Review of Research on Physical and Mechanical Properties and Engineering Application of Metal Tailings

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Abstract. Processing and storage requirements for metal residues are becoming stricter to achieve the carbon neutralization target. The physical and mechanical properties of tailings affect the stability of tailing dams. Metal tailings can be used as secondary resources, and it is easy to pollute the environment under poorly managed conditions. Therefore, it is necessary and urgent to reuse these deposits such as iron tailings, copper tailings, zinc tailings et al. This article discusses the current research on the mechanical properties of metal tailings and its engineering application. Based on previous research, it is pointed out that there still needs more attention on the mechanical properties of metal tailing sands, especially under different conditions like dry-wet, freeze-thaw, dynamic loads and large-scale application. In the future, research on the filling of metal tailings as roadbed and new building materials will be one of the directions to solve the problem of tailing pond accumulation.

Keywords. Tailings, Geotechnical engineering, physical properties, mechanical properties, comprehensive utilization.

1. Introduction

Metal tailings are wastes that discharged after the ore is crushed, ground, sorted through multiple processes and finally piled up in the form of tailing ponds [1-2]. These wastes contain secondary resource components such as re-selectable metal ore and non-metal ore. After mine reclamation process these tailings can also be used in other engineering fields such as road construction and civil engineering. Pilled tailings not only take lots of land, wastes a big sum of money, but also severely pollutes the surrounding environments. Tailings dam break accidents have occurred sometimes during past decades, causing enormous and irreparable loss of life and property. At the end of 2020, the cumulative tailings in China have exceeded 20 billion tons, but the total annual comprehensive utilization of tailings is only 335 million tons [3-4]. The annual comprehensive utilization rate is less than 30% [5]. In recent years, the prevention and control of tailing pond pollution have been listed in the national major development strategy in China. The Ministry of Emergency Management of the People's Republic of China clearly stated that the number of tailings pond must decline from 2020, it also demands that the comprehensive utilization rate of tailings must be increased. Therefore, based on the deep and comprehensive understanding of the mechanical properties of metal tailings. It is of great significance to continuously improve the utilization rate to solve the risk of tailing leakage and meet the requirements of carbon neutralization.

For now, papers concern the characteristics of metal tailings are becoming more and more, however, most study of tailings focus on one material. External factors under different conditions also introduced
2. Composition and Particle Size of Metal Tailings Sands

Different types of metal deposits are affected by geological conditions resulting in the diversity of material composition. Therefore, the mineral composition and chemical composition of metal deposits are relatively complex. The main mineral components of iron tailings sand are plagioclase, quartz, and chlorite, calcite, flaky biotite [7]. Common components mainly include TFe, SiO₂, Fe₂O₃, CaO, Al₂O₃, MgO, K₂O, MnO, Na₂O, et al [8]. Among which the content of SiO₂ between copper tailings fluctuates from 31.88% to 80.10%. The composition of SiO₂ lists at the top.

Due to the difference in types and mining processes, the distribution of particle size after beneficiation varies greatly. Studies have shown that the particle size of metal tailings sand usually varies from 0.075mm to 5mm. The particle size of metal tailings sand has a great influence on its engineering characteristics. Existing research mainly focus on the classification of tailings sand and particle size. The grouping of metal tailings has not yet formed a unified standard. According to the classification of rock and soil particle groups in classical soil mechanics, Wu [9] defined the tailings particle size less than 75μm as fine sand. Cao et al [10] studied the selection of physical parameters of tailings and found 12 parameter indicators that can represent the physical properties of tailings. These 12 indicators were divided into 3 categories and the particle size can be used as a basic indicator. 795 sets of data were statistically analysed and discussed separately [11]. By using Scanning Electron Microscopy and image processing technology, Yang et al [12] quantified the flatness, roundness, convexity, and roughness of tailings sand. As the particle size increases, the flatness of the tailings decreases, indicating that the shape of the tailings particles changes from needle-like to spherical.

Under different particle gradation conditions, the strength of tailings is different [13]. Saturated samples were subjected to isotropic consolidation undrained shear tests under confining pressures of 100kPa, 200kPa, and 300kPa respectively. The stress-strain curve of the tailings sand sample is softened, and as the confining pressure gradually increases, the softening degree gradually weakens. Under the same confining pressure, the stress-strain curve of the same density and different gradation samples have different softening degrees. The triaxial shear test shows that the fine particles of the sample are more likely to lose their shear strength under the action of continuous pore water pressure. Therefore, the finer particles in the sample with the same density, the lower the effective stress under the same confining pressure. The faster it is, the easier it is to soften. The sedimentation characteristics of tailings sand under different particle size gradation conditions are different. With the increase of fine particles of tailings sand, the maximum underflow concentration of tailings sand after sedimentation shows a downward trend [14]. Yang et al [15] studied the effect of the particle size of tailings sand on the shear strength of tailings. The results showed that as the median diameter increases from 83.23μm to 149.9μm, the unsaturated tailings cohesive force decline and the friction angle increases. Ma et al [16] investigated the influence of ore phase transition after roasting at different temperatures.

Particle characteristics, especially the particle size distribution of tailings sand have an important influence on tailings sand. The graphic visualization of tailings sand particles can reflect the microscopic morphology of particles. However, the microcosmic study of tailings sand particles is still in the state of two-dimensional interface, and the three-dimensional microcosmic simulation is important in the next stage. The properties of tailings sand particles change under the condition of high temperature roasting, so it is necessary to further study the mineral phase changes of tailings sand particles under different gradation conditions at high temperature. Most of the current research focus on iron ore but the research on copper ore and other minerals is also very important. The classification of tailing sand particle size has been discussed in the above literatures, but there are still relatively few studies on viscous particles with different particle sizes. It is necessary to further study the distribution of viscous particles with different particle sizes.
3. Strength Characteristics of Tailings Sand

3.1. Strength Characteristics
The high pressure has an important influence on the strength of tailing sand [17]. Yang et al [18] conducted research on the strength characteristics of tailings, and through consolidated drained test and compression test, respectively, explored the strength characteristics at different degrees of compaction. They pointed out that as the porosity ratio of tailings increases, tailings are compressibility increased, but the compressive modulus is negatively correlated. The change of soil sample plasticity index affects the dynamic strength of tailing sand particles [19]. The tailing sand was tested with a dynamic triaxial instrument and it was pointed out that the existence of initial static shear stress reduced the strength of tailing sand particles. The residual strength is lower than the initial strength and its decay rate decreases with the increase in the plasticity index. The change characteristics of the particle strength of tailings sand in the saturated state are different from tailing sand under unsaturated state [20].

Different vibration frequencies affect the strength of tailings sand [21]. At the same time, the shear rate under different stress also influences the strength characteristics of tailings sand [22]. When the shear rate increases, the shear strength of tailings sand particles will decrease. Changes in the low confining pressure state are less pronounced than the high confining pressure state. An et al [23] conducted an experimental study to show the shear strength of tailings sand under dry-wet cycles. During the dry-wet cycle, the internal particle structure of tailings changed due to the repeated action of dry-wet. After several cycles, the effective cohesion $c'$ and the internal friction angle $\phi'$ have a certain regularity.

3.2. Compression Characteristics
Cao et al [24] studied the influence of the compression and consolidation coefficient. The results showed that the consolidation coefficient increases with the change of the consolidation pressure and decreases gradually after reaching the peak, finally tends to be stable. The consolidation coefficient decreases with the particle size. The change of compaction degree and water content also have an important effect on the compression characteristics of tailing sand particles [25]. The standard consolidation test found that both compaction and moisture content have an impact on the compressibility and consolidation coefficient. With the increase of the degree of compaction, the compressibility and consolidation coefficient of tailings sand particles decrease simultaneously, but the change of the compression coefficient and consolidation coefficient caused by water content is relatively complicated. Wu et al [26] conducted a correlation study on the particle properties of tailings sands on compression and consolidation characteristics. The results showed that tailing sands with different particle compositions have different characteristics, compression characteristics of tailings sand are greatly different from each other in composition, particle size and shape of tailing particles.

Different types of tailing sand have great differences in mechanical properties, and the mechanical properties of tailings sand particles are a key factor to meet the specific purpose especially in highway construction and civil engineering. The current research on the mechanical properties of tailings sand particles is only focused on certain factors. Comprehensive consideration of various factors is of great value for the compression characteristics of tailings sand.

4. Study on the Stability of Tailings Dams
The research on tailings stability mainly focuses on the tailings dam under external forces especially nature force. The stability analysis of the Dashi river tailings dam under the action of the earthquake shows that the earthquake can cause cracks in the tailings pond and water spraying, sanding leakage [27]. Psarropoulos et al [28] found that the stability of tailings dams gradually decreased under static and dynamic cycling conditions. Uniaxial compression test and triaxial shear laboratory are used to study the stability of tailings dams. The stability of tailings dams is also affected by the following factors such as permeability, capillary water, dry and wet cycles [29]. Unify these parameters into a model to describe the stability of tailings dams is one of the directions. The external force such as earthquake acting on the internal factors of the tailings remains to be studied. The coupling of a single factor or
double factors is the current research hotspot. The research on the correlation between internal factors and external factors is a key point.

4.1. The Influence of Earthquake on the Stability of Tailings Dams
The liquefaction of tailing sand often occurs under earthquake which has a negative effect on the stability of the dam. The discriminant method of seismic liquefaction is obtained by considering several different working conditions and analysing the results of two-dimensional seismic response analysis of tailing dam [30]. Based on the relationship between the anti-liquefaction degree and the pore pressure ratio, a simplified calculation formula for the excess pore pressure on the tailings dam is proposed [31], the calculation indicates that the area near the water’s edge of the upstream slope is the easiest area to liquefy, followed by the initial dam. The length of the dry beach has a great influence on the seismic liquefaction stability of the tailings dam. Through sensitivity analysis and reliability calculation analysis [32]. It is found that the internal friction angle and severity need to be included in the stability analysis of the tailings pond for further improvement. Hu et al [33] pointed out that the main indicator of anti-sliding stability is the shear strength and used separate calculations to evaluate the stability of its tailings. The calculation results show that the infiltration line affects its stability. Comparative studies have found that tailings with different particle sizes have different stability performance under seismic action [34]. Under high intensity test, large area deformation occurs at the top of the tailings dam slope, resulting in large amounts of sand blasting and dam liquefaction caused by cracks [35]. The numerical simulation software also analysed the stability of tailing dams. Despite the overall stability of the dam body behaves well, there is still a risk of liquefaction and dam failure under the action of earthquake [36]. Conventional treatment methods for tailings dam reinforcement usually adopt gravel pile or sand pile [37].

4.2. The Influence of Freeze-Thaw on the Stability of Tailings Dams
According to the geographical distribution of tailings ponds 91.4% of tailings ponds suffer different degrees of freezing in winter. Field surveys revealed [38] that in winter, except surface freezing, there are deep frozen layers of tailings dam in alpine areas. These solid frozen layers have a great influence on the stability of tailings dams. They will affect the seepage field of the tailings dam and reduce the stability of the dam body. At worst, they will lead to deformation and failure of tailings dam when the temperature rises. However, the research on the mechanical properties and factors of frozen tailings is rarely reported. The research results showed that there are three types of uniaxial compression failure of frozen tailings. The uniaxial stress-strain curve of frozen tailings can be divided into 4 stages: initial strain softening stage, linear strain hardening stage, nonlinear strain hardening stage and nonlinear strain softening stage. Among the 4 influencing factors, the uniaxial compressive strength of frozen tailings has logarithmic relationship with average particle size, exponential relationship with dry density, linear increasing relationship with water content, and quadratic parabolic growth relationship with loading rate. However, the deformation modulus of frozen tailings has a natural logarithmic relationship with average particle size, an exponential relationship with dry density, a quadratic parabolic relationship with water content, and an exponential growth relationship with loading rate [39]. In addition to the conventional influencing factors, the stability of the mine should also consider the hazards caused by seasonal freezing and thawing. This freeze-thaw cycle will significantly change the connection structure among the tailings sand particles and directly affect the changes in physical and mechanical properties [40-41].

The construction of tailings projects in China often adopts the upstream method to build dams, but the upstream method is prone to geological disasters and dam break accidents. The study of the stability of tailings dam shows that many factors have an important impact on the tailings dam, the maintenance and management of the tailings pond also bring the increase of cost to the mining enterprise. It is one of the effective way to change the disposal way of tailings and increase the exploitation of tailings resources to eliminate the hidden trouble that may happen in the operation of tailings ponds.

5. Comprehensive Utilization of Secondary Resources of Tailings
Li et al [42] proposed to strengthen the utilization and protection of mineral resources and provided
relevant ideas for the development and utilization of non-metallic minerals. Gu [43] proposed the possibility of comprehensive utilization of tailings and proposed some methods for the use of building materials. Li [44] discussed the development and utilization of metal mines in China and briefly introduced the current situation and characteristics of metal mine tailings resources. Ding et al introduced more specific examples of the utilization of different types of tailings such as iron ore tailings and copper ore tailings [45]. Direct application of metal ore tailings and non-metallic ore tailings also carried. Xu et al [46] used asbestos tailings to conduct research on glass-ceramic decorative panels and the parameters of asbestos tailings as the main raw material can be as high as 60%. The physical and chemical properties of the product are better than natural marble and granite. Its simple production method and reasonable parameters is a new way for the development and utilization of asbestos tailings. Ye et al [47] briefly introduced the utilization status of kaolin from pyrite tailings in southern Sichuan and commented on its comprehensive utilization methods. They pointed out that kaolin from pyrite tailings in southern Sichuan can also be used as a preparation method. Carbon black, activated clay, synthesis of zeolite, production of refractory materials etc. Yang et al [48] pointed out that the valuable mineral resources in the beneficiation plant are poor, fine, and hybrid. Limited by conventional beneficiation technology, resulting in low concentrate grades, recovery rates, and poor economic benefits.

There are few discussions on copper tailings and most of them focus on the utilization in the mine engineering fields [49]. The discussion of lead-zinc tailings is mostly focused on material, not on it is application in other engineering. At present, the engineering construction of China is in and will be in the period of large-scale construction for a long time. Therefore, it is necessary to combine the comprehensive utilization of tailings with civil engineering construction and highway construction. Through large-scale application of engineering and rapid iteration of products, the cost of development and application will constantly reduce, and finally a new effective way of comprehensive utilization of tailings is explored.

6. Engineering Application Tailings Sand
At present, the method of comprehensive utilization of tailings in China is mainly used as filling of underground mining, followed by the construction of roads, pavement materials, anti-skid materials, coastal land reclamation, and construction materials. Little tailing materials are used to re-select [50]. In 2018, the total quantity of tailings used for building materials and value components in China was approximately 184.43 million tonnes.

6.1. Technology for Manufacturing Cement Clinker Using Tailings Sand.
Li et al [51] observed the thermal reaction characteristics of fine tailings under different high temperature conditions through high-temperature experiments. The higher the temperature, the greater the characteristic kurtosis intensity. The test after tailings and CaO blended combustion showed that: The main phase composition after calcining at 1400 °C is basically the same as that of ordinary Portland cement clinker. Barati et al [52] used phosphorous tailings to configure a sintering aid suitable for new dry process production and appropriately adjusted cement clinker. Tests showed that the clinker has high strength. The solubilizing effect improves the strength of the clinker. Huang et al [53] discussed the possibility of using lead-zinc tailings as cement ingredients based on the opinion that the composition of the oxides in lead-zinc tailings are similar to that of cement raw materials. The test results show that the lead-zinc tailings under different proportions have different characteristics and some lead-zinc tailings cannot be used as ingredients for cement production because they contain elements that are not conducive to the combustion of clinker. With better lead-zinc tailings, it can improve the flammability of the raw cement material, and increase the strength of the fired cement, while meeting the national environmental protection requirements. Zhao et al [54] conducted experimental research on copper tailings calcined cement and pointed out that it is feasible for copper tailings to replace iron powder to calcinate cement clinker and determine the appropriate conditions for copper tailings to burn Portland cement are 1350°C, the holding time is 30 minutes.
Wei et al [55] used low-silicon iron tailings to study the preparation of cement. The results showed that the strength index of belite cement for 3 and 28 days reached the requirement of PI42.5 cement by calcining iron tailings with a mass fraction of 30.90% and limestone with a mass fraction of 69.10% in 1350°C for 1h and adding activator gypsum equal to 0.60% of clinker mass. Liu et al [56] studied the preparation of magnesium portland cement from magnesite tailings. The test showed that the composition point of the mixture fell within the line of 2CaO·SiO$_2$, 3CaO·SiO$_2$ and MgO, and the M/S ratio in the raw material was 2/1 which is feasible to make cement tailing sand within 2.1~2.56.

6.2. Used As Subgrade Filling

Subgrade filling has certain requirements for the selection of filling material [57]. The selection of tailing sand should consider both the influence of radioactivity and the influence on the water environment. Considering the difference between the actual situation of subgrade compaction and the laboratory test, it is necessary to carry out the soil-mixed test on tailings. In the pilot project, the mixing ratio is lime: fly ash: tailing sand =8:22:70. The unconfined compressive strength of 7d field sampling test is 0.56 MPa, the compaction degree is 97%, and the measured bending and subsidence value of the top of the base is 0.91mm, which meets the design requirements and can be used for the road bottom base [58]. In the same type of project, the stability of the clay-bound tailings sand subgrade was analysed, and the analysis results showed that the stability of the clay-bound tailings sand subgrade can meet the requirements of specification [59]. The construction of highway engineering has higher requirements for roadbed materials. Under the premise of meeting environmental and construction technical requirements, through quality control during the construction process and monitoring of key points, stability of roadbed filled with tailings sand turned out to be good, which has obvious economic and social benefits [60].

7. Summary and Conclusions

To sum up, the current research on tailings mainly focuses on the tailings dam in different regions, and its strength characteristics stability characteristics, pore water migration law, freeze-thaw law and other studies have been relatively rich. Much has been achieved in the use of tailings secondary resources, but relevant research on the scale of application has yet to be completed. Based on current research, it is suggested that further investigation of tailings engineering characteristics should include:

1) In order to provide design basis for tailings construction in freeze-thaw area, it is necessary to expand the range of negative temperature to conduct strength and thawing test of tailing sand and study the influence of pore water on strength characteristics and deformation characteristics before and after the secondary phase transformation in tailing sand

2) At present, the research on the stability of tailings is mainly focus on the macro scale and most of the research is only considering the influence of geological forces, mainly represented by earthquakes. There is a lack of research on the key mechanisms of the permeability, void content, water content, etc in the tailings sand. Therefore, it is necessary to study the correlation between internal factors and external factors of tailing sand, investigate the influence of external forces represented by earthquake on various internal elements, as well as the correlation degree between different elements, so as to build the connection of mechanical properties in macro and micro states.

3) The stacking and disposal of tailings in mining enterprises is only a temporary measure. limited by the development of technology, the secondary extraction technology resources from tailings cannot be qualitatively changed in a short time. Consequently, it is necessary to extend the mind of using mine residues both on the supply side and on the demand side. There is a strong demand for materials in road construction. It is meaningful to further explore the use of tailing sand as roadbed filling in order to achieve economic and social benefits while solving the problem of unhealthy and danger tailing reservoirs.

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