Geotechnical engineering and alternative aggregates, tailings

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Abstract. Originally geotechnical engineering is connected with ground with rock and soil environment, focused on geotechnical structures which are in interaction with ground, and therefore we often speak about construction on, with or in ground. However, during last decades, especially with increasing focus on environment protection, geotechnical engineering is dealing also with other materials, denoted as alternative aggregates. They are mostly a by-product of mining or industrial activities for which a method of future use is being sought. Typical examples are fly ash, construction and demolition waste, slag and different tails from chemical treatment of target ores which have similar character as natural soil and are produced in large volumes. Therefore, there is legitimate question about their possible use in earth structures, preferably of transport engineering. If external circumstances (e.g. distance of origin from the place of use) are favourable, geotechnical engineering is focused on two basic aspects – on possible negative impact on environment due the chemical composition of leachate or on structural stability. If there is no opportunity for their further use we have to guarantee safe deposition. In this case we are speaking about earth structures of environmental engineering as tailing dams, spoil heaps, landfills and are responsible for their safety. The paper is therefore focused on three main problems: Utilization of alternative aggregates (e.g. large volume waste) in transport engineering; Problems of earth structures of environmental engineering, where large volume waste is stored, as e.g. tailing dams and Structural collapse of tails studied in micro scale in laboratory.

1. Introduction

General currently accepted principle relates with utilization of different residues/tails of the industrial activity. Earth structures of transport engineering offer such possibility, namely for tails produced in large volumes. They can substitute natural aggregates – soil, rock, and in this direction to change usually demanded balance between volumes of excavated soil and volumes of deposited soil in embankments. They can be used also for the protection embankments along transport infrastructures with the main aim to reduce the impact of noise, light on closer environment, namely in the vicinity of development. Main sources of residues with similar character as natural ground are:

- **Construction and demolition waste** produced by construction industry. They are produced in large volumes, as the result of natural hazards (earthquakes, floods), military activities on one side or as the result of natural alteration of buildings with regard to their moral aging.

- **Mining residues/tails/waist rock** which are created either during deep mining or during surface mining, when overlying materials are subsequently deposited in different spoil heaps, mostly without any compaction, only by free fall.

- **Residues/tails after coal burning** – although the role of coal for energy purposes is declining still there is large volume of such residues, where typical example is flying ash. Character of ash and
possibilities for its utilization strongly depend on the selected methods of desulphurization. Therefore, some of them have typical character as frictional soil, some of them are closer to cohesive soils firstly when lime was applied during desulphurization method.

- **Residues/tails after chemical treatment of ores in concentrator factories.** The ore rock is crushed up to fine powder/silt and ore is extracted by chemical treatment. Therefore, the character of these tails strongly depends on the type of ore (where special attention deserves uranium ore) and chemicals used for. In this case the character of leachate from such residues deserves more attention than structural collapse.

- **Residues/tails from metallurgy,** when slag is typical product. Slag has character of gravel, on the first view is a rather strong, however as the different types of treatment are applied the final product is different from the view of structural stability.

1.1. Control of utilization via structural stability

Even between natural soils, typically used as fill material, there are some differences between structural stability. Basic difference is between sediments and residual soils. They significantly differ in the shape of particles. For rounded particles of sediments, the interparticle strength on the contact of individual grains is higher than for residual soils for which the contact is not so much smooth as an irregular shape. For them the initial deformation is also relatively small but overcrossing this interparticle strength causing destruction of these mutual contacts is followed by sudden increase of deformation (figure 1).

![Figure 1. Structural collapse on deformation curve.](image)

Alternative materials mentioned above are even more sensitive to the destruction of individual contacts, not only caused by shape of particles but very often also by porosity inside of individual grains. Ash is typical example and it is the reason of small dry density. Opposite deformation of compacted soil – swelling – is an exceptional case, valid only for compacted clay of high plasticity of the hard consistency when getting in contact with water. Such behaviour was observed also for alternative aggregates, for special case of slag.

1.2. Control of utilization via possible negative impact on environment

Basic question before final decision about future utilization is connected with potential impact on the environment. From the above mentioned five different residues this risk is most typical for tails after chemical treatment of ores in concentrator factories. Therefore, they are typically not used but stored in tailing dams. In principle there are two main ways how to control this risk generally. The first one is via chemical analysis of the leachate. For a certain chemical element is received initial contamination $c_0$ when leaving deposited tails. National environment protection authorities usually define the limit of the individual chemical substance, element. The second one is utilizing the results of the first step and apply numerical calculation method for contaminant spreading in ground to control whether a certain
chemical compound with concentration $c$ will reach recipient (usually water source, watercourse) with still acceptable quality (concentration) valid for the given type of water source (figure 2).

![Figure 2. Schematic illustration of the contaminant spreading problem: (a) contaminant source, (b) contamination paths and (c) contaminant recipient (adopted from figure 4.31 from [1]).](image)

The change of contaminant concentration as a function of position $x$, $z$ and time $t$ can be expressed by the following differential equation (adopted from equation 4.7 from [1]):

$$n \frac{\partial c}{\partial t} = n \cdot D \frac{\partial^2 c}{\partial x^2} + n \cdot D \frac{\partial^2 c}{\partial z^2} - n \cdot v \frac{\partial c}{\partial x} - n \cdot v \frac{\partial c}{\partial z} - \rho_d \cdot K \frac{\partial c}{\partial t}$$

This equation considered that the contamination spreading depends on Advection ($v$), Diffusion ($D$) and Sorption ($K$).

2. Brief specification of the different tails for earth structures of transport engineering

2.1. Construction and demolition waste

The percentage of utilization of the construction and demolition waste is now close to 90% in some countries as there exist different possibilities of their utilization. This high percentage of utilization requires a certain treatment – collection on predestined places, where organic compounds are removed (e.g. wood), extremely large blocks are crushed down, steel and concrete are separated from tails of reinforced concrete and finally the aggregates are sorted out by fraction size. Special care is devoted to the removal of potentially dangerous construction materials as is e.g. asbestos.

Coarse fraction containing mostly pieces of bricks, concrete, ceramic, glass is able to substitute natural gravel, sandy gravel. Typical case is a road foundation but also a drainage layer or capillary break layer. However, compression test is recommended to control sensitivity to cyclic loading. Fine fraction, let say smaller than 8 or 16 mm, containing dust from plaster and painting, or from plasterboard, can be used as natural soil, compacted in layers. Compaction sensitivity to the initial moisture content should be determined in this case.

2.2. Mining residues

The residues from deep mining usually contains blocks of waste rock, with relatively high strength and therefore their utilization is similar as for the coarser fraction of construction and demolition waste. More problematic questions are connected with a utilization of residues from surface mining. The quantity of materials which overlay e.g. layer of brown coal, can be enormous. Typical characterization of this overlaying material is soil with hard consistency or soft rock. Direct application is very problematic, as individual clods are large one and after deposition between them are macro pores. As individual clods can degrade after moisture content increase an additional settlement due to structural collapse is limiting the application in transport engineering without special treatment. Similar problems are well known for excavated material from underground structures – metro, tunnels.

Therefore, most of this mining residues are backfilling mining pits, creating so called inner spoil heap of quite high height. The utilization of the surface of this inner spoil heap for transport infrastructure is another interesting problem. Prediction of the total settlement development in time is
first step subsequently combined with methods for limiting differential settlement of the top layers [2] and [3].

2.3. Residues after coal burning
Properties of ash from electric power stations is very close to frictional material, mostly fine sand. Shear parameters are rather high, \( \varphi_{ef} = 38 - 47^\circ \), with \( c_{ef} \) usually zero. Main difference is for the dry volume density, as for ash this value is close to 1 000 kg. m\(^{-3}\). As this value is about twice lower than natural soil, an ash is predominantly used as fill material where the subbase settlement should be reduced. One of such places is contact of embankment with bridge abutment, not only to reduce the settlement but also lateral pressure on this abutment or to reduce negative skin friction if this abutment is founded on piles. In this case some special nonstandard aggregates can be used as well as is e.g. foam glass, or expanded clay, for which dry volume density is extremely low [1]. However, the potential risk connected with structural collapse is even much more important than for ash.

Preferential arrangement of ash layers in embankment is sandwich arrangement, as more permeable ash can speed up consolidation of soil layers of clay character. Special attention should be devoted to the surface erosion of ash, as well smaller bearing capacity especially on inclined terrain (so it means of the slope of embankment). Therefore, ash should be protected at least by layers of engineered fill and topsoil to protect direct exposition of ash and to increase surface erosion.

2.4. Residues from metallurgy
Residues from metallurgy is marked as metallurgy slag, which is the result of smelting and refining metals. For different processes the metallurgy slag is divided at least on blast-furnace slag and steel slag, both arising as a by-product during conversion of iron into steel. Mechanical properties of this by-product are very good, including good abrasion resistance and high bearing strength. However, there are also some limits, not only from the environmental point of view but also from the view of volume instability, sensitivity to swelling in the presence of moisture, which can cause the heaving of pavements and uneven, rough and cracked pavement surfaces such as shown in figure 3.

![Figure 3. Uneven road pavement due to differential settlement of underlying fill.](image)

Sensitivity to swelling is interpreted due to presence of free lime and magnesium oxides that have not yet reacted with silicate structures. Motz and Geiseler are distinguishing two basic types of slag, [4]. Basic oxygen furnace slags contain up to 10% of free CaO and up to 5 – 8 % of MgO, while electric arc furnace slags have less CaO and more MgO. Therefore, the first control is via chemical composition of slag, but better control is via swelling test, usually recommended is steam test. But
very good mechanical properties can be utilized even for slags with high swelling potential as anti-erosion protection of slopes, due to high dry density and roughness of particles.

3. Earth structures of environmental engineering – spoil heaps, tailing dams

As was written before, not all produced tails can be used in civil engineering. First of all, the main reason is extremely high volume (as e.g. for tails from surface mining) but also due to large distances between the place of tails creation and place of theoretical utilization. According to the potential risk to the environment we can destinies two main types of deposition. When the potential risk is relatively small, tails can be deposited by free filling, creating so called spoil heaps, waste dumps. For potentially higher risk it is necessary to select some barriers around deposited material. The majority of tails as is ash and tails after chemical treatment of ores in concentrator factories can be stored in tailing dams, where the main attention from the environment protection is focused on the quality of leachate (bottom sealing system). Special protection, full encapsulation, deserves tails after chemical treatment of the uranium ore rock in concentrator factories. In this case the protection barriers are similar to these used in landfills when storing municipal or chemical waste.

Nevertheless, for any sort of tails deposition, the principle of minimizing land use for deposited material applies. The result is that there is a tendency to construct such earth structures of environmental engineering as high and as steep as possible. However, this requires special attention from the slope stability point of view.

3.1. Spoil heaps

Mining residues create enormous quantity of material, especially for surface mines, where the mined material, such as brown coal, is located at relatively great depths. The so-called overlap ratio (volume of tails to the volume of coal) can reach values greater than 10. Such situation is for example in the Czech Republic (but also in other countries like Germany, Hungary, Greece and many others) and total amount of excavated overlaying material is close to 200 mil. m$^3$ per year. In this case, Tertiary brown coal is overlaid by Tertiary sediments, mainly clays of stiff, hard consistency. Mining machines have large dimensions and the size of the mined clods corresponds to this. After deposition just by free fall on the final place, between the individual clayey clods exist a great macropores. In early phases of mining the excavated material was deposited on existing ground, out of mining area, creating outer spoil heaps. However now prevails the deposition into excavated mining pits and inner spoil heaps are created and their surface can be subsequently used for, also for the transport infrastructure. To guarantee long term slope stability and to prognose the settlement of the surface of spoil heaps with time, special care to the structural stability of individual clods should be devoted. The starting point for monitoring changes in the deposited material is the fact that they have been extracted from a relatively large depth and therefore have a negative pore pressure inside the clods after excavation. The clods thus show a great tendency to water absorption, to weathering, and thus to the change of consistency and continuous closure of macropores. Most dangerous case is when water is fulfilling macropores, for example when the bottom of mining pit is not drained. After that the consistency can change up the soft one and the result is soft clay. It is the extreme case when the character of fill – nearly rockfill - is changing to the second extreme – to the soft clay. The result of such change is slope stability decrease, as with continuous kneading shear strength can drop up to the residual one. As residual shear angle is very often in the range of 8 to 14° the problem of slope stability is very sensitive, namely when water is flowing through. There have even been documented cases where the original slope of soil heaps inclination of 1V:2H changed to 1V:8H.

This process of degradation and softening can be reduced by restricting water access. Such possibility is dewatering of the bottom of the mining pit and relatively quick filling of spoil heaps. Due to load increase and crushing at the contacts of the individual clods the macropores are gradually filled with material of stiff to hard consistency, which in turn reduces further water intake and fill softening. Special attention is devoted to the upper roughly 15 meters. There are roughly two basic reasons. Load increase there is not sufficient for macropores closure and transport infrastructure situated on the surface of spoil heap is much more sensitive to differential settlement than to the total settlement. Final decision about appropriate time to start with transport infrastructure construction will depend on
the surface settlement monitoring with time. Figure 4 shows the surface of spoil heap with high up to 160 m, which surface was used for motorway and railway and also for transfer of water stream in tubes [2] or [3]. Differential settlement is rather smooth and allows comfortable car ride up to velocity close to 90 km/hour.

![Figure 4](image.png)

**Figure 4.** Utilization of the surface of high spoil heap for transport infrastructure.

The last note is directed to the fact that similar behaviour as clay clods have some other materials for which the degradation of clods with time and with water increase is similar, like claystone, clayey slates, schists. It does not necessarily have to be only mining residues but also soils excavated during construction in cities such as underground garages, metro etc.

### 3.2. Tailing dams

According to some specialists (e.g. [5], [6] and [7]) the tailing dams are defined as a natural or artificial space on the earth surface, serving for permanent or temporal deposition of hydraulically transported tails; component part of tailing dams is also embankment system. This definition covers many different variants depending on:

- **Deposited tails**, when our attention is focused on materials similar to natural soils as flying ash from electric power and heating stations or tails from concentrator factories. Grain size has character of fine sand with significant content of silt particles. Mechanical properties are very close to the natural soils. The main difference is with respect to the saturated density as for ash is much smaller than for sand (roughly 13 kN/m³), while for tails after chemical treatment of ores in concentrator factories this value is higher than for sand, higher than 20 kN/m³.
- **Tailing dam location**, where three basic types are distinguished: tailing dams situated in valley; on inclined terrain and finally planar – horizontal type – with embankment along whole circumference – figure 5.
- **Embankment system**, preferably constructed step by step with very strong tendency to substitute natural soil for this embankment by deposited aggregates. Wherein the raising of the embankment can take place both against the water and in the direction of the retained water.

With respect of construction technology, the tailing dams have some specificity as well:
- **Time - step by step construction** on the full high is taking very long time compared with other structures.
- **There is strong effort to receive as low porosity** of deposited material as much as possible, not only for storage of more tails in one cubic meter, but as a priority to improve mechanical properties – shear strength and compressibility, resp. to decrease the potential risk of liquefaction, typical for loose non-cohesive materials. To reach closer particle arrangement, the tails transported by hydraulic way
should sediment on “beach”, on surface closer to the main (additional dam), not on the area with free water table. There is the preference for more outlets from the main supply pipe to reach more uniform sedimentation with coarser particles closer to the main dam.

- **Drainage system** should be able to hold phreatic line sufficiently far off the downstream face of the tailing dams. This requirement should be valid for all lifetime expectancy; therefore, the capacity of drains should be designed on very conservative side.

![Diagram of tailing dam location](image)

**Figure 5.** Different types of tailing dam location.

When limit states design approach is used in accordance with European code EN 1997 Geotechnical design, the following limit states determine the overall safety of tailings dams:

- **Slope stability.** General slope inclination depends on the volume density of saturated material and on phreatic line, how close is to the downstream face. For lighter ash the general inclination is close to 1:6, for tails from the concentrator factories is it about 1:3. As subsoil is preferably impermeable (what is valid for artificial bottom sealing system) pore pressure development can have negative impact on slope stability due to quick loading (quick speed of filling), namely if bottom contact is inclined.

- **Internal erosion.** Drains should be well protected by filters and well approved filtration criteria should by applied for both grain and geotextile filters. Laboratory experiments for filtration criteria verification are preferred, namely for geotextile filters.

- **Surface erosion,** caused by both water and wind. As deposited material is very sensitive to erosion – due to character of particles – fine sand, silt, it is necessary to limit this possibility. Most of the protection measures is using capping layer from organic soil on the downstream slope and also for the crest. A great care should be devoted to the monitoring of any leakage from pipes situated close to the dam surface as well to the potential risk of crest overflowing During dam increase, when hydraulic filling is stopped, the water table in the reservoir is lowered and deposited tails after drying are sensitive to wind erosion. Water spraying or application of nonwoven geotextile are one from different possibilities.
Limit state of serviceability mostly associated with vertical settlement is not so sensitive in this case, however the possibility of damage of different pipes and drains by this settlement should be controlled.

Potential risk of tailing dam’s failure is relatively high, compared to other geotechnical structures, and in addition to the above, it can be:

- Extremely high sensitivity to seismic events
- Needs of control for decades
- Less qualified workers than for classical dam construction. In this direction is mentioning better cooperation between mining and geotechnical engineers [8].
- 2 D effect – as failure can occur in weakest point, when length of circumferential embankment can be very high, up to tens of kilometres.

Number of failures really confirm this high potential risk of failure. Some of them can be mentioned briefly:

- Chile 1965 – 22 tailing dams with sediments from concentrator factories failed during earthquake with intensity of 7.0 – 7.7 degree.
- Italy 1985 – Dolomites, Val di Fiemme Valley – two tailing dams with sediments after extraction of fluoride subsequently failed and wave with elevation up to 30–40 m, during only 20 seconds destroyed buildings in the valley and about 300 people died.
- Czech Republic – Neratovice – main dam from the compacted ash failed due to overflowing. A significant part of the ash deposited in tailing pond flowed out and reached watercourse.

As the forecast of all aspects influencing tailing dam’s safety is very complicated, Morgenstern [9] already in 1994 recommended to apply observational method of design. This method is part of EN 1997 and in principle is based on the approximate behaviour of the geotechnical structure and its monitoring. Both for the verification of assumptions and for possibility of reaction if the results of monitoring are outside the expected range. This observation method was applied for tailings dam from oil sands in Alberta, Canada. Monitoring and realized improvement during phase of construction helped to hold this tailing dams safe, even when some conditions are really extreme. Subsoil is composed from plastic clay-shales and perimeter of dam is 18 km with height between 32 to 90 m (in 2001). Similar steps are followed for another extreme tailings dam located in Poland – Zelazny Most [10].

Nevertheless, even when the application of this observation method is more often used, some problems were registered also recently. Just to mention some of them – copper and gold mine tailings in British Columbia, Canada in 2014. From failed dam leaked about 4.5 mil. m$^3$ of slurry which contaminated watercourse situated below. One million m$^3$ of “red mud” (by-product of alumina production) from failed Ajka dam in Hungary flooded the village Kolontar and town Devescer and reached the river Danube in 2010. 10 people died, 123 injured, 260 houses became uninhabitable and significant ecological damage occurred.

Failures of tailing dams in Brazil in last years attracted much attention, as dams were well monitored and failures occurred very quickly without any warnings.

The Samarco tailings dam failure in November 2015 was considered to be a turning point and a step change towards the improvement of the tailings dam safety. However, since 2015 there have been over 20 similar failures, resulting in the deaths of around 400 people and affecting upwards of 68,000 people through impacts to property, infrastructure or the environment. Unusual behaviour focused attention on the significance of sudden structural changes/collapse, and the outcome of the early stages of research in this area is described in the following chapter.

4. Microstructure of tailings and the impact on performance

4.1. Background

The key attributes that are understood to control the soil behaviour are the applied stresses and the soil structure, which is influenced by many factors such as mineralogy, stress history, void ratio etc. [11]. Most of the modern soil constitutive soil models identifies a void ratio as a crucial parameter
indicating the changes in the soil select during shearing of soils. The question is however whether the void ratio is the best indicator of the soil structure and whether it can change without influencing the stress parameters and vice versa, which was investigated using modern microscopic methods.

4.2. Tested materials
The residue samples for the researched were acquired from conventional bauxite operations in Spain (sample ALSP) and Western Australia (sample ALWA). Both operations use the Bayer process and the tailings fraction tested was separated from the bauxite residue stream using hydrocyclones. For comparison a reference sample comprising river type sand (sample RESN) with gradation similar to the gradation of the tailings samples was also tested as part of the program.

The study into the soil microstructure focused on the distribution of voids within the soil matrix and the meaning of the void ratio in the context of the soil structure. For this reason, the investigations included, in additional to the traditional index tests, the following:

- Scanning Electron Microscope (SEM) with an Energy Dispersive Spectroscope (EDS).
- X-Ray Diffraction to confirm chemical composition of the samples
- Mercury Porosimeter Results
- Nanoindentation test
- Shear strength tests

Further details on the completed microscopical assessment are provided in Herza et al. [12]

4.3. Geotechnical classification tests
Two samples of tailings (and one sample of the reference sand) were tested using conventional particle size distribution (PSD) and Atterberg Limit tests and specific gravity test. The results of the PSD are plotted (figure 6). The Atterberg Limits test could not be completed as all samples were non-plastic.

Based on the classification testing the residue sands and the reference sand samples were classified as poorly graded medium to fine sands (SP) in accordance with ASTM.

![Figure 6. PSD plots of tailings samples and reference sand.](image)

To estimate the impact of the internal structure on the particle sizes, the PSD test was repeated on sample of tailings sheared in the ring shear apparatus. The results indicated that shearing the tailings
samples (discussed later in Chapter 4.8) made them finer, with the proportion of fines increasing by up to 12% (see Figure 6). Remoulding of the RESN sample did not have a noticeable impact on the sample PSD. The PSD results indicate that the shearing of the residual sands can breakdown the inter-aggregate bonds with further impacts on the material performance.

4.4. Scanning Electron Microscope

Despite the sandy appearance of the tailings sample (figure 7, left) the SEM images revealed the complex nature of the individual tailing’s aggregates (figure 7, middle), which are formed from many smaller sized particles. This is juxtaposed with typical sand grains which are formed from compact masses of solid matter (figure 7, right).

![Figure 7. Tailings sample images (left and middle) and quartz sand (right).](image)

The EDS (Energy Dispersive Spectroscope) analyses indicated that the tailings sample comprises mainly aluminium and iron oxides and hydroxides, with minor presence of titanium and sodium oxides. The oxides, most commonly Goethite, Hematite and Gibbsite were found to be bonded together by aluminium oxide bonds (figure 8, left) to form very porous grains ranging in size from units of microns to hundreds of microns. The larger aggregates were also found to be bonded by oxide/hydroxide bridges to form even bigger complexes (figure 8, right).

![Figure 8. EDS elements composition mapping.](image)
4.5. X-Ray Diffraction results

The results from the X-ray powder diffraction (XRD) tests completed on pulverised sample (1) confirmed the preliminary composition of the material indicated by SEM and EDS. As shown in 1, the specific gravity of the various minerals that form the tailings aggregates was as much as 100%. The SEM images showed that the distribution of the various minerals is not homogeneous and thus the material SG can be spatially variable (table 1).

| Name of mineral | Chemical formula | % content by weight in ALSP sample | % content by weight in ALWA sample | Specific gravity of minerals |
|----------------|-----------------|-----------------------------------|-----------------------------------|-----------------------------|
| Goethite       | FeO(OH)         | 52.8                              | 17.9                              | 3.80                        |
| Hematite       | Fe2O3           | 21.6                              | 14.6                              | 5.26                        |
| Gibbsite       | Al(OH)3         | 13.2                              | 20.2                              | 2.34                        |
| Boehmite       | AlO(OH)         | 12.4                              | 0.7                               | 3.03                        |
| Quartz         | SiO2            | 0.0                               | 43.4                              | 2.65                        |

4.6. Porosimeter results

The porosimeter test was completed in a mercury porosimeter on loose samples. If the samples were in denser states, the distribution of the void sizes would be different. However, the method only detects voids with maximum size of 100 μm and hence the relatively large spread of the loosely packed sample aggregates does not significantly impact the results. As can be seen in figure 9, a large proportion of the porosity of samples ALSP and ALWA is formed by voids with a pore size smaller than 1 μm. Given the sandy nature of the tested samples and based on the SEM images, it appears that the sub 1 μm voids are the voids within the bonded aggregates. From this perspective the samples have dual porosity, which can be delineated as the intra-aggregate porosity and the inter-aggregate porosity and the same applies to the void ratio.

![Figure 9. Mercury porosimeter results.](image-url)
4.7. Nanoindentation test
An instrumented indentation technique was used to estimate the elasticity modulus (E) of goethite and hematite aggregates and 44 micro dents were made. Figure 10 shows the nanoindentation marks on the cut and polished surfaces of the tailing’s aggregates. The resistance of the target aggregates was found to be similar to the resistance of hydrated cement. The modulus of elasticity was calculated to vary between 23 and 33 GPa, which corresponds to the values presented by Chicot et al. [13]. For comparison the E values of pure goethite and hematite are an order of magnitude greater (> 500 GPa), a pure quartz has E close to 100 GPa and E of common sands is in the order of tens of MPa.

![Figure 10. Nanoindentation marks on polished surfaces of tested tailings aggregates.](image)

4.8. Shear strength testing
The shear strength characteristics of the tailings samples was tested in a 100 mm diameter ring shear apparatus in fully drained conditions to a total strain of 100 mm. As can be seen in figure 11, the tailings shear resistance increased rapidly in small strains and then reduced by almost 30% before stabilising. The sample volume and thus the average void ratio was however, constantly reducing until the end of the test, indicating structural decay of the tailings aggregates, which was later confirmed by the PSD tests.

![Figure 11. Results of a ring shear test.](image)
4.9. Discussion on tailings microstructure

Based on the geotechnical classification tests, the tested tailings materials and the reference sample were identically classified as poorly graded sands with similar PSDs. However, the mineralogical and SEM analyses identified tailings sample did not contain any or very small proportion of quartz. The microscopic assessment of the residue structure confirmed that the majority of the samples were composed of iron and aluminium oxides and hydroxides, which are bonded together to form a very porous, sand-size aggregates. These aggregates are then bonded together by oxide and hydroxide bridges to form yet larger complexes. Given the heterogenous properties of the individual particles forming the bonded aggregates (figure 12) it is questionable whether or not the homogenisation and the use of the average value (e.g. SG) of tailings skeleton is appropriate.

The nanoindentation probing indicated that the elasticity modulus and hardness of the bonded aggregates is in the same order of magnitude as is quartz. Because the elasticity modulus of sands and other soils is two orders of magnitude smaller than the elasticity modulus of the bonded aggregates, it is unlikely that loading of the soil (in compression or shear) would cause complete destruction of the aggregates. Therefore, a very large proportion of the measured voids would not take part in the volumetric changes during shearing and would remain passive in respect with the interaction between the effective confining and deviator stresses. However, the PSD tests before and after the residue remoulding and the shear strength tests indicated that the bridges between the bonded aggregates can
be easily broken. It appears that the continuous shearing gradually breaks down the bonded structure (figure 13) impacting the stress redistribution and the ‘active’ void ratio of the tailings may increase throughout the shearing.

Because the void ratio of the residue sand comprises both passive and active voids and because the balance between these two groups may be changing during shearing and other deformations, the average void ratio of the soil mass may not be the best indicator of the residue state for constitutive geotechnical models.

5. Conclusions
This paper discusses non-standard aggregates, the nature of waste, properties of which are similar to the properties of natural soils and are produced in excessive and still increasing volumes. Finding a cost effective and safe use for these materials in earth structures of transport and civil engineering or ensuring their permanent storage is a significant challenge for the current and the next generations of geotechnical engineers.

Two key properties having an important impact on the reuse or the permanent storage of the non-standard aggregates and waste are the character of leachate and the mechanical properties of the aggregates. While the character of leachate is important from the environmental point of view, the stability of the earth structures and the waste storage facility depends on the mechanical properties of the soil aggregates.

The mechanical properties and structural stability were studied using microscopical investigation methods applied on tailings produced during mechanical and chemical treatment of bauxite ores. Scanning microscope images revealed weak points (bridges) between individual particles, to be sensitive to structural collapse and which were also found to be composed of bonded aluminium and iron minerals.

The structural decay was also shown in the results of the shear strength tests, as shearing of non-standard aggregates approved grain size destruction of finer fraction. As this collapse can occur very quickly, unexpectedly, with pore pressure increase and so shear strength reduction, this phenomenon deserves our great attention.

Typical phenomenological constitutive models used in geotechnical practice do not account for structural decay and thus may not be capable of predicting the conditions before the structural failure and further research is required in this area.

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