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Study on mechanical characteristics of composite alkali-activated materials-stabilized gold tailings under direct shear

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Abstract:

In this study, the traditional industrial waste residue and some alkaline activators were mixed to prepare a new composite alkali-activated materials (CAAMs), which was used to stabilize gold mine tailings (GMTs). Due to emissions of greenhouse gases and solid dust, alkali-activated materials have been widely used to replace Portland cement to solidify geotechnical materials to enhance their mechanical properties. Different admixture of CAAMs (i.e., 0, 3, 5, 8%) and gold mine tailings were prepared, and the samples were cured in saturated water and under no air conditions. In order to investigate the mechanical characteristics of CAAMs-stabilized GMTs, laboratory direct shear tests were carried out on samples after curing them for 3, 7, 14 and 28 days, respectively. The test results showed that as the curing periods increased, the brittleness of the samples increased, and the stress-displacement curves for all the cured specimens changed from plateau-type to peak-type curves. The curing periods and the content of CAAMs are both beneficial for enhancing the shear strength of CAAMs-stabilized GMTs samples, but the increase rate decreased as the vertical confining pressure increased. Furthermore, the influence of CAAMs content on shear strength increment was larger than that of curing periods. An exponential growth model could be well used to describe the change of shear strength with the curing periods at different vertical stresses.

Key words: Gold mine tailings; Compound alkali-activated materials; Curing periods; Shear strength; Direct shear test

1. Introduction

Portland cement has been widely used to stabilize geotechnical materials and to increase their strength (Lee et al. 2005; Moon et al. 2009; Faramarzi et al. 2016; Pu et al. 2019). The production of Portland cement consists mainly of firing and mixed grinding, which consumes a lot of mineral resources, fuel and electric energy. More importantly, the consumed resources and energy cause cement production to release a large amount of dust, greenhouse gases, and harmful gases. Incalculable damage has been done to nature and the environment by this production. In 2009 (Ke et al. 2013; Andrew 2018), cement production emitted 1.6 billion tons of CO₂, 20 million tons of dust, and millions of tons of sulfide and nitrogen compounds, which directly led to continuous haze emission, room temperature rise and acid rain corrosion. However, with the rapid development of industrialization and urbanization all over the world, a large amount of construction materials need to be invested in infrastructure construction. The demand for cement that is one of the important materials for infrastructure construction has always been high (Scrivener et al. 2018; Naqi and Jang 2019). In recent years, alkali-activated cementitious materials have been proposed as a new curing agent, which effectively uses materials with volcanic ash properties or potential hydraulic properties (Contrafatto 2017) and alkaline activator (catalyst) (Rodriguez et al. 2013) to prepare composite alkali-activated materials. They have good physical and mechanical properties. In addition, their hydration fast hardness, corrosion resistance, freeze-thaw resistance and thermal stability are also excellent. Therefore, alkali-activated materials instead of Portland cement have been widely applied to solidification in the field of geotechnical engineering.

Mining industries around the world generate huge amounts of residues and tailings. Mine tailings are finely ground geotechnical materials after the valuable minerals and metals extraction operations (Zhang et al. 2020). Due to high cost for migration, the main treatment method of tailings is in-situ storage behind tailings dams, which requires adequate site selection (Li et al. 2020). With economic development for ore and metal demand and land use restrictions, it is necessary to build more large tailings dams to store more tailings. Tailings contain complex mineral components. If the tailings dam breaks, it will cause serious pollution to the environment and may cause grave loss of people's lives and property (Kossoff et al. 2014). On April 30th, 2006, a destruction occurred in a gold mine tailings reservoir in Shanxi province, northwest China, causing 17 deaths, 2 people missing and 5 injuries, as well as 76 houses destroyed and flooded (Ju et al. 2012). On January 25th 2019, the structure damming a pond containing mine tailings break down at Brumadinho City, Brazil. About 11.7 million m³ of a tailings-mud mixture was released from the dam, resulting in damage 300 km along the Paraopeba River toward the São Francisco River (Owen et al. 2020).

Many studies have been conducted on the impact of different curing agents on enhancement of the stability

and mechanical properties of geotechnical materials. Curing agents mainly include cement (Qiao et al. 2007), lime (Boardman et al. 2001), and polymers (Li et al. 2020) and so on. However, these have certain limitations for improving the properties of tailings. In most cases, the tailings materials are substituted as river sand to be stabilized by curing agents, which are used as the subbase. That is construction component for engineering purposes of mining filling (Chu et al. 2018), subgrade (Yin et al. 2012), wall (Ahn et al. 2011). Few researches focus on the influence of curing agents on mechanical properties of tailings with respect to tailings dam stability. Thus, it is urgent to study the mechanical properties of CAAMs-stabilized tailings, which is not only friendly to the environment, but also can consider the feasibility of replacing cement-based curing agents to improve the safety and stability of tailings dams from the perspective of economy.

The safety of tailings dams and the economic requirements of mining enterprises are both considerable. This paper studies the mechanical properties of CAAMs with different content as curing agents to stabilize GMTs for preliminary exploration. To study the role of the CAAMs content and curing periods in supplying additional shear strength, laboratory quick direct shear tests were conducted on a mixture of CAAMs and GMTs at various CAAMs contents and curing periods. Moreover, CAAMs-stabilized tailings can potentially be extended to other industrial applications. The obtained test results can provide theoretical support for the application of CAAMs to enhance the stability of tailings dams.

2. Materials and methods

2.1 Materials

2.1.1 Tailings materials

The gold mine tailings used in this study were obtained from Longnan Gold Mine in Gansu province, China. The dry beach surface of the tailings dam is shown in Fig. 1. The color of the raw tailings is charcoal grey with a little particle aggregation in water and mainly fine particles. Uniformity coefficient C_u and Curvature coefficient C_c are 10.01 and 1.23 respectively. The GMTs have a poor gradation according to the Unified Soil Classification System (USCS) (Stevens 1982), with a grain-size distribution curve shown in Fig. 2. The average grain size is 0.015mm. The specific gravity of the gold mine tailings is 2.77. Its initial water content is 15.9%.

Fig. 1. Longnan gold mine tailings dam and its dry beach

Fig. 2. Grain size distribution of the tailings materials used

An X-ray diffractometer (XRD) (Panakot Aeris, Netherlands) was used to analyze the mineralogy of the gold mine tailings using a quantitative Rietveld XRD method (Scrivener et al. 2004). The highest characteristic peak in the mineral composition of gold mine tailings is quartz, and the main mineral components are quartz and illite, with a combined content of nearly 90%, which plays a leading role in the strength of tailings. The gold mine tailings also contains a small amount of clinochlorite, calcite and dolomite. The mineralogical composition is shown in Fig. 3. According to the scanning electronic microscope (SEM) analysis test method (Kang et al. 2017), the shape topography of gold mine tailings particles was determined by SEM at magnifications of 800 and 2000 times. Fig. 4 shows the SEM spectrum of tailings, indicating that the gold tailings are the granule materials with a random shape. The surface of some particles is uneven and flaky, and there is plenty of debris in the pores between the particles.

Fig. 3. X-ray diffraction patterns and mineralogical compositions of gold mine tailings

Fig. 4. SEM spectrum of gold mine tailing particles

2.1.2 Compound alkali-activated materials

CAAMs were made up of ground granulated blastfurnace slag (GGBS, S95 mineral powder), fly ash (FA, low calcium, particle size $< 45 \mu\text{m}$ accounted for 80%), calcium carbide residue (CCR, particle size $< 75 \mu\text{m}$ accounted for 60%), metakaolin (MK, light pink powder), sodium hydroxide (SH, NaOH, superior grade pure, glass bead-like solid particles) and plaster gypsum (PG, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, light grey powder), with mineral components images as shown in Fig. 5. It is worth noting that all the components of the CAAMs are acquired from widespread mines and industrial markets. An X-ray fluorescence spectrometry (XRF) (Shimadzu, Japan) was used to analyze the chemical composition of the CAAMs. The compositions are summarized in Table 1.

Fig. 5. Diagram of mineral components for CAAMs

Table 1 Chemical compositions of CAAMs tested.

Major oxides (wt.%)	GGBS	FA	CCR	MK	SH	PG
SiO ₂	30.8	49.5	2.8	52.2	-	-
Al ₂ O ₃	14.8	35.0	2.2	44.0	-	-
CaO	41.1	4.8	68.9	0.3	-	41.2
Fe ₂ O ₃	0.3	4.7	0.2	0.7	-	-
MgO	8.5	0.5	0.1	0.3	-	-
K ₂ O	0.5	1.3	0.2	0.7	-	-
Na ₂ O	-	-	0.1	0.2	99.0	-
SO ₃	2.1	0.8	0.8	0.3	-	58.8

2.2 Methods

2.2.1 Stabilized sample preparation

According to particle size and the Chinese standard for soil direct shear test method (GB/T50123, 1999), samples for the direct shear tests are in the shape of a circular disc with 61.8 mm in diameter and 20 mm in thickness. The procedures for the stabilized sample preparation are as follows:

(1) Preparation of raw materials, gold mine tailings and CAAMs are dry, as shown in Fig. 6 (1). So as to mix the raw materials uniformly and prevent the moisture from overflowing during the compression of the sample, samples were prepared with a moisture content above the plastic limit and below the liquid limit of gold tailings, and the water content of the sample is set to 20 %.

(2) Preparation of mixture. According to the targeted CAAMs content, the corresponding gold mine tailings, CAAMs and needed water were weighed. The raw materials were thoroughly stirred and mixed to a uniform sample, and then the required water was added for further stirring together to prevent excessive local CAAMs in the sample from causing faster hydration resulting in uneven strength of the sample. The obtained mixture prepared for the experiment is shown in Fig. 6 (2).

(3) Samples maintenance. In accordance with the compaction state of the gold mine tailings, the initial dry density of samples is set to 1.5g/cm³. The mixture is carefully added to a standard direct shear sampler to

ensure that each sample has the same quality. The compressed samples with the cutting ring were removed from the sampler, and each sample is separated by a glass sheet, as shown in Fig. 6 (3).

(4) Sample curing. Finally, in order to prevent the sample from breaking down easily in the water, the samples were cured at room temperature (25° C) and 90% humidity for one day. Then, all the samples were cured by immersion in water to simulate the curing environment in saturated state for tailings, as shown in Fig. 6 (4).

Fig. 6. Sample preparation procedures. (1) Preparation of raw materials; (2) Mixture preparation; (3) Sample maintenance; (4) Curing samples under water

2.2.2 Test apparatus and procedure

According to ASTM, D. 3080-04 (2004), the direct shear test was carried out on stabilized sample. A typical strain-controlled direct shear apparatus produced by Nanjing Soil Instrument Factory was used for this study. Fig.7 shows a photograph and a schematic of the apparatus. Before the shear testing, the sample should be installed in the shear box immediately when was removed from the water. The shear rate of tests was controlled at 0.8 mm/min, with a maximum shear displacement of 8 mm. In order to quantify the effect of CAAMs content and curing period on the mechanical properties of the stabilized gold mine tailings, all the shear tests were conducted under the same conditions. The initial normal stresses in this test are 50 kPa, 100 kPa, 200 kPa, and 300 kPa respectively based on the standard for soil test methods. Concurrently, a group of four specimens under the same curing period were sheared synchronously on direct shear cell so minimize the impact of curing time on strength. For comparison, tests on the saturated gold mine tailings samples without the addition of CAAMs were subjected to shear under different vertical pressures.

Fig. 7. (a) Photograph of direct shear apparatus; (b) Diagrammatic drawing of strain-controlled direct shear apparatus;

According to the ratio of curing agent and soil designed by Chen (2006) and Sukontasukkul (2012), the proportion of the CAAMs and gold mine tailings is expressed by the mixture for weight ratio of dry tailings (S), CAAMs (C) , and water (W). CAAMs content (C_w) is defined as the ratio of the mass of CAAMs to the that of tailings (m_C/m_S). Moisture content (A_w) is defined as the ratio of the mass of water to the sum of the mass of CAAMs and gold mine tailings ($m_w/(m_C+m_S)$). For the convenience of narrative, the samples are numbered in GTAAx-y format, wherein, GTAA represents gold tailings stabilized by composite alkali-activated materials. x is the content of CAAMs added (e.g. 5%); y is the curing period (e.g. 7 days).

According to the shear force measured in the shearing tests, the shear stress on the shear surface can be calculated considering the continuous reduction of the shear area. Generally speaking, the direct shear test is on the basis of the hypothesis that the stress distribution in the sample is uniform when a soil sample with a certain thickness is subjected to shear at plane strain. Therefore, the shear stress along the shear failure surface can be calculated using the following Eq.(1), which is obtained from the displacement parameters recorded by the movement of the shear box.

$$\tau = \frac{2T}{d[\cos^{-1}(s/d).d - s]} \quad (1)$$

Where T is the shear force applied to the shear box; d is the diameter of the sample, $d = 61.8\text{mm}$; s is the shear displacement; when $s=0$, the shear surface area is 30cm^2 , it is the initial cross-sectional area of the sample; when $s=8\text{ mm}$, it is the final value of the shear displacement, and the actual shear surface area is 25.05 cm^2 .

3. Results and analysis

It is known from the stress-displacement relationship of the cured samples that there are mainly two types of relationship curves. One is that the shear stress gradually increases with the horizontal displacement, and the ultimate shear stress is used as the shear strength, a plateau-type curve. The other is a typical relationship curve with peak value, and the peak shear stress is used as the shear strength. For all the same specimens, the cohesive force and the internal friction angle are calculated using the shear stress at four different vertical pressures mentioned above, according to the Mohr-Coulomb strength criterion. The results

of each test are summarized in Table 1.

Table 1 Direct shear test results for CAAMs-stabilized gold mine tailings samples

Sample ID	$C_w(\%)$	$A_w(\%)$	Curing period (d)	τ_{ult} (kPa)				c (kPa)	ϕ (°)
				$\sigma=50$ kPa	$\sigma=100$ kPa	$\sigma=200$ kPa	$\sigma=300$ kPa		
GTAA0-0	0	15	0	25.45	60.05	118.74	154.98	5.59	25.22
GTAA3-3	3	15	3	27.55	85.95	130.87	180.18	12.66	26.34
GTAA3-7	3	15	7	29.56	90.33	137.14	201.38	16.68	29.77
GTAA3-14	3	15	14	31.63	92.88	140.90	215.79	21.36	31.84
GTAA3-28	3	15	28	34.66	98.96	160.83	229.42	22.48	32.94
GTAA5-7	5	15	7	75.09	104.12	158.85	245.18	36.93	31.59
GTAA5-28	5	15	28	89.37	121.15	189.71	257.27	54.81	33.82
GTAA8-7	8	15	7	130.13	176.86	226.68	363.32	79.86	37.01
GTAA8-28	8	15	28	179.33	219.35	304.24	387.94	136.69	39.93

3.1 Influence of curing duration on shear stress-displacement responses

Fig. 8 shows the stress-displacement curve of the tested samples under different curing periods when the content of CAAMs is 3%. It is apparent that the stress-displacement response curve for the cured tailings specimens under different curing periods has changed significantly. Under all vertical pressures, the shear stresses of all samples without maintenance have been increasing with the horizontal displacement, which the stress-displacement curves belong to the platform type without a peak value. Therefore, in this case, the shear stress corresponding to the maximum displacement (of = 8mm) is determined as shear strength. Shear strength and initial elastic modulus of all stabilized samples increase with curing periods. Under the vertical pressure of 50kPa, the shear stress of all specimens increases with the increase of curing time at the same shear displacement. Except for samples without curing, the stress-displacement responses of all other samples are peak-type. The shear stress reaches the peak, and then reduces in magnitude of stress and exhibits a reduction in strength, that is, residual strength (Zhao et al. 2017; Xu et al. 2018), remaining a stable state at a large deformation. Under the vertical pressure of 100kPa, for all the cured samples, the peak-type stress-displacement response is more significant, and their residual strength is gradually close to the shear strength of the uncured sample at large deformation. The main reason is that after the peak, the occlusal function is gradually broken until the failure of the sample is completed. Its structure is completely loosened into a friction flow body with constant strength, which a continuous shear deformation with a constant volume occurs under the shear stress equivalent to the residual strength. Under the vertical pressure of 200 kPa, there is an obvious peak-type stress-displacement relationship curve for the sample at the curing period of 28 days. This relationship weakens under other curing periods. Under the vertical pressure of 300 kPa, only the stress-displacement response for the sample at the curing period of 28 days is peak-type, the ultimate shear strength of a plateau curve can be obtained for the other samples.

Based on the above analysis, the curing period has a beneficial impact on the shear strength of stabilized tailings samples. The horizontal displacement corresponding to the peak shear stress decreases with the curing period, indicating that the water curing makes the sample more brittle, and the hydration products produced strengthen the bite between tailings particles during the curing process. It can also be seen from the change of the cohesion in Table 1. The increase in curing periods makes the loose tailings particles dense, and the stress-displacement relationship curve changes from plateau-type to peak-type. This result also appears in the solidification of other soil materials (Polettini et al. 2004; Wang et al. 2020). Furthermore, as the vertical pressure increases, the dominance of curing period on the stress-displacement response weakens, and the vertical pressure becomes the main factor to dominate the mechanical behavior of the stabilized sample.

Fig. 8. Stress-displacement curves for stabilized samples after five different curing periods: (a) vertical pressure of 50 kPa; (b) vertical pressure of 100 kPa; (c) vertical pressure of 200 kPa; (d) vertical pressure of 300 kPa.

In order to quantitatively describe the effect of curing time on the shear strength of solidified gold tailings, an enhanced shear strength ratio is proposed, which is defined as the following Eq. (2):

$$I_e = \frac{\tau_{ult} - \tau_0}{\tau_0} \quad (2)$$

Where I_e is the enhanced shear strength ratio, which delegates the ratio of shear strength reinforcement for the stabilized gold mine tailings caused by the curing periods; τ_{ult} is the shear strength of the stabilized

227 samples; τ_0 is the ultimate shear strength of the basal level sample, and gold tailings samples without
 228 CAAMs and not cured are selected here in this case.

229 For the samples with 3% CAAMs content, the variations of I_e value of the stabilized tailings samples
 230 under the four vertical pressures are shown in Fig. 9. The shear strength of all samples increases with the
 231 curing period increasing under different vertical pressures, whereas, the shear strength reinforcement caused
 232 by the curing period is the highest under vertical pressure of 100 kPa. For instance, the shear strength ratio
 233 I_e value is approximately 43.1%, 50.4%, 54.7% and 64.8% at curing period of 3, 7, 14 and 28 days,
 234 respectively. The maximum strength increment of the samples is about 35% at all curing periods under other
 235 vertical pressures, and I_e shows a linear growth with curing period. This may be due to the fact that the
 236 hydration products generated during the curing increase the friction contact and interlocking effect between
 237 particles under a vertical pressure. With the increase of vertical pressure (from 100 kPa to 300 kPa), the friction
 238 contact and interlocking effect on the shear strength of the specimen are weakened. Under the vertical
 239 pressures of 200 kPa and 300 kPa, the growths of I_e are close to each other, approaching that in the case of
 240 50 kPa. It shows that the maximum enhancement effect of curing period on shear strength is at a vertical
 241 confining pressure in the range from 50 kPa to 200 kPa. In addition, it can also be observed that the strain
 242 softening is more obvious under the vertical pressure of 100 kPa than that under other vertical pressures at
 243 different curing periods. (see Fig. 8).

244
 245 **Fig. 9.** Enhanced shear strength ratio of the different stabilized samples at four different vertical stresses

246 **3.2 Influence of CAAMs content on shear stress-displacement responses**

247 The shear stress of tailings was influenced by the combined effect of curing period and CAAMs content

(C_w). The influence of C_w on stress-displacement response of CAAMs-stabilized GMTs under different vertical pressures is illustrated in Fig. 10. For the samples subjected to the same curing periods, the shear strength increases with the increase in the C_w . For instance, under the vertical pressure of 100 kPa, the shear strength of GTAA3-7, GTAA5-7 and GTAA8-7 are 90.33 kPa, 104.12 kPa and 176.86 kPa, which are approximately 50.4%, 73.4% and 194.5% higher than that of the sample without CAAMs (GTAA0-0). The initial elastic modulus increases with the increase of CAAMs content. The stress-displacement curve gradually changes from plateau-type to peak-type curve with the change becoming more obvious with the increase of C_w . It indicates that the brittleness of the sample becomes stronger with the increase of CAAMs content. For the stabilized samples with 3% CAAMs content, the residual stresses of samples for the cured periods of 7 and 28 days are close to each other at the various vertical pressures. Under the vertical pressure of 50kPa, for the samples with 5% and 8% CAAMs content, there is a significant difference in the residual strength under different curing periods. Under the vertical pressure of 100 kPa, the residual strength of the sample with only 8% CAAMs content varies greatly under different curing periods. The residual strength of all samples with the same CAAMs content is similar under the vertical pressure of 300 kPa. The influence of curing period on the residual strength of the sample is weakened with the increase of pressure, which is consistent with the conclusion above. The residual strength of the sample is mainly related to the sliding friction of the particles on the shear surface, so the increase of external pressure will lead to the same arrangement between the particles of the hydration products formed in the curing process. This is similar to findings in other types of geotechnical materials (Choobbasti et al. 2019; Al-Bared et al. 2019).

Fig. 10. Stress-displacement curves for stabilized samples with different CAAMs content: (a) vertical pressure of 50 kPa; (b) vertical pressure of 100 kPa; (c) vertical pressure of 200 kPa; (d) vertical pressure of 300 kPa.

Fig. 11 shows the enhanced shear strength ratio of the stabilized-GMTs with different C_w under the four vertical pressures. The shear strength ratio decreases with the increase of vertical pressure except for the sample with 3% CAAMs, as been explained previously. When the curing period is 28 days, the shear strength ratio of the sample is approximately equal under the vertical pressure of 200 kPa and 300 kPa. It indicates that with the increase of C_w and curing period, the combined reinforcement influence of CAAMs content and curing period reduces on carrying load under a high vertical confining pressure. The shear strength increases with the increase of C_w and curing period, but the increase rate decreases with the increase of the vertical pressure. The reinforcement difference between the two is mainly induced by the enhancement of the interlocking effect and friction of the material particles on the increase of the shear strength.

Fig. 11. Enhanced shear strength ratio with C_w variation; (a) curing period of 7 days; (b) curing period of 28 days

Different degrees of strain softening (Van et al. 1997; Long et al. 2017) occur in the stabilized tailings samples with different C_w and curing periods under direct shear conditions. Generally, the reduction in strength of strain-softening geotechnical materials is described by the brittleness index (Munoz et al. 2016; Liu et al. 2021). It reflects the shearing properties and the possibility of shear slip failure for a soil. The brittleness index I_b can be defined as:

$$I_b = \frac{\sigma_f - \sigma_r}{\sigma_f} \quad (3)$$

Where I_b is brittleness index. σ_f is peak shear strength; σ_r is residual shear strength.

According to Eq. (3), the brittleness index ranges from 0 to 1. The greater the brittleness index, the more serious the shear strength reduction. For materials with a high brittleness index, strain softening will lead to

progressive large deformation. However, the initial strain softening may not result in large deformation for materials with a low brittleness index. Fig. 12 presents the variation of brittleness index with vertical applied stress. The brittleness index increases with the increase of curing period and CAAMs content. More obviously, the C_w has a more significant influence on the increase of brittleness index, indicating that the gold mine tailings become a high brittleness material with the increasing in C_w . It also indirectly demonstrates that although the increase of C_w increases the shear strength of the CAAMs-stabilized GMTs sample, large deformation will produce immediately once the failure occurs. The brittleness indexes of all samples increase first and then decrease with the vertical pressure. The brittleness index of the samples is largest under the vertical pressure of 100 kPa.

Fig. 12. Brittleness index with vertical confining stress variation

3.3 Influence of curing period and CAAMs content on strength parameters of stabilized-GMTs

According to the ultimate shear strength of GTAA specimens with similar conditions (curing period, C_w) under different vertical pressures, the cohesive force and internal friction angle were calculated using the Mohr-Coulomb failure criterion. The strength parameters of all specimens are shown in Table 1. The effect of curing period on cohesive force and internal friction angle of the stabilized-GMTs is shown in Fig. 13(a). The cohesive strength and internal friction angle increase rapidly at first and then slowly with the curing period. During the curing period from the beginning to 14 days, the cohesion strength increases from 6 kPa to 21 kPa, and the internal friction angle increases from 25° to 32° , whereas the cohesive strength is around 21-22 kPa

309 and the internal friction angles are in the range of 32° and 33° between 14 and 28 days of curing. It indicates
 310 that the influence of curing period on internal friction angle is significant in the early stage of curing, and its
 311 influence is gradually negligible in the later stage. It can be predicted that the curing is completed around 28
 312 days.

313 Fig. 13(b) and (c) show the relationship between the shear strength parameters and CAAMs content. The
 314 cohesive strength increases with the increase of C_w in the stabilized-GMTs samples. The cohesive strength
 315 increases slowly with the C_w when the CAAMs content is less than 3%, but it increases significantly for
 316 CAAMs content exceeding 3%, no matter whether in the early or late curing period. The internal friction angle
 317 increases more linearly with the content of CAAMs than the cohesion. More importantly, as the CAAMs
 318 content increases from 0 to 8%, the increase of the hydration products in the samples directly leads to more
 319 bond contact between tailings particles. Particularly, the specimen obtained a more stable structure with higher
 320 shear strength.

321

322

323

Fig .13. Effect of curing period and C_w on strength parameters: (a) curing period (3% CAAMs content); (b) C_w (curing period of 7 days); (c) C_w (curing period of 28 days).

4. Discussion

4.1 Relative enhancement of the shear strength for CAAMs-stabilized GMTs

The increase of curing period and CAAMs content improves the shear strength of stabilized-gold tailings samples as mentioned above. In order to study the enhancement effect by CAAMs content and curing period in aspects of shear strength, a relative enhanced shear strength and a relative increase rate are adopted and expressed as follows:

$$I_r = \frac{\tau_{ult,GATT} - \tau_{ult}}{\tau_{ult,GATT} - \tau_0} \quad (4)$$

Where I_r is the relative enhanced shear strength of stabilized GMTs; $\tau_{ult,GATT}$ is the shear strength of stabilized GMTs samples, and the results of GATT3-28 and GTAA8-7 are selected as baseline for studying the enhancement effect of curing period and CAAMs content, respectively; τ_{ult} is the ultimate shear strength of a sample containing 3% CAAMs or a sample cured for 7 days; τ_0 is the shear strength of the sample without CAAMs added and not cured, and GTAA0-0 is selected here. The denominator, $\tau_{ult,GATT} - \tau_0$, expresses the total enhancement shear strength provided by CAAMs content and curing period, and the numerator, $\tau_{ult,GATT} - \tau_{ult}$, expresses the enhancement provided by CAAMs content or curing period in Eq. (4).

$$I_p = \frac{C_{GTAA} - C}{C_{GTAA}} \quad (5)$$

Where I_p is the relative increase rate; C_{GTAA} is the curing period of GATT3-28 or the CAAMs content

344 of GATT8-7; C is the curing period or CAAMs content.

345 It can be seen from Fig. 14 that I_r increases with the increase of I_p , that is, with the increase in curing
 346 period or CAAMs content, and the enhancement increase of the shear strength provided by the content of
 347 CAAMs is more than that provided by the increase of curing period at the various vertical pressures. Hence,
 348 the effect of curing period on the shear strength of tailings samples is less than that of CAAMs content,
 349 probably due to the stronger compression properties for the sample with a higher content of CAAMs.
 350 Furthermore, the increase of cohesive force caused by CAAMs content is also greater than that caused by
 351 curing period.

352

353 **Fig. 14.** Effect of the relative increase rate of curing period or C_w on variations of the shear strength of stabilized

354 GMTs at different vertical pressures: (a) 50 kPa; (b) 100 kPa; (c) 200 kPa; (d) 300 kPa.

4.2 Enhancement effect of curing period or CAAMs content on the shear strength

As shown in Table 1, for the CAAMs-stabilized GMTs, the combined action of CAAMs content and curing period can remarkably improve the shear strength of tailings. On the basis of the experimental results, the enhancement of shear strength for the stabilized GMTs can be quantified by curing period and CAMMs content. Obviously, the strength of stabilized GMTs samples with a certain content of CAAMs increased during a certain curing period, but beyond a certain curing time, the strength of the sample did not change. Based on this, the relationship between shear strength and curing period can be established:

$$\tau_{ult} = b + c \cdot P_0 \cdot n^d \quad (6)$$

Where τ_{ult} is the ultimate shear strength of the stabilized samples; b , c and n are the test constants for tailings materials; P_0 is the atmospheric pressure; d is the curing period.

Eq. (6) was used to fit the relationship between maximum shear stress and curing period under different vertical confining pressures. The test constants are shown in Table 2.

Table 2 Fitted test constants for tailings materials

Vertical pressure (kPa)	b	c	n
50 kPa	36.61	-0.11	0.94
100 kPa	103.25	-0.36	0.90
200 kPa	167.37	-0.46	0.95
300 kPa	236.01	-0.75	0.93

Fig. 15 shows the influence of curing period on shear strength under various vertical pressures, from which we can see that the change of shear strength with curing period are in good agreement with the fitting curves. Thus, Eq. (6) can be used reliably to describe the relationship between shear strength and curing period. With the increase of curing period, the shear strength is increased exponentially.

The test constant b refers to the shear strength when the curing is complete, when the hydration reaction ends, and the interlocking effect between tailings particles is enhanced to the maximum. The test constant c decreases with the increase of the vertical pressure, reflecting the linear change of shear strength, whereas, the constant n varies little with the vertical pressure, reflecting the nonlinear growth of shear strength. Therefore, the nonlinear behavior of the shear strength for the CAAMs-stabilized GMTs sample has no obvious difference under various vertical pressures, but the degree of change increases with the increase of vertical pressures.

Fig .15. Effect of curing period on the shear strength of stabilized GMTs

Fig. 16 presents the relationship between the content of CAAMs and the increment of shear strength. The values of shear strength increment increase exponentially with the increase in CAAMs content, and the increase rate also increases. Moreover, the linear growth behavior under the curing period of 28 days weakens the enhancement effect of CAAMs content on the shear strength. However, it should be noted that although the increase in the content of curing agent increases the hydration reaction and enhances the cementation between the particles, the enhanced shear strength dose not exceed that of the sample only containing curing agent. Therefore, this property is limited to the change of strength for the stabilized tailings sample within a certain content of CAAMs at a certain curing period. A similar explanation is also given in relevant literature (Alam et al. 2019; Chen et al. 2020).

Fig .16. Effect of CAAMs content on the shear strength increment of stabilized GMTs: (a) the curing period of 7 days; (b) the curing period of 28 days.

5. Conclusions

Based on the test results presented in this paper, we have derived the following conclusions:

(1) The stress-strain characteristics of uncured gold mine tailings are strain hardening under various vertical confining pressures. The stress-strain relationship of the stabilized samples gradually changes from strain hardening to strain softening as the curing period increases, and this change is more significant under low vertical pressure (100 kPa). Under high vertical pressures (300 kPa), strain softening occurs only when the curing period reaches 28 days. It indicates that the external load plays an important role in controlling the stress-strain relationship.

(2) The enhancement effect of curing period on shear strength for the stabilized tailings is the highest under the vertical pressure of 100 kPa. When the content of CAAMs is 3%, the optimal enhancement effect for the shear strength of tailings sample is at a vertical confining pressure in the range from 50 kPa to 200 kPa. The brittleness index of the samples is more sensitive to the content of CAAMs, and increasing the content of CAAMs makes the sample more brittle after a certain period of curing. All stabilized samples have the strongest brittleness under the vertical pressure of 100 kPa.

(3) The effect of curing period on shear strength parameters increases rapidly at first and then slowly. The difference is particularly obvious between curing period of 14 days and 14 to 28 days. The cohesive strength increases slowly and then sharply with the CAAMs content. The internal friction angle increases more linearly than the cohesion with the increase of CAAMs content.

(4) The increase of curing period and CAAMs content promotes the hydration reaction between tailings particles and CAAMs to form more bonding and interlocking, so as to improve the shear strength of stabilized-gold mine tailings samples. To obtain the shear strength of stabilized gold mine tailings with a certain content of CAAMs at various vertical pressures, an exponential model is established. The exponential model can well predict the shear strength of the stabilized tailings sample when the hydration reaction is completed. The shear strength increases exponentially with the content of CAAMs, and the increase rate also increases.

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