Study on the Size Effect of high-water materials

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Abstract. The use of high-water materials in mining and filling is conducive to stope stress control and goaf stability. Since the filling body is huge, the size effect tends to affect the mechanical and deformation characteristics to some extent. Therefore, study in this respect is beneficial to engineering design and construction. To study the size effect of the high-water materials with different water-cement ratios, this paper first carries out experimental analysis of the size effect of high-water materials with different aspect ratios and explores the influence of aspect ratio changes on their mechanical characteristics; this paper then studies the size effect of high-water materials while taking the aspect ratio as 2:1. The test results are as follows: (1) the strength of high-water materials decreases first and then decreases with the increase of aspect ratio; the strength reaches the minimum with a low degree of discretization when the ratio is 2. (2) With the increase of aspect ratio, the plasticity of high-water materials decreases, while its modulus increases continuously; the strain corresponding to the peak strength decreases, and the residual peak ratio decreases continuously, so the specimen is more prone to instability. (3) Splitting failure is the failure mode of high-water materials, which does not change with size; based on Von. Mises theorem, the consistency of theoretical and experimental results is proved. (4) The strength of the high-water material decreases with the increase of size; the size effect becomes more significant as the water-cement ratio increases.

1. Introduction

Due to the difference in the shape and size of particles as well as internal arrangement of the material during formation, many voids and micro-defects tend to exist and distribute randomly inside the material, leading to extremely complicated mechanical properties. The property of changing mechanical parameters with the change of size is called the size effect[1]. Research on the size effect of rock and soil has been highlighted by many scholars and is of great significance to engineering practice. Experimental research on the size effect of different kinds of geotechnical materials has delivered fruitful results. Hudson et al. carried out uniaxial compression tests on marble samples with different aspect ratios, showing that the compressive strength of rock varies with the aspect ratio[2]. Rilem pointed out that the compressive strength of concrete specimens increases with the decrease of its aspect ratio[3]. Shengqi Yang et al. concluded that the influence of the length-diameter ratio on the strength and fracture of rock, and put forward the theoretical model of the size effect of marble material based on the uniaxial compression test[4].

As the economy develops, the demand for resources is growing every day. Gradually exhausted resource on the ground leads people to the mine deeper underground. As for the goaf area, stress
control and stability are the main factors restricting its development, and filling and mining can be of some help. The filling body in the goaf is large, and its mechanics and deformation characteristics are influenced by the size effect to some extent. Therefore, it is necessary to study the size effect of the filling material. Lijie Guo put forward the size effect conversion factor of the filling body of a certain size based on the preliminary study on the size effect of the strength of the waste rock tailings consolidated backfill[5]. Deqing Gan and Liang Han tested the size effect of compressive strength of the cemented backfill and studied the size effect of the full tailings cemented filling material[6]. Miaofei Xu et al. also studied the size effect of the strength of the full tailings cemented backfill[7].

High-water material, a kind of cement-based cementing material with high a water-cement ratio, has the advantages of high water, rapid setting, easy pumping, micro-expansion and high early strength. Therefore, it is widely used in filling and mining[8]. However, current research on the size effect of the filling material mainly focuses on the tailings cement filling material, but little on the high-water filling material. In order to fill the gap, this paper first conducts experimental analysis of the size effect of high-water materials with different aspect ratios and explores the influence of aspect ratio change on their mechanical characteristics; this paper then studies the size effect of high-water materials of different volumes using the appropriate aspect ratio. The results are expected to contribute to engineering design and construction.

2. Analysis of the size effect of high-water materials with different aspect ratios

2.1. Design of aspect ratio test

High-water materials mainly consist of four materials, namely, A, A-A, B, and B-B. A is mainly the sulfoaluminate cement; A-A, the retarder; B, the mixture of lime and gypsum; B-B, the mixture of early strength and suspending agents[9].

The test takes the mass ratio of high-water materials as A: A-A: B: B-B=1: 0.1: 1: 0.04. Five samples are made for each aspect ratio of 1:1 (Φ 50 mm×H 50 mm), 2:1 (Φ 50 mm×H 100 mm), 3:1 (Φ 50 mm×H 150 mm), 4:1 (Φ 50 mm×H 200 mm), 5:1 (Φ 50 mm×H 250 mm), 6:1 (Φ 50 mm×H 300 mm) and 7:1 (Φ 50 mm×H 350 mm), totaling 35 samples, while the water-cement ratio is kept at 4:1.

After de-molding the prepared samples, immerse them in the clean water to prevent them from dehydrating and weathering in the air. The curing temperature is kept at 20±3 °C. For sample preparation and maintenance, see Figure 1. The strength of the standard sample (Φ 50 mm×H 100 mm) is basically stable after 7 days of maintenance[9]. Therefore, this paper takes 7 days as the test age.

![Figure 1. Sample preparation and maintenance flow chart](image)

This paper carries out the unconfined uniaxial compression test using the ETM electromechanical test system of Sichuan University. The loading rate is controlled at 3 mm/min, and the test stops at the occurrence of residual stress or through cracks [10].
2.2. Results analysis

2.2.1 Analysis of mechanical characteristics: The average strength of the specimens with different aspect ratios measured in the unconfined uniaxial compression test are shown in Table 1.

| Aspect ratio | 1:1 | 2:1 | 3:1 | 4:1 | 5:1 | 6:1 | 7:1 |
|--------------|-----|-----|-----|-----|-----|-----|-----|
| Strength (MPa) | 0.95 | 0.92 | 0.96 | 0.96 | 0.95 | 0.94 | 0.93 |

The change of strength with aspect ratio is shown in Figure 2. Max and Min represent the maximum and minimum strength values measured in the test, respectively.

It can be seen from Table 1 and Figure 2 that the average strength of the high-water material decreases first and then decreases with the increase of the aspect ratio. When the aspect ratio is 2, the strength is at its minimum of 0.92 MPa; when the aspect ratio is between 3 and 4, the strength is at its maximum of 0.96 MPa; when the aspect ratio is greater than 4, the compressive strength decreases slowly with the increase of the aspect ratio. The average maximum strength value is only 0.04 MPa higher than the minimum, a variation of only 4.3% of the strength of the standard specimen (Φ 50 mm×H 100 mm), indicating that the change of the aspect ratio has little effect on the average strength value of high-water materials. As the aspect ratio increases, the measured strength values become more unstable, with a maximum fluctuation of 5.4%.

The stress-strain curve of the uniaxial compressive strength at different aspect ratios is shown in Figure 3.

![Stress-strain curve](image)

Figure 3. Stress-strain curves of uniaxial compressive strength under different aspect ratios

It can be seen that high-water materials with different aspect ratios all have the typical characteristic of elastic-plasticity. As the aspect ratio increases, plasticity gradually decreases, while the brittleness increases continuously. In addition, the strain corresponding to the maximum strength gradually reduces, and the characteristic of yielding gradually weakens, thus delivering a step-shaped curve.

When high-water materials are used for mine filling, the filling body tends to reach its bearing limit in many cases and is at a stage of post-peak residual strength under the long-term formation pressure. Under this circumstance, strong plasticity and deformability can meet the requirements for the flexible support of surrounding rock[11]. Greater residual strength leads to stronger plasticity, then the filling material can better in adapting to deformation. This paper sets the residual-peak ratio \( \kappa = \) residual...
strength/peak intensity with an understanding that the larger the residual peak ratio, the better the post-peak bearing capacity. As shown in Figure 4, the residual peak ratio gradually decreases as the aspect ratio increases.

![Figure 4. Trend of residual-peak ratio with aspect ratios](image)

The modulus is the determinant factor of the ability to adapt to the deformation of surrounding rock for high-water materials. As a typical elastoplastic material, the deformation properties of high-water material can be described using tangent modulus $E$ and deformation modulus $E_0$ [12], as shown in Equations (1) and (2):

$$E = \frac{d\sigma}{d\varepsilon} \quad (1)$$

$$E_0 = \frac{0.5\sigma_c}{\varepsilon_{0.5}} \quad (2)$$

In the equations, $\sigma_c$ is the peak strength of the high-water material (MPa); $\varepsilon_{0.5}$ is the strain value corresponding to the elastic phase strength of 0.5 $\sigma_c$ (mm/mm); $E$ is the slope of the elastic phase (the tangent slope corresponding to the intensity value of 0.5$\sigma_c$).

Figure 5 shows the tangential modulus and deformation modulus of high-water materials with different aspect ratios. It can be seen that both modulus increase gradually as the aspect ratio increases. Linear fitting shows that both modulus increase with the aspect ratio.

![Figure 5. Trend diagram of tangent modulus and deformation modulus with aspect ratio](image)

2.2.2 Analysis of failure mode: The failure mode of high-water materials with different aspect ratios is shown in Figure 6.

![Figure 6. Failure modes of high water materials under different aspect ratios](image)
It can be seen from Figure 7 that the failure modes are basically the same, namely, splitting failure: the cracks first appear at the ends, and then gradually develop along the axial direction to the middle of the specimen and to the other end because of the pressure, resulting in the failure of the high-water material specimen. The change of size has little effect on the failure mode.

Figure 7. Failure forms of high-water material

Take the aspect ratio of 2:1 as an example, as shown in Figure 7, the shear failure occurs first on the top of the specimen under the upper pressure. Due to the hoop effect of the machine, obconical shear cracks appear at the top. Since the cone area at the end is under three-dementional compressive stress, it is stronger and is more difficult to break[13]. Under the further action of the pressure, tension cracks caused by extrusion appear in the middle of the specimen, and they expand from the one end to the other along the axis, thus generating macro-cracks, causing splitting damage.

Excessive aspect ratio tends to cause instability during the loading process[14]. The first type of instability is shear instability, as shown in Figure 8(a). It is mainly due to defects caused by residual pores and bubbles during specimen preparation. Since the defected area suffers from concentrated stress, cracks appear in this area first and then extend.

The second type of instability is breaking. There are mainly two cases. First, the whole specimen buckles and breaks under the compressive stress. Second, the specimen is split into several components, which are bent and broken under the eccentric pressure, as shown in Figure 8(b).

Figure 8. Two kinds of instability forms of high water materials

High-water materials used for filling and mining shall have the strength and rigidity as well as the post-peak deformation and bearing capacity in order to meet the bearing and deformation requirements [15]. Test shows that if the aspect ratio of the high-water material is too low, the material has low rigidity, thus leading to huge deformation. When the aspect ratio is too high, the material is poor in post-peak deformation and bearing performance, making it prone to instability. The minimum value is achieved with low degree of discretization when the aspect ratio is 2. Therefore, this paper takes the aspect ratio of 2:1 to study and analyze the size effect of high-water materials with different sizes.

3. Experimental analysis of size effect of high-water materials

3.1. Test design
Prepare A slurry by mixing A and A-A, and prepare B slurry by mixing B and B-B. Prepare high-water filling body by mixing A slurry with B slurry. The mass ratio used in the test is A: A-A: B: B-B=1: 0.1: 1: 0.04. The water-cement ratios are 2:1, 3:1 and 4:1, while the aspect ratio is maintained at 2:1. Five samples are made for each water-cement ratios of Φ 25 mm×H 50 mm, Φ 50 mm×H 100 mm and Φ 75 mm×H 150 mm, totaling 45 samples. After de-molding the prepared samples, completely immersed them in the clean water to prevent them from dehydrating and weathering in the air. The curing temperature is at 20±3 °C, and the test and maintenance methods are the same as above.

3.2. Result analysis

The average strength of specimens measured in the unconfined uniaxial compression test is shown in Table 2.

| Water-cement ratio | D=25mm | D=50mm | D=75mm |
|--------------------|---------|---------|---------|
| 4:1                | 0.97    | 0.84    | 0.76    |
| 3:1                | 1.59    | 1.40    | 1.27    |
| 2:1                | 2.77    | 2.57    | 2.38    |

Take the strength at D=25mm as 100%, and compare it with the strengths at D=50mm and D=75mm, as shown in Figure 9. In this way, the change of the size effect of high-water materials with different water-cement ratios can be obtained.

Figure 9. The change of the size effect of high-water materials with different water-cement ratios.

It can be seen from that as the size increases, the strength of the high-water material gradually decreases. When D increases from 25 mm to 75 mm, the strength of the specimen with a water-cement ratio of 4:1 decreases by 21.6%, that of the specimen with a water-cement ratio of 3:1, 20.1%, and that with a water-cement ratio of 2:1, 14.1%, which indicates that the size effect of the high-water material is positively correlated with the water-cement ratio. As the water-cement ratio increases, the size effect of the high-water material is more significant.

The stress-strain curves of high-water materials with different volumes when the water-cement ratio is 3:1 are shown in Figure 10.

Figure 10. Stress-strain curves of high-water materials with different volumes.

It can be seen that the stress-strain curves share the similar trend. With the increase of size, the peak stress, the peak strain, and ultimate strain decrease gradually, while the elasticity modulus gradually increases.

The failure characteristics of high-water materials with different water-cement ratios when the
water-cement ratio is 3:1 are shown in Figure 11.

The cracks gradually expand to the middle and the other end of the specimen along the axis, thereby causing the specimen failure. The size change of high-water materials has little effect on the failure mode.

4. Analysis of failure mechanism

Von. Mises criterion (isotropic material) and Hill theory criterion (orthotropic material) are mainly used for elastic-plastic materials. The high-water material is an isotropic material with good uniformity, so Von. Mises criterion is adopted here.

Von. Mises criterion is derived from the distortion energy theory in the classical strength theory. It indicates that the reason for the material to reach a dangerous state (fracture or yield) under certain deformation conditions is that the distortion per unit volume exceeds a certain limit, that is, when the second invariant \( J_2 \) of the stress deflection tension at a point inside the object reaches a certain value, this point begins to enter a plastic state[16]. Therefore, in order to prevent the material from entering a dangerous state, the following formula must be met:

\[
\sigma_v = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]} \leq \sigma_s
\]  

where \( \sigma_v \) is Von. Mises equivalent stress, \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the main stress, and \( \sigma_s \) is the critical stress.

According to the generalized Hooke law,

\[
\begin{align*}
\epsilon_1 &= \frac{\sigma_1 - \mu(\sigma_2 + \sigma_3)}{E} \\
\epsilon_2 &= \frac{\sigma_2 - \mu(\sigma_1 + \sigma_3)}{E} \\
\epsilon_3 &= \frac{\sigma_3 - \mu(\sigma_1 + \sigma_2)}{E}
\end{align*}
\]  

When stress concentration is not taken into consideration, axial compression will cause lateral expansion. Due to the end constraint, the specimen will expand laterally and non-uniformly. At this time, the unit will be constrained by the adjacent units, and is pressed in the vertical direction and pulled in the laterally direction, thus forming a three-dimensional stress state, as shown in Figure 12. Adjacent cells at the same radius from the axis on the cross section suffer the same constraints, that is to say, the stress state caused by the compressive stress \( \sigma_0 \) is the same at the same radius. On the same cross section, the closer to the center, the stronger the constraint, the smaller \( \epsilon_2 \) and \( \epsilon_3 \), the smaller \( \sigma_2 \) and \( \sigma_3 \), and the larger \( \sigma_1 \) and \( \epsilon_1 \). According to the Von. Mises criterion, on the same cross section, \( \sigma_1 \) is the same at the same radius; the closer to the center, the larger the \( \sigma_1 \); therefore, it is the axis of the pressed specimen that first enters a plastic state and causes damage.
Figure 12. Force sketch of micro-element of high water content material specimens

The cone area at the ends of the specimen is in the three-directional compression zone, thus having a smaller $\sigma_v$, but the middle of the specimen has a larger $\sigma_v$ under the axial compression and the radial tensile action is larger. Therefore, the axis of the specimen enters a plastic state earlier and is more prone to cracks than the cone area at the ends.

The change of the length has little effect on the stress state on the same cross section. In other words, when the diameter of the specimen is constant, the change of the length has little effect on $\sigma_v$, so it has little effect on the compressive peak stress. Under the same strain condition, larger specimen has larger $\sigma_v$ at the center. Therefore, larger specimen reaches the limit state and fails earlier.

5. Conclusion

Based on the above tests and analysis, this paper draws the following conclusions:

1) the strength of high-water materials decreases first and then decreases with the increase of aspect ratio; the strengthen reaches the minimum with a low degree of discretization when the ratio is 2.

2) With the increase of aspect ratio, the plasticity of high-water materials decreases, while its modulus increases continuously. At the same time, the strain corresponding to the peak strength decreases, and the residual peak ratio decreases continuously, so the specimen is more prone to instability.

3) Splitting failure is the failure mode of high-water materials, which does not change with size. Based on Von. Mises theorem, the consistency of theoretical and experimental results is proved.

4) The strength of the high-water material decreases with the increase of size; the size effect becomes more significant as the water-cement ratio increases.

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