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Experimental Study on Strength Weakening of Gypsum Rock with Effect of Long-Term Overlying Strata Pressure

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Abstract: A long time lag is the main characteristic of gypsum mined gob collapse disasters. With the coring of a gypsum rock specimen from the supporting pillars in gob, which formed over several years, the strength weakening effect of the gypsum rock with long-term overlying strata pressure is revealed by experimentation. The results show that: uniaxial compression stress–strain curves represent major differences in different lateral depths of the same supporting pillar. With the increase in lateral depth, peak strength increases and the corresponding strain decreases, which becomes more obvious as the age increases. As a function of time, peak strength decreases and the corresponding strain increases in the shallow part of the pillar as the age increases. Peak strength fluctuates in the middle part and increases in the deep part; the corresponding strain fluctuates in the middle and deep parts, but demonstrates the opposite changing law. Finally, the reason for the above law was comprehensively and thoroughly researched and demonstrated. The maximum strength weakening rate of gypsum rock in the shallow part of a supporting pillar of 0.5 m depth was 21.06% in the year 1996. The slow strength weakening effect of gypsum rock with long-term overlying strata pressure is the essential reason why gypsum mined gob collapses occur in subsequent years or even decades.

Keywords: gypsum rock; strength weakening; mine gob collapse; uniaxial compressive strength; elastic and plastic

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1. Introduction

According to incomplete statistics, the amount of underground mined gob in metal–non-metal mines is as high as 432 million cubic meters in China, which formed after other mineral resources had been mined. It has become one of the most serious problems in the mining field, both at present and in the future [1]. Gypsum is an indispensable and important mineral resource in the field of civil and construction engineering. At present, underground gypsum mines mainly use the room-pillar and strip mining methods, which have formed a large area of the hanging mine gob. According to statistics, only in Shandong Province, China is the hanging mine gob of a gypsum mine as high as 2.5 million square meters. Gypsum rock pillar is the main supporting structure in gypsum mined gob, and it can remain stable with long-term loading. After several years or even decades, large areas of hanging mine gob may collapse integrally, induced by damage and the sudden failure of the gypsum rock pillar. For example, the Wanzhuang gypsum mine, located in Hubei Province, China, was put into operation in 1996 and closed in 2012, but a large portion of the mine's gob collapse accident occurred in 2015 [2]. Gypsum mine gob collapse accidents display the significant characteristics of the chaining effect and large scale of the space and a long time lag (20 years or even longer).

Aiming at the gypsum mined gob collapse disaster, many scholars have researched the collapse mechanisms and influential factors. In terms of the collapse mechanism, Xu et al. constructed a plastic supporting system of pillar-beam for the gypsum mined gob and analyzed the collapse mechanism by applying mutation theory [3,4]. Xia et al.

constructed a cusp mutation model of a "pillar-roof and protecting layer" support system and studied the mechanism of structural instability, which was combined with nonlinear dynamics [5,6]. Zheng et al. revealed the long-term stability evolution mechanism and damage mode of gypsum mined gob [7,8]. Extensive works have focused on factors influencing gypsum mined gob's collapse. Li et al. analyzed factors influencing gypsum mined gob's collapse systematically [9]. Aiming at water's effect on the stability of gypsum rock, Liu et al. studied the influence of water on the strength weakening mechanism of gypsum rock, from aspects of the water-filled state and brine immersion through designing different experiments [10–12]. Creep is the typical mechanical property of gypsum rock. Liu et al. researched the creep characteristics of gypsum rock and its stability through uniaxial compression experiments and the step loading test [13–15]. A large number of other scholars have also carried out research work on the collapse hazard of gypsum mined gob based on different methods and perspectives [16,17].

Gypsum rock pillars exist in complex geological environments. During the decades from gypsum mined gob formation to collapse, how does the strength of gypsum rock change under the long-term pressure of the overlying strata and the coupling effect with water and disturbance? The clearing strength and weakening mechanism effects of the gypsum rock with long-term overlying strata pressure are the keys to revealing the collapse mechanism of gypsum mined gob and predicting the collapse's lag time. A few scholars have conducted some studies on time's effect on rock strength. Zhou et al. proposed a model of the temporal evolution of rock strength, based on analyzing a large number of experiment results [18,19]. Liu et al. conducted an experiment and simulation study on the time effect of the fracture extension of deeply buried barite in Jinping, Sichuan Province, China [20]. Jin et al. established a rock weathering model considering time and buried depth [21]. Li et al. established a non-probability reliability prediction model based on interval theory for the time-dependent stability of gypsum rock, considering various factors [22,23].

In summary, revealing the strength evolution law of gypsum rock with long-term loading is the key to predicting and preventing a large percentage of gypsum mined gob collapse accidents. To this end, relatively little research work has been attempted thus far. In the paper on the Luneng gypsum mine in Shandong Province, China, as an engineering background, gypsum rock cores were extracted from different gypsum rock pillars in different types of mined gob, which formed in different years. The uniaxial compressive strength of gypsum rock is used as a reference to reveal the strength evolution law of gypsum rock at different depths in the lateral direction of the gypsum rock pillar and the strength weakening effect of gypsum rock with long-term overlying strata pressure.

2. Coring from the Gypsum Rock Pillar

2.1. Situation of Gypsum Mine Gob

The Luneng gypsum mine is located in Tai'an City, Shandong Province, China and was put into production in 1996, with a production scale of 600,000 t/a. It adopts the shallow-hole and room-pillar mining methods, with a width of 4–5 m for gypsum rock pillar, 4–5 m for room, and 4 m for mining height. Over the past several years, the Luneng gypsum mine has continued mining operations and has formed a large-scale hanging mine gob—more than 750,000 m^2—supported by gypsum rock pillars.

2.2. Coring from Gypsum Rock Pillars

Once the mining area was mined over, the area was closed. Especially for gob that had been mined over for many years, the environment of the mine gob is complex and changeable, and original power and water supply systems are unavailable, which makes the coring work difficult and dangerous. Combined with basic equipment, such as an electric drill, battery and coring sleeve, simple and portable equipment for coring from gypsum rock pillars was used. The coring sites are different gypsum rock pillars of II-1 gypsum layers in different mine gob, which formed in different years. The thickness of the

II-1 gypsum layer is 5.86 m. The mechanical parameters of gypsum rock are as follows: uniaxial compressive strength 24.12 MPa, tensile strength 3.61 MPa, internal friction angle 29.8°, cohesion 2.75 MPa, and Poisson's ratio 0.29.

In order to ensure the accuracy of sampling and comparability of subsequent indoor tests as much as possible, all of the coring sites of gypsum rock pillars were carried out in gob of the relatively stable II-1 gypsum layer, with similar geological and mining technical conditions and the same size. Three to five gypsum rock pillars with high integrity and a width of 5 m were selected for coring in the middle position of mine gob in different years. The coring location was 1.0–1.5 m from the bottom of the gypsum rock pillar, and coring holes were taken at an angle of 45° on both sides of pillar to the oblique top, with a depth of 2.5–3.0 m, so that drill holes on both sides could cross in the middle of the pillar, which ensured that all cores within the lateral range of the gypsum rock pillar could be obtained. Drilled cores were sorted and numbered by year and then processed into standard specimens in the laboratory. The coring process is shown in Figure 1.

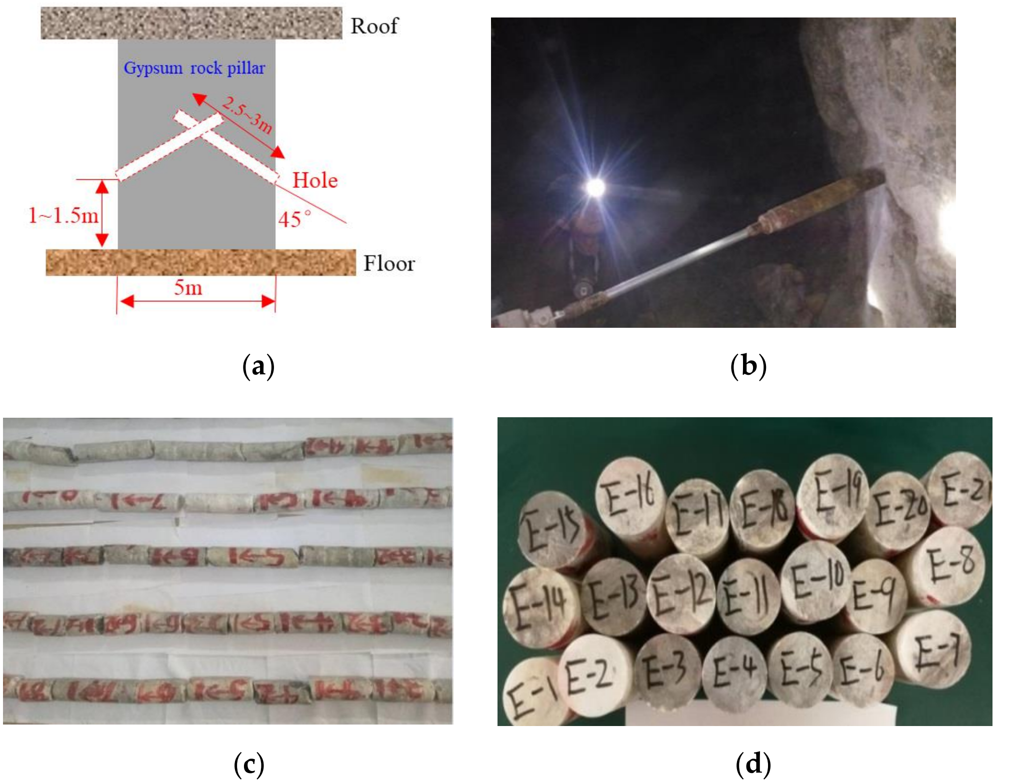
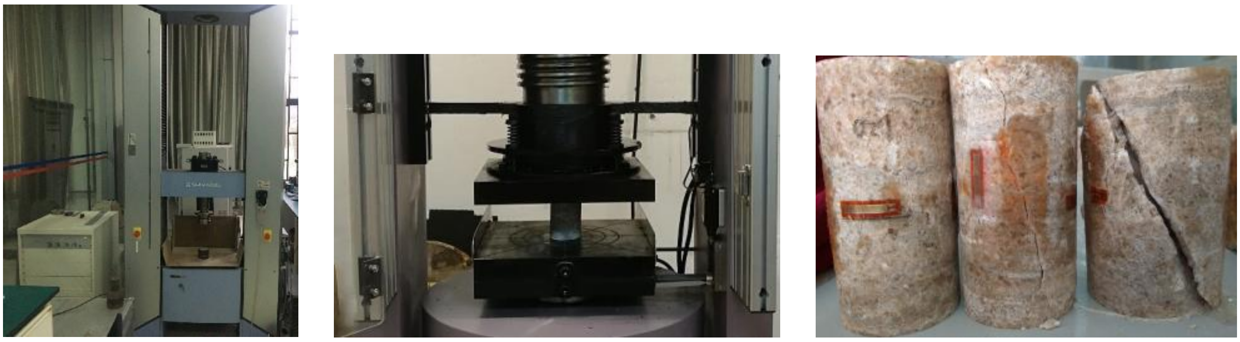


Figure 1. Coring method and gypsum rock specimen. (**a**) Coring parameter, (**b**) scene picture, (**c**) gypsum rock cores, and (**d**) standard gypsum rock specimen.

3. Uniaxial Compression Strength Test of Gypsum Rock

3.1. Experimental Equipment

The experiment mainly uses a Shimadzu AG-X250 rock testing machine, which is mainly used for uniaxial compression, tension, cyclic compression, and other experimental research of rock and concrete, with 0.2 ms interval sampling accuracy. The experimental equipment and process are as shown in Figure 2.

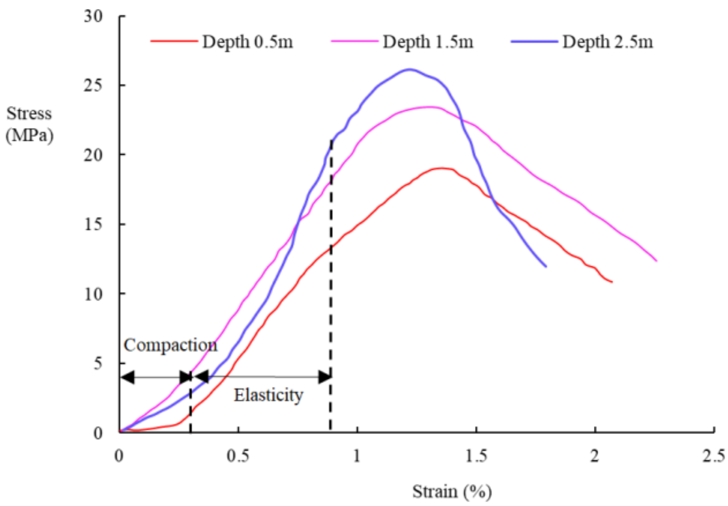


(**a**) (**b**) (**c**)

Figure 2. Experimental equipment and process. (**a**) Shimadzu testing machine, (**b**) process, and (**c**) failure of gypsum rock specimen.

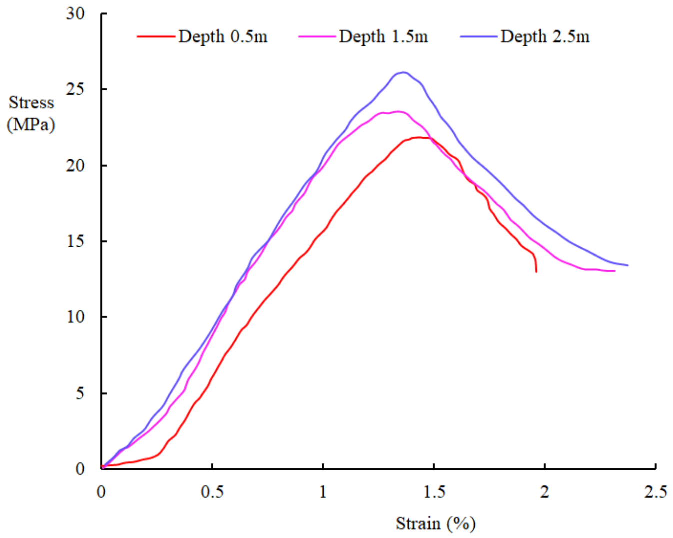
3.2. Uniaxial Compression Strength Curve

In order to study the strength variation law along the transverse of a gypsum rock pillar in different years and the strength weakening effect of gypsum rock with long-term overlying strata pressure, gypsum rock specimens in 0.5 m, 1.5 m, and 2.5 m at the lateral depth of the pillar in different years were selected for a uniaxial compression test. Considering the intermittent and broken features of cores during field coring of gypsum rock pillars in mine gob, gypsum rock test specimens were allowed to fluctuate by 0.1 m at the lateral depth of the pillar, for which the final selected gypsum rock test specimens were 0.5 ± 0.1 m, 1.5 ± 0.1 m, and 2.5 ± 0.1 m at the lateral depth of the pillar. In order to maintain the accuracy of the test, displacement control was selected as the loading mode, with a parameter of 0.01 mm/s. The uniaxial compression stress–strain curves of gypsum rock in different years and lateral depths of the pillar are shown in Figure 3.

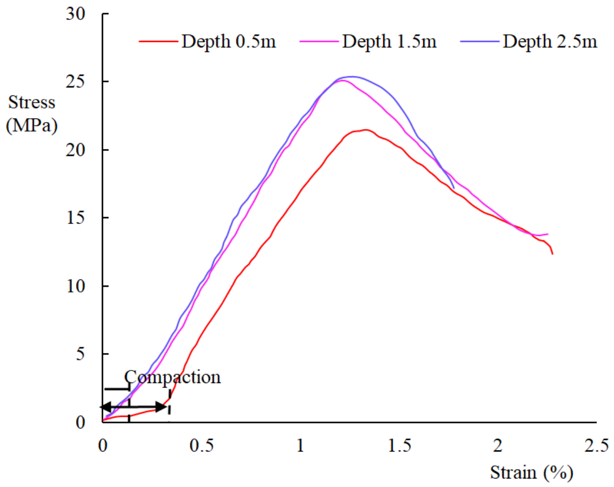


(**a**) In 1996

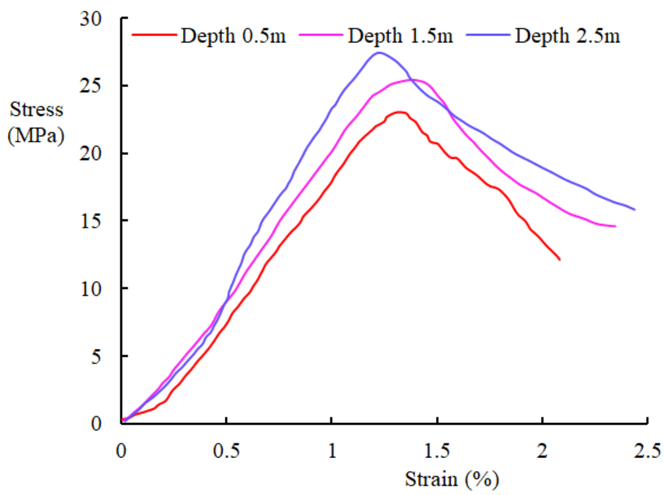
Figure 3. *Cont.*



(**b**) In 2000

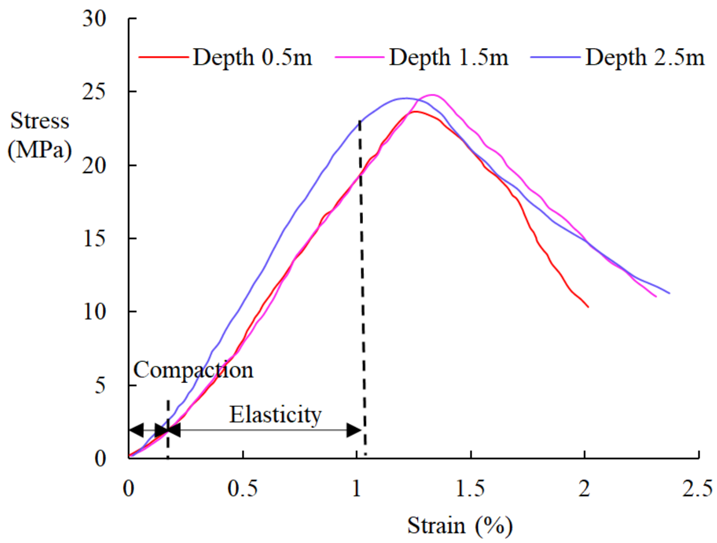


(**c**) In 2008



(**d**) In 2013

Figure 3. *Cont.*



(**e**) In 2017

Figure 3. Uniaxial compression stress–strain curve of gypsum rock in different years. (**a**) Year of 1996, (**b**) year of 2000, (**c**) year of 2008, (**d**) year of 2013, and (**e**) year of 2017.

3.3. Evolution Law of Strength Curve

By comparing the uniaxial compression stress–strain curves of gypsum rock in different years and at different lateral depths of pillars, the following laws can be obtained:

(1) The peak strength of gypsum rock gradually increases with the increase in lateral depth, and the trend is more and more obvious with the increase in age. The difference value of peak strength in different lateral depths gradually increases as the age increases. For example, the maximum difference value of the uniaxial strength of gypsum rock at the lateral depth of the pillar in 1996 was 9.41 MPa, while it was only 1.15 MPa in 2017.

(2) With the lateral depth of the gypsum rock pillar increasing, strain values corresponding to the peak strength of gypsum rock display a decreasing trend, and the difference value of the strain gradually increases as the age increases. For example, the maximum strain difference value corresponding to the peak strength in different lateral depths was 0.3% in 1996, while it was only 0.13% in 2017.

(3) The compaction stage of the uniaxial compression stress–strain curve of gypsum rock gradually increases and the elastic stage decreases as the age increases. For gypsum rocks located in the shallow part of the pillar, such as at 0.5 m, the increase in age was especially obvious. The compaction stage tends to decrease gradually with the increasing lateral depth of the pillar, and it becomes less and less obvious with decreasing age. For example, the compaction stage and stress–strain curves of gypsum rock in different lateral depths of the pillar in 2017 were basically the same.

4. Strength Weakening of Gypsum Rock

4.1. Evolution Law of Peak Strength

The uniaxial compression strength of gypsum rock as a reference parameter can reveal peak strength and strain evolution law of the effect of time in different years, ss shown in Figures 4 and 5.

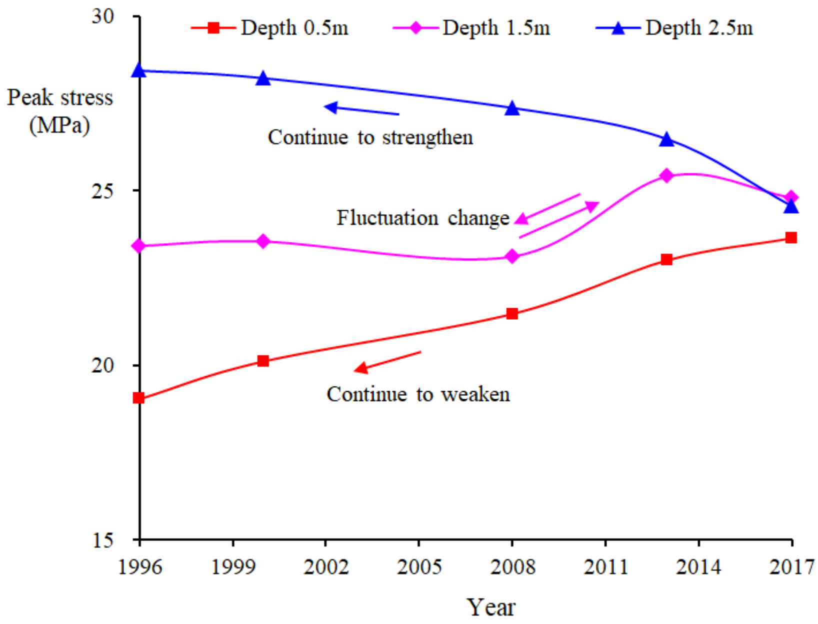


Figure 4. Evolution law of peak strength in different years.

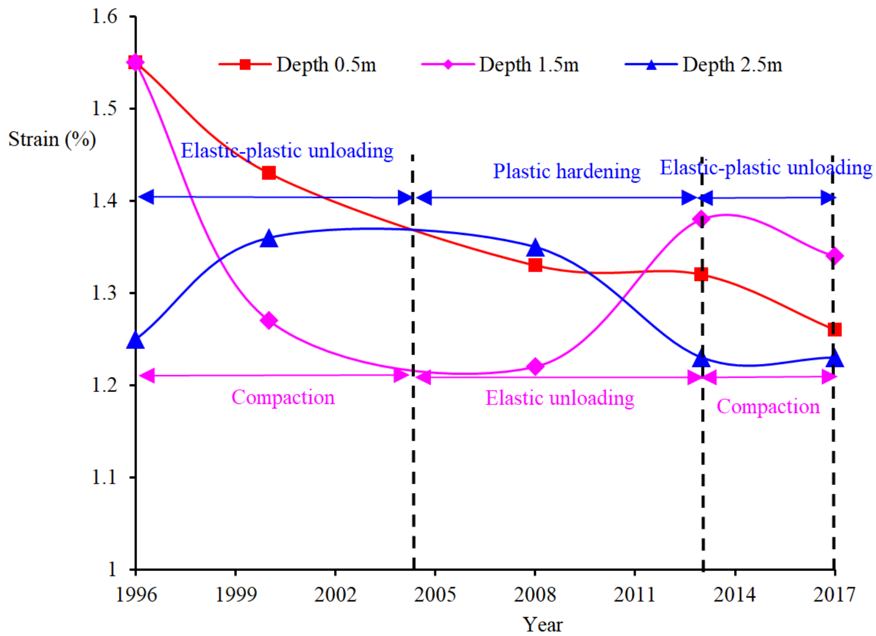


Figure 5. Evolution law of strain in different years.

Based on the changing curve of peak strength and corresponding strain of gypsum rock in different lateral depths of pillars and different years, the following conclusions can be drawn:

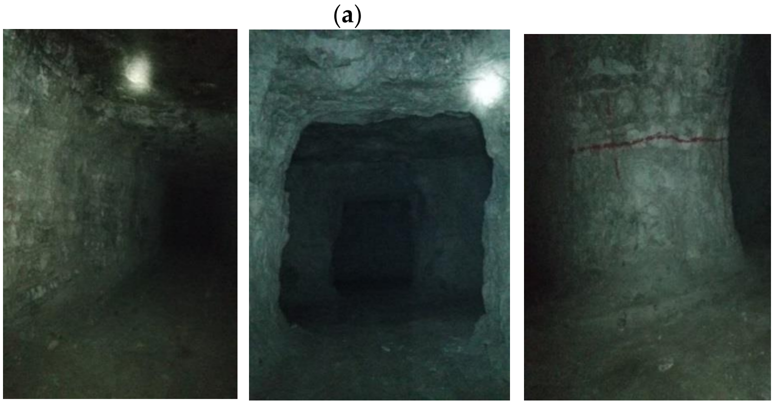
(1) Peak strength and strain of gypsum rock in different lateral depths of pillars display different evolutionary laws with increasing age, which indicates that load magnitude and the elastic–plastic state of gypsum rock in different lateral depths are different, with long-term overlying strata pressure [24,25].

(2) In the shallow part (0.5 m) of the gypsum rock pillar, the peak strength of gypsum rock continues to decrease with increasing age, for example, peak strength was 19.04 MPa in 1996, but 23.65 MPa in 2017, and both of them were smaller than the original peak strength of gypsum rock, which was 24.12 MPa, while the corresponding strain to peak strength exhibits an opposite evolutionary law, that is, continues to increase with increasing age.

(3) In the middle of the gypsum rock pillar (1.5 m), the peak strength of gypsum rock fluctuates with increasing age, and is greater or less than the original peak's strength. At a deep location of the gypsum pillar (2.5 m), peak strength of gypsum rock continues to increase with increasing age and greater than original peak strength, which indicates that plastic hardening has occurred in the gypsum rocks [26,27]. The strains corresponding to peak strength in the middle and deep locations both exhibit fluctuating changes, but fluctuating changing patterns are opposite, which indicates that the loading state of the gypsum rock pillar with overlying strata pressure is not fixed.

(4) Gypsum rock pillars are subjected to weathering with long-term loading, and phenomena of surface-to-internal fragmentation and swelling, exfoliation and shedding gradually appear. This intensifies with increasing age, and conical pillars even appear, as shown in Figure 6.

(**a**)



(**b**)

Figure 6. Pictures of gypsum rock pillars in different years. (**a**) Formed in 1996 and (**b**) formed in 2017.

With long-term overlying strata pressure, the most superficial layer of the gypsum rock pillar is gradually broken and dislodged as a function of stress concentration and weathering. The failure of the most superficial layer caused increasing loads at the middle of the gypsum rock pillar, which induced the internal structure of the gypsum rock to be compressed and dense, and strain corresponding to peak strength decreased, while the load at the deep position of the gypsum rock pillar decreases and produces elastic–plastic unloading, inducing strain corresponding to increasing peak strength. When the most superficial layer of the gypsum rock pillar is exfoliated, it leads to stress concentration in the inner layer of the gypsum rock pillar, which induces elastic unloading in the middle position of the gypsum rock pillar and strain corresponding to increasing peak strength. On the contrary, an increasing load in the deep position of the gypsum rock pillar induces plastic hardening, and the peak strength rises and corresponding strain decreases. With long-term overlying strata pressure, the gypsum rock pillar maintains the cycling process mentioned above, which indicates that the broken gypsum rock pillar is formed by layer-by-layer denudation and shedding.

(5) Due to the weathering effect on the surface layer of the gypsum rock pillar, inducing fracture of gypsum rock by extending and crack through causes the quality index RQD of the actual cores taken out at the site to be smaller, which is also the reason why the compaction stage continues to increase and strength continues to decrease in the shallow part of the gypsum rock pillar with increasing age. The shallow part of the gypsum rock pillar causes continuous shedding and is an effective support area of the pillar, which induces a loading state in the middle of the changing gypsum rock pillar. Finally, alternately generating pressure-dense and elastic unloading induces changes in peak strength and strain fluctuations. The deep part of the gypsum rock pillar as the main bearing part continues to creep with a long-term load and plastic hardening occurs, which has been proved by an obvious jamming phenomenon during coring. That leads to continuously increasing peak strength of the gypsum rock and is greater than the original peak strength. The fluctuating change in the loading state of the gypsum rock pillar causes an increasing or decreasing load in the deep part of pillar, which induces elastic–plastic unloading and plastic hardening. This is the reason why the strain corresponds to fluctuating peak strength changes.

4.2. Strength Weakening of Gypsum Rock

To quantitatively evaluate the strength weakening effect of gypsum rock with long-term overlying strata pressure, the strength weakening rate of gypsum rock in different years is assumed to be [28–30]:

$$\eta = \frac{\sigma_c - \sigma_T}{\sigma_c} \times 100\% \tag{1}$$

where σ_c is the original peak strength of gypsum rock, MPa, and σ_T is the peak strength of gypsum rock in different years, MPa.

Based on the peak strength of gypsum rock specimens in different years and at lateral depths, the strength weakening rate curves of gypsum rock were obtained, as shown in Figure 7.

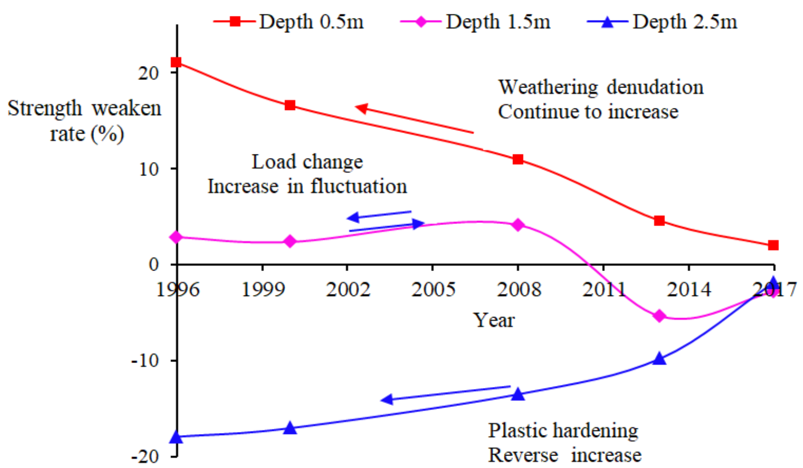


Figure 7. Strength weakening rate of gypsum rock in different years.

The strength weakening rate curves show a similar pattern with peak strength variation. The strength weakening rate of gypsum rock in the shallow part (0.5 m) of the pillar continues to increase with increasing age, to a maximum of 21.06% (1996). The middle part of the pillar (1.5 m) displays a fluctuating increase, while the deep part (2.5 m) exhibits an inverse increase. However, both strength weakening rates are low. The weathering of the gypsum rock pillar in closed gob is an extremely slow process. In other words, peak strength, magnitude of strain change, and strength weakening rate are small and slow. The gypsum rock pillar can maintain long-term stability, which is the essential reason why gypsum mined gob collapses after years or even decades.

5. Conclusions

Aiming at significant characteristics of the lagging gypsum mined gob collapse disaster, the strength weakening effect of gypsum rock with long-term overlying strata pressure was revealed by experiment. The main conclusions are as follows:

(1) There are significant differences in the uniaxial compression stress–strain curve of gypsum rock in different years and at different lateral depths of gypsum rock pillars. The peak strength of gypsum rock increases as the lateral depth of the pillar increases, and the corresponding strains exhibit a decreasing trend. With increasing age, this becomes more obvious. The compaction stage shortens with increasing lateral depth but increases with increasing age. The stress–strain curves in different depths tend to be consistent with decreasing age.

(2) Peak strength and the corresponding strain of gypsum rock are different in different lateral depths and years. In the shallow part of the gypsum rock pillar, peak strength decreases with increasing age, while strain displays the opposite evolutionary law. Peak strength fluctuates in the middle part and continues to increase in the deep part, which becomes greater than the original peak strength. The strain in the middle and deep parts exhibits fluctuation changes, but the fluctuating laws are opposite.

(3) Subjected to long-term weathering, the compaction stage increases and strength decreases in the shallow part of the gypsum rock pillar. The pillar's layer-by-layer shedding causes changes in the pillar's effective supporting area, inducing the loading state of the fluctuating changes in the middle part of the pillar, alternately producing a compaction stage and elastic unloading along with peak strength and strain fluctuating changes. The deep part is the main load bearing part, with the phenomenon of plastic hardening due to continuous creep with a long-term load, inducing a peak strength increase.

(4) The maximum strength weakening rate of gypsum pillar in the shallow part (0.5 m) is 21.06%. Weathering in closed gob is an extremely slow process, and peak strength, strain change, and the strength weakening rate are all small. This is the reason why gypsum mined gob collapse occurs after years or even decades.

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