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Research Article

APPLICATION OF POSTFLOTATION TAILINGS IN HYDROENGINEERING STRUCTURES

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ABSTRACT
Economic development stimulated by the increased demand for production of consumer goods and the growing human population result in increasing the amounts of various wastes, including tailings. Mining industry in Poland, comprising also mining of non-ferrous metal ores, is a strategic branch of the national economy and, at the same time, a leading waste producer. Tailings management is a significant problem both in Poland and worldwide. Frequently, considerable amounts of wastes are accumulated in mine spoil tips, in areas not always suitable for their deposition, thus leading to the degradation of the surrounding environment. At the huge volume of produced wastes their rational and economically viable management is becoming crucial. On the other hand, depletion of natural aggregate deposits is an important incentive to search for substitutes, which would be suitable for the development of road infrastructure or which could be used in earth structure engineering to construct hydroengineering objects. Since no profitable recovery technologies are available at present, tailings generated by copper mining are deposited in tailings storage facilities. The largest and at the same time the only currently operating facility in Poland is the Żelazny Most Mining Tailings Storage Facility, belonging to KGHM Polska Miedź S.A. The paper presents criteria for material quality and density imposed on the material embedded in the static core of the tailings pond dam. For this purpose studies were conducted to confirm applicability of sorted tailings as a material for the construction of earth structures.

Keywords: postflotation tailings, earthen dams, density measures, grain size parameters

INTRODUCTION

Development of global economy is connected with the need to obtain various raw materials. Copper, a priority raw material, is extracted in south-western Poland. In the course of its 50-year history KGHM Polska Miedź S.A. has extracted over one billion tons of mine run and produced 18 million tons of copper, while current resources will be sufficient for further extraction within the next 50 years. As a result of such high extraction rate of this polymetallic mineral subjected to various technological process considerable amounts of waste are formed, referred to as postflotation tailings. This results e.g. from the flotation-based technologies of copper ore beneficiation, as a result of which copper concentrate is separated from the rest of the run, composed of crushed rock. Flotation tailings account for approx. 94% all mine run. For this reason it is crucial to dispose of tailings generated by copper production, including also their re-use.

The primary method of flotation tailings disposal is their storage at the Żelazny Most Mining Tailings Storage Facility. At the same time sorted tailings material is used to construct dams of this facility. As it is well known, depletion of natural aggregate resources results in high demand for alternative sources of materials which could be used e.g. in earth structure engineering, with postflotation tailings being a potential solution in this respect. This problem is also extensively discussed in numerous literature sources. Applicability of tailings in hydroengineering and earth structures as well as land reclamation has been presented e.g. by Zapał [2007], Góralczyk et al. [2011] and Kugiel et al. [2012].

In order to clarify the applicability of waste in hydroengineering structures this paper presents results of studies conducted on postflotation tailings, which meet criteria imposed on the material embedded in the dam core.

CHARACTERISTICS OF POSTFLOTATION TAILINGS

The amount of postflotation tailings deposited annually at the Żelazny Most MTSF ranges from 20 to 26 million tons. Postflotation tailings generated in the production of copper concentrate are mixed with large amounts of water, producing slurry with water content of approx. 90%. Next they are transported through a network of main pressurized pipelines from the Ore Enrichment Plants to the Żelazny Most MTSF. The facility is filled using the gravity-based discharge method. Tailings are discharged inside the facility using spigots arranged at every 200 m on the dam crown in individual sections, which results in the development of the so-called beaches at an adequate slope. This guarantees the maintenance of the edge of the supernatant pond at a distance of min. 200 m from the dam crown [Monografia KGHM Polska Miedź S.A. 2007].

Such a method of tailings deposition causes their natural sedimentation segregation, which in turn is manifested in the zoning of their geotechnical characteristics. Tailings with coarser grain size are deposited closer to the spigots within the broad beach, while finer particles are transported to the supernatant pond.

Physical characteristics result, first of all, from the character and the petrographic distribution of the bedrock. The type and initial composition of gangue determines the mineral composition of postflotation tailings, which contains various proportions of minerals as well as metallic and non-metallic components [Grotowski et al. 1995]. Copper ore extracted in the mines of the Copper Mining District is found in three different lithological types-shale, carbonate and sandstone, varying in their petrographic composition [Monografia KGHM Polska Miedź S.A. 2007].

In terms of the physical characteristics of tailings the three basic properties having the greatest effect on their behavior include grain size composition of deposited tailings, the shape of grains and particles as well as mineral composition of the silty fraction [Parylak 2000, Tschuschke 2006]. Thus tailings may be classified in terms of the standard classification of cohesive and noncohesive natural soils, including the particularly difficult to assess transition soils [Grotowski et al. 1995, Tschuschke 2006, PN-86/B-02480]. The greatest effect on such a broad grain size variation is found for the technology of mine run grinding, type of transport and deposition in the facility. It is also needed to stress the effect of tailings diversity in terms of both their physical and mechanical properties in view of their applicability as construction material.

POTENTIAL APPLOCABILITY OF POSTFLOTATION TAILINGS

A fundamental area for the legislative bodies of the European Union is connected with environmental protection, including the creation of policy concerning tailings management. Due to the large amounts of tailings generated by exploitation of copper deposits, accumulated over extensive areas, their rational and economically viable management is crucial. As a result of no available cost-effective recovery technology, tailings produced by copper mining are most frequently deposited in tailings disposal facilities. Introduction of practical solutions in tailings management effectively limits their amounts and frequently leads to their re-use. The concurrent demand and the increasing depletion of sources of natural materials is an incentive to search for novel tailings reclamation solutions [Sybilski and Kraszewski 2004].

It is necessary to focus on the potential re-use of stored tailings, which are generally environmentally neutral. In a view of recent research, we may distinguish two main concepts for the utilization of postflotation tailings. Firstly tailings may be considered to be the so-called poor anthropogenic deposits, while – as it is indicated by research results – recovery of useful minerals is not cost-effective [Speczik et al. 2003]. Secondly, tailings may be used as commercial material, e.g. in the production of construction materials such as cellular concrete, foamed concrete (carbonate-type tailings), plasterboard, bricks or cement, as indicated e.g. by contents of SiO_2 and CaO. Tailings may also be used in road construction in building roads: road embankments, asphaltic concrete, mineral-asphalt mix, for the construction of pavements and conceptually as filler in bituminous materials replacing the so-called mineral silt [Łuszczkiewicz 2000, Speczik et al. 2003, Sybilski et al. 2004, Balaweider et al. 2007]. Stored tailings may also be used in the mining industry as filling material, as well as agriculture as mineral fertilizer.

Moreover, postflotation tailings may be efficiently used in hydroengineering and earth structures, in land reclamation, in engineering works and as sealing materials [Łuszczkiewicz 2000, Góralczyk 2011]. However, most frequently these tailings are accumulated in tailings disposal facilities and – following earlier verification of their suitability, they may be re-used in the development of hydroengineering structures.

EXPERIMENTAL PROCEDURES

In order to verify the applicability of postflotation tailings as material to construct earth structures, studies were conducted in superstructure fragments of dams surrounding the Żelazny Most Mining Tailings Storage Facility, establishing gauging nodes in each section of the silted cone [PN-EN 1997-1,2:2008 Eurokod 7]. In each experimental gauging point substrate parameters were determined, i.e. layers, in which the new dam was founded, and next parameters of each successive layer (of 0.5 m in thickness) of the currently formed dam. A total of 38 experimental nodes were established, arranged in the axis of the dam crown, in which 19 verification tests were conducted individually, using the static probe tests (CPT) and 38 volume samples were collected. On-going compaction control, in the course of dam formation, was conducted using a Troxler 3440 isotope gauge [Manual of Operation and Instruction 1995].

Volume samples were collected from the bottom of experimental pits by the vertical, static thrust of the 50 cm^3 gauging cylinder. In each experimental node 5 deposit samples were collected from specific depth ranges. Laboratory methods were used to determine bulk density (ρ) and natural moisture content (w_n) of the collected material and next bulk density of the soil skeleton (ρ_d). In order to determine compatibility parameters of the tested material samples were collected from each experimental node for compatibility analysis using the Proctor I method [16]. This test provided maximum bulk density of the soil skeleton (ρ_{dmax}) at optimal moisture content (w_{opt}). The density index I_s (1) is based on the recorded values of bulk density of the soil skeleton (ρ_d) and maximum values of bulk density of the soil skeleton (ρ_{dmax}), read from the Proctor curve.

$$I_s = \frac{\rho_d}{\rho_{d\,\max}} \tag{1}$$

The density index I_s is a criterion defining suitability of a soil as a material to be used in hydroengineering structures. Following the guidelines [Tschuschke 2003], the value of the index characterizing postflotation tailings embedded in the dams should be $I_s \geq 0.92$.

Another criterion defining suitability of a material for construction uses is connected with its grain size, specifically the maximum content of the silty fraction of 30%.

In order to determine the grain size composition of the tested material volume samples collected from each experimental node were combined within each node. Analyses of the grain size composition were conducted on 19 samples using the sieve test including washing through the finest sieve (the wet method).

Moreover, studies conducted over the period of many years within the geotechnical monitoring of forming dams made it possible to create an empirical dependence providing the maximum bulk density of the soil skeleton (ρ_{ds}) in a case when it is impossible to conduct the Proctor test, based on the parameters of grain size curves (eq. 2). This formula is updated annually in accordance with the recommendations given in the Instructions for Monitoring of Density and Selection of Material for Dam Formation in the Żelazny Most Mining Tailings Storage Facility [Tschuschke 2006].

$$\rho_{ds} = 1.893 - 0.032SFR - 0.723d_{60} + \\ + 0.001SFR^2 + 0.039SFR \cdot d_{60} + 0.590d_{60}^{\,2} \tag{2}$$

where: d_{60} – the size such that 60% of the sample consists of particles having a smaller nominal diameter;
SFR – grain size distribution index.

Another criterion of the density measures is the relative density $D_R \geq 0.7$. The relative density of the analyzed material was verified in situ. Tests were conducted using a standard cone penetration test (CPT) electric cone by A.P. van den Berg (Holland). Cone resistance q_c and friction on the friction sleeve f_s were recorded continuously at 2cm/s. Measured values q_c were compared with boundary values determined assuming the required relative density $D_R \geq 0.7$. Boundary values were determined using a formula developed for the group of postflotation tailings at the Żelazny Most MTSF, classified in terms of grain size distribution as silty sands [8]. In this formula the required criterion for density was assumed to be $D_R = 0.7$, obtaining formula 3, defining the minimum value of cone resistance in a specified state of stress and at the assumed density criteria.

$$q_c = \exp\left(\left(36.81 \cdot \ln\left(\sigma_{v0}\right) + 73.3\right) / \left(17 \cdot \sigma_{v0}^{0.0876}\right)\right) \quad (3)$$

where: σ_{v0} – overburden stress [kPa]

Tests conducted with the CPT were also used to verify grain size composition of the used material. Boundary value $R_f = 1.3$, which was determined from empirical dependencies and long-term studies of postflotation tailings, makes it possible to identify tailings with the silty fraction content below 30% (for $R_f > 1.3$).

RESULTS

Material collected from all the testing points made it possible to conduct 19 analyses of the grain size composition of tailings. Example results are presented in the form of an area of grain size variability in the analyzed postflotation tailings (Fig. 1). Tests showed that the material in terms of its grain size composition used for dam formation in the most part corresponds to silty sands, while scarce samples were composed of fine sands.

Figure 2 presents medium and maximum contents of the silty fraction (fp < 30%), meeting the assumed criterion of admissible contents. The maximum content of the silty fraction was 28.13 %.

The quality of density of postflotation tailings embedded in the newly formed dams was assessed using two independent measures of density, i.e. density index I_s and the relative density D_R. Density of the dam and the dam subsoil was verified based on a comparison of values of density index I_s from the two testing methods. For this reason the first stage comprised assessment of the density index of postflotation tailings obtained

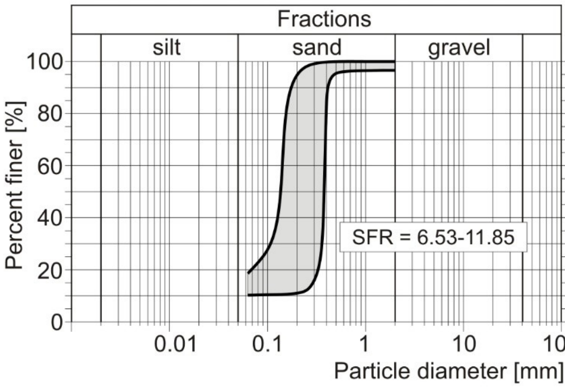

Figure 1. The area of variation in grain size composition of analyzed postflotation tailings

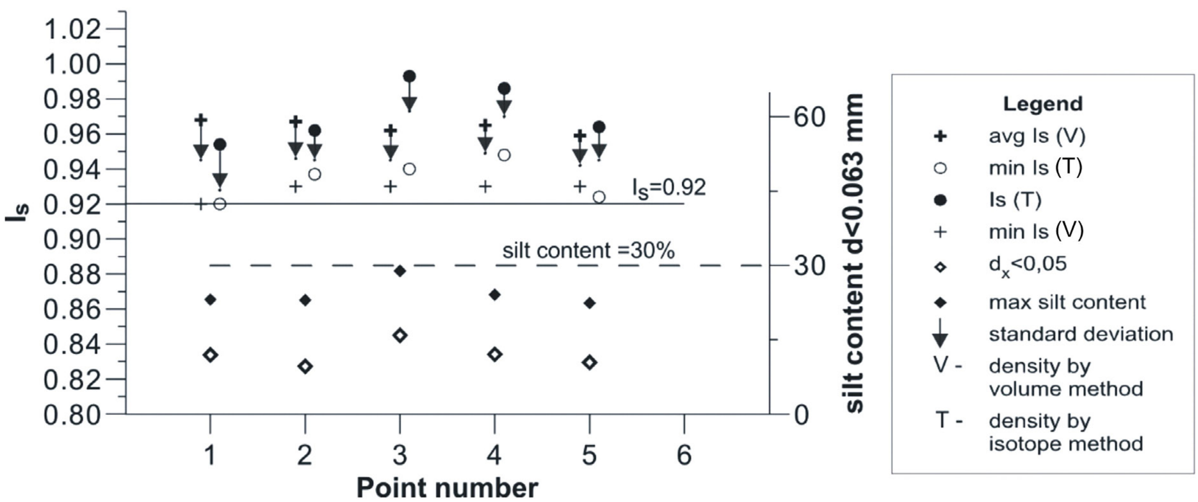

Figure 2. A comparison of example Is values determined from two different methods

during the dam slope formation using a Troxler isotope density gauge. These values were compared with I_s values of tested tailings determined at a specified, randomly selected depth using the volume method and the Proctor test (Fig. 2).

Monitoring of density of forming dams showed that at all the selected gauging points density index I_s, determined from two independent methods, met the assumed criterion $I_s \geq 0.92$. The minimum recorded value of density index was $I_s = 0.924$, at standard deviation of 0.019.

In the second stage of the study density quality was determined for the dam together with the 0.5 m layer of the subsoil (jointly 3.0 m or 4.0 m in thickness). This assessment was made based on the analyses of CPT results, determining the distribution of the relative density with depth. Figure 3 presents boundary values of density and grain size criteria in view of the example CPT characteristics.

Analysis of the recorded results indicates that density of the core superstructure is appropriate and meets the density criterion $D_R \geq 0.7$. In relation with the above it may be declared that CPT results confirm earlier observations concerning the required density of an earth structure. Moreover, the analysis of the friction ratio R_f confirms the results of the grain size analysis, while providing no indication that the analyzed zones of the test profiles may contain tailings with contents $f_\pi > 30\%$ ($R_f > 1.3\%$) (Fig. 3).

CONCLUSIONS

In accordance with the principles of sustainable development tailings management is connected with the prevention and minimization of their production in the mining industry thanks to their rational utilization and limitation of their adverse effect on the natural environment as well as human health and lives. This paper presents one of the above-mentioned directions for sustainable economy, i.e. potential re-use of postflotation tailings in hydroengineering structure construction.

Conducted studies showed that sorted tailings, corresponding in their grain size composition to silty and fine sands, may constitute an alternative source of aggregates and natural soils in the construction industry, at the same time markedly limiting exploitation of the natural sources. Considering that storage of postflotation tailings, at their significant environmental impact, is noxious to the immediate environment, we need to target our actions at the development and implementation of procedures connected with the re-use of deposited material. For this reason it seems advisable to use postflotation tailings in hydroengineering structure construction.

Conducted analyses confirmed the assumptions presented in this paper and may indicate directions for further actions undertaken in order to manage considerable significant amounts of postflotation tailings with no need to construct huge tailings storage facilities, such as the Żelazny Most MTSF.

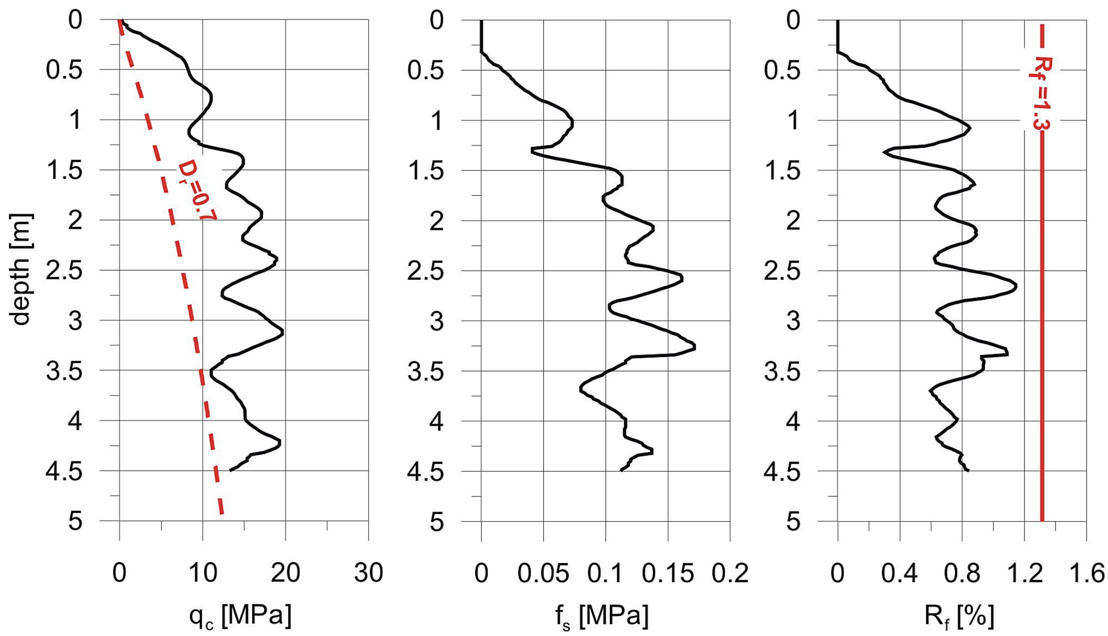

Figure 3. Example results of CPT

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