 kg m^{-3}	1 390 ± 100 kg m^{-3}	1 840 kg m^{-3}	1 850 ± 100 kg m^{-3}
- 60 days	1 380 kg m^{-3}	1 380 ± 100 kg m^{-3}	1 800 kg m^{-3}	1 800 ± 100 kg m^{-3}
- 90 days	1 360 kg m^{-3}	1 360 ± 100 kg m^{-3}	1 780 kg m^{-3}	1 800 ± 100 kg m^{-3}
Compressive strength according to ČSN EN 12390-3				
- 28 days	0.1 MPa	≥ 0.1 MPa	19.2 MPa	≥ 15 MPa
- 60 days	0.1 MPa	≥ 0.1 MPa	20.9 MPa	≥ 18 MPa
- 90 days	0.3 MPa	≥ 0.3 MPa	21.4 MPa	≥ 20 MPa
Hydration temperature according to ČSN EN 196-9	Max 21.8 °C at 152 minutes	≤ 25 °C untill 250 minutes	Max 22.3 °C at 44 hours 49 minutes	≤ 25 °C until 50 hours

Table 7. Results of monitoring, development of the strengths and condition of the samples.

compactness of the samples. Both binders, due to their chemical and mineralogical nature, should not suffer chemical damage from the acid mine water which was used for the samples. Monitoring of the development of the strengths and condition of the samples with test results with comparing to the declared properties of backfilling mixtures with and without static function are shown in the Table 7.

All tests and trials were carried out according to the following list of technical regulations and standards.

- ČSN EN 206+A2 Concrete-Specifications, properties, production, and compliance
- ČSN EN 12390-3: Testing of hardened concrete – Part 3: Compressive strength of test bodies
- ČSN EN 12390-7: Testing of hardened concrete – Part 7: Bulk density
- ČSN EN 933-1: Testing of geometric properties of aggregates - Part 1: Determination of gradation – Sieve analysis
- ČSN EN 1097-6: Testing of mechanical and physical properties of aggregates – Part 6: Determination of bulk density of grains and water absorption, Chapter 9
- ČSN EN 1015-3: Test methods for mortars for masonry – Part 3: Determination of consistency of fresh mortar (using a shaking table)
- ČSN EN 196-9: Test methods for cement – Part 9: Determination of heat of hydration – Semi adiabatic method

4. Conclusion

Aggregate samples were taken and analysed from existing deposits and stockpiles at the "Cínovec and Zlaté Hory" locations. Samples simulating cleaned mining residues were prepared by gravity separation methods. Samples of stockpile mixtures for the foundation of areas with requirements for static and non-static function during active mining were developed, prepared, and tested. In doing so, a nearly waste-free technology was developed to produce stockpile mixes while maximizing the use of existing tailings. Simulations of tailings purification and tailings preparation with the constituents of interest removed were performed. It was demonstrated for the windrowed samples of landfill mixtures for the foundation of areas with static and non-static function requirements that:

- According to the measured results, it can be concluded that it is possible to prepare relatively well-flowing mixtures with very high-water coefficients.
- It is possible to achieve good strength results with extremely low dosage of binder based on fly ash mixtures under placement conditions without static function.
- Modified and recycled aggregates free of heavy pyrite components after ore extraction are very suitable for use in ash fly ash mixtures.

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