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Research Article

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Posted Date: June 14th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-335036/v1

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on August 9th, 2021. See the published version at https://doi.org/10.1007/s11356-021-15638-z.
Deformation and instability properties of cemented gangue backfill column under step-by-step load in constructional backfill mining

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Abstract: Constructional backfill mining with cemented gangue backfill column can solve the environmental issues caused by mining activities and the accumulation of waste gangue at a low cost. To study the deformation and instability properties of cemented gangue backfill columns during the advancement of coal mining face, five step-by-step loading paths were adapted to mimic the different loading processes of the roof. The lateral deformation at different heights and axial deformation of the sample were monitored. The results show that the deformation and instability of the backfill column have the properties of loading paths and are affected by the step-by-step loading path. When stress-strength ratio (SSR) is less than 0.6, the lateral of backfill column shrinks during the creeping process. In high-stress levels, lateral creep strain develops faster than axial creep strain. The backfill column has characteristics of axial creep hardening and lateral creep softening during the step-by-step loading process. The instantaneous deformation modulus and instantaneous Poisson’s ratio show an upward trend. The bearing capacity of backfill column under the step-by-step load is related to loading paths and is no less than uniaxial compressive strength. The non-uniformity of the lateral deformation of backfill column leads to excessive localized deformation that mainly occurs in the middle, causing the overall instability. The development of cracks of backfill column under step-by-step load could be divided into 4 stages according to SSR. Under different step-by-step loading paths, the axial creep strain rate is nearly a constant before entering the accelerated creep stage. A nonlinear creep constitutive model with a creep strain rate trigger was proposed to depict the development of axial strain under step-by-step load. This research will provide a scientific reference for the design of the advancing distance and cycle for the hydraulic support, and reinforcement of the backfill column.
Keywords: Cemented gangue backfill column; step-by-step load; deformation; instability; nonlinear creep constitutive model

1 Introduction

Cemented gangue backfill mining technology is an important part of the “green mining” system for coal mining, it not only controls the movement of the overlying strata and the surface subsidence effectively, but also consumes a large amount of coal gangue (Chen et al. 2016a). The material used for coal mine backfill mining is made of coal gangue, cement, fly ash, and water. Generally, the method of full backfilling is used in coal mining, that is, all mined-out space is filled with cemented gangue backfill material. However, the cost of cement and fly ash is relatively high, and the production of coal gangue only accounts for about 20% of the output of raw coal (Liu et al. 2020). The high cost and limited raw materials impede the promotion of coal mine full backfill mining; thus, partial backfill mining (Zhu et al. 2017) and constructional backfill mining (Feng et al. 2019; Du et al. 2018) are proposed, and the roof is supported by strip and column backfill bodies (Zhu et al. 2017; Wang et al. 2019a), as shown in Fig. 1. The support of the unconfined backfill columns can improve the stress state of the surrounding rock in the goaf, maintaining the stability of the mined-out area and controlling surface subsidence, and forming a large amount of underground space that can be used for other purposes such as underground reservoir (Feng et al. 2019; Du et al. 2019a). During the advancing process of the coal mining face, the pressure applied on the unconfined columns increases gradually as the advancement of hydraulic supports step-by-step (Zhang et al. 2017). Therefore, the deformation and mechanic responses of the backfill column under the step-by-step load are closely related to the stability of the goaf. It is necessary to study the stability of the backfill column under the step-by-step load to ensure the safety of workers during the mining process.

Many scholars have carried out a series of studies on the mechanics and deformation characteristics of cemented gangue backfill material (Du et al. 2018; Du et al. 2019a). The mechanic and deformation properties of cemented paste backfill (CPB) are affected by external conditions. The main considerations are the use of stirrups (Du et al. 2019b); the loading method (uniaxial compression and triaxial compression) (Fall et al. 2007); the different temperature and
sulphate environment (Fall et al. 2010); the structural factors (filling time, interval, and surface angle) and loading rate effect (Cao et al. 2017; Cao et al. 2019); the particle size distribution of aggregates (Wu et al. 2021a); interface angles between rock and backfill (Yin et al. 2021); curing temperature and silica fume (Xu et al. 2020); curing under stress (Yilmaz et al. 2014; Guo et al. 2020); under triaxial cyclic loading and unloading (Wang et al. 2019b); mixing method of raw material (Sun et al. 2019b); and dynamic loading (Li et al. 2020). Except for the external factors, the proportion of raw material and additions can also affect the deformation and mechanical properties of CPB (Liu et al. 2019; Qi et al. 2015; Chen et al. 2020). However, none of the above studies involve step-by-step load.

The instability of the backfill body does not happen immediately but occurs gradually over time, the creep characteristics of the backfill body and the stability of the goaf are closely related. The creep properties of cemented gangue backfill material under uniaxial compression and triaxial compression were investigated (Wu et al. 2021b). Cemented gangue backfill is a visco-elastoplastic material with obvious rheological properties, and the disturbance will accelerate the creep process of the backfill body (Sun et al. 2018). Besides, the cemented gangue backfill has creep hardening characteristics, and the creep hardening mechanism and the creep properties under high-stress areas are explored (Chen et al. 2016b; Ran et al. 2021). The triaxial creep properties of cemented gangue-fly ash backfill under seepage-stress coupling were also tested (Hou et al. 2020). The above studies only focused on the axial creep deformation of the backfill body and did not consider the lateral deformation characteristics. However, many researchers have found that the lateral creep of the rock shows obvious anisotropy and has a significantly accelerated stage, and it appears earlier than the axial accelerated creep stage (Fu et al. 2007; Fan et al. 2005). Besides, since the lateral deformation of the backfill body restricts the lateral deformation of the surrounding rock, the backfill body and the surrounding rock share the load, especially when the backfill column is used to strengthen the stability of the coal pillar (Hou et al. 2019; Qi et al. 2019; Yin et al. 2020). Therefore, it is necessary to study the lateral deformation of the unconfined cemented gangue backfill column.

As shown in Fig. 1, the backfill columns in the goaf bear the vertical load from the roof,
and the pressure increases step by step with the advancement of the coal mining face (Zhang et al. 2017). When the hydraulic support advances, the load from the roof will increase accordingly; however, when the hydraulic support stops, the load applied to the columns will be nearly constant. The deformation and instability characteristics of the backfill column under this step-by-step loading condition are important physical properties of the constructional backfill mining, and the step-by-step load is also a method used for rock creep tests (Fu et al. 2007; Fan et al. 2005; Shi et al. 2019; Jia et al. 2018; Wu et al. 2018). In addition, due to the influence of factors such as the advancing speed of the coal mining face and the facilities maintenance, the moving distance and cycle of the hydraulic support are different. Therefore, the step-by-step loading increment exerted to the backfill columns is different, and it is not all uniform. In this study, the axial and lateral deformation characteristics and bearing capacity of test samples under five step-by-step loading paths are analyzed, the axial nonlinear creep constitutive model is established, and the instability mechanism of the backfill column is discussed. This research could provide a scientific reference for the advancing distance and cycle of the hydraulic support, and reinforcement of the backfill column.

2 Material and methods

2.1 Sample preparation

Cemented gangue backfill material (CGBM) is a paste-like material made of ordinary Portland cement (190 Kg/m$^3$) Type 42.5, secondary fly ash (380 Kg/m$^3$), coal gangue (950 Kg/m$^3$), and tap water (350 Kg/m$^3$) (Du et al. 2019; Qi et al. 2015; Wang et al. 2021; Wang et al. 2020). Fly ash is sampled from thermal power plant of the Fenxi mining group. Coal gangue
was collected from gangue mountain of Tunlan colliery located in Shanxi province of China. The crushed coal gangue was divided into three groups (0–5 mm, 5–10 mm, and 10–15 mm) according to the nominal diameter, which accounted for 30%, 35%, and 35%, respectively, of the total aggregate mass (Wang et al. 2020). The morphology of raw materials and test samples are shown in Fig. 2. The fineness module of the fine aggregate (0–5 mm) was 3.10. The moisture content and specific gravity of coal gangue aggregate were tested, by 0.74 % and 2.3 g/cm$^3$, respectively. Table 1 shows the physical properties and chemical components of cement and fly ash. Fig. 3 presents the particle size distribution of coal gangue and fly ash. The Φ 50×100 mm mold was used to cast the test samples (Chen et al. 2016b; Sun et al. 2018). Samples were removed from the molds after casting for 24 h, and then it was placed in a standard curing room for 28 d (Sun et al. 2018). The end faces of the test samples were polished to meet the dimensional requirement and the smoothness requirement of the international rock mechanics test standard.

![Morphology of raw material and test samples.](image)

**Table 1** Chemical components and physical properties of fly ash and cement.

| Chemical components | Fly ash | Cement |
|---------------------|---------|--------|
| SiO$_2$             | 52.42%  | 22.36% |
| Al$_2$O$_3$         | 32.48%  | 5.53%  |
| Fe$_2$O$_3$         | 3.62%   | 3.45%  |
| CaO                 | 3.05%   | 65.08% |
| MgO                 | 1.01%   | 1.27%  |
| TiO$_2$             | 1.26%   | -      |

| Physical properties | Fly ash | Cement |
|---------------------|---------|--------|
| Specific gravity [g/cm$^3$] | 2.2 | 3.1 |
| Specific surface [m$^2$/ kg] | 415 | 349 |
| Fineness (>45μm) [%]     | 42.54% | 5     |
| Moisture content [%]     | 0.56%  | -     |
2.2 Experimental test protocol

To simulate the process of applying the pressure to the backfill columns by the roof, the step-by-step loading test was carried out on the ETM-205D computer-controlled electromechanical testing machine. The pressure head of the press moves from top to bottom, which can conduct two loading methods of force loading and displacement loading, and can perform a uniaxial compressive creep test. After 28 d of curing, the ultrasonic pulse velocity of the specimens was tested by an NM-4B nonmetal ultrasonic instrument, and the specimens with a P-wave velocity of 2.5 ± 0.05 Km/s were selected for the tests.

2.2.1 Deformation monitoring

The TST3822E-20 static resistance strain equipment was used to monitor the axial and lateral strain of the specimen. As shown in Fig. 4, the strain gauges were vertically distributed along with the axial and lateral directions on the specimen surface. To distinguish the position of the strain gauges, L and R represent the left side and right side of the sample, respectively. The axial strain gauges were attached to the middle of the specimen, and three radial strain gauges were arranged at equal intervals (Li et al. 2020). To monitor the deformation at various positions, eight strain gauges were symmetrically stuck on the specimen, and the length of the strain gauge (20 × 4 mm) was greater than the maximum particle size of the aggregate.
2.2.2 Step-by-step loading test

The displacement loading method was used in the uniaxial compression test and step-by-step loading test, and the loading rate was 0.15 mm/min. The average uniaxial compressive strength (UCS) of the test CGBM samples was 5.05MPa. To realize the different loading paths are exerted to the unconfined backfill column, according to the average UCS, the stress–strength ratio (SSR) growth plan is adopted. The first-level SSR is 40%, and five step-by-step loading paths are designed, as shown in Table 2. The 20% UCS is regarded as a large increment that is used to simulate the long moving distance of the hydraulic support each time, and the 10% UCS is regarded as a small increment that is used to simulate the short moving distance of the hydraulic support each time. According to the literature (Chen et al. 2016b), when the load reached the set value, the pressure is kept constant for 5 h, and the duration of the last step depends on the specific damage of the backfill column until the test sample undergoes creep failure. To avoid the test sample from being completely crushed so that the macro cracks can be seen, the press stops working when the load drops more than 10%.

| Steps | A                | B                          | C                  | D                  | E                  |
|-------|------------------|-----------------------------|--------------------|--------------------|--------------------|
|       | Large increment  | Small increment             | Large increment    | Small increment    | Large increment    |
|       | uniform load     | uniform load               | and small increment| uniform load       | and small increment|
|       | uniform load     |                             | alternate load     | uniform load       | alternate load     |
| 1     | 40%              | 40%                         | 40%                | 40%                | 40%                |
| 2     | 60%              | 50%                         | 60%                | 50%                | 60%                |
| 3     | 80%              | 60%                         | 70%                | 60%                | 80%                |
| 4     | 100%             | 70%                         | 90%                | 80%                | 90%                |
| 5     | …                | 80%                         | 100%               | 100%               | 100%               |
| 6     | 90%              | …                           | …                  | …                  | …                  |
| 7     | 100%             |                             |                    |                    |                    |
3 Results and discussion

3.1 Deformation under uniaxial compression test

Fig. 5 shows the stress–time curve and strain–time curve of the CGBM specimen in uniaxial compression. The failure process of the CGBM sample can be divided into five stages: initial compaction stage, elastic stage, plastic stage, rapid decline stage, and residual bearing stage. During the initial compaction stage, the stress increased slowly with time, and the porosity of the CGBM sample was compacted; there is no obvious strain variation in the lateral direction. The axial strain and lateral strain increased slowly in the elastic stage, and the lateral expansion of the specimen appeared firstly at the middle and top (the positions of the strain gauges). During the plastic stage, the lateral strain at the middle and top positions increased rapidly. In the rapid decline stage and residual bearing stage, the lateral strain at some positions increased sharply due to the production of macrocracks on the surface, while the lateral strain at some positions decreased continuously because the strain gauges were separated from the specimen or the block of the measured part was separated from the main body, which means that the sample loses its bearing capacity completely.

By comparing the lateral strain–time curves at different positions of the test sample, it can be concluded: the lateral expansion of the test sample under compression was not uniform; when the test sample was destroyed, the largest lateral deformation occurred at the middle of the specimen; the rapid growth of lateral localized deformation eventually led to the overall instability of the specimen (Sun et al. 2019a).
3.2 Axial deformation under step-by-step load

3.2.1 Stress-strain curve

Fig. 6 shows the stress–strain curve under the step-by-step load and the uniaxial compression. The axial strain increased with the increase in stress. When the stress increased to the peak value, the strain rate increased suddenly and the specimen was destroyed. Except for group A, the peak stresses under the different step-by-step load paths were significantly greater than the peak stress under the uniaxial compression test. Because of the creep process, the peak strains of the CGBM sample under different step-by-step loading paths were larger than the peak strain under the uniaxial compression. The cemented gangue backfill column showed axial creep hardening characteristic during the step-by-step loading process (Chen et al. 2016b). However, the bearing capacity of the backfill column under the step-by-step load was closely related to the step-by-step loading paths. The ultimate bearing capacity of group A was the same as the average UCS, and the highest UCS was group C. Groups B, D, and E were basically the same. The bearing capacity of backfill column under the step-by-step load is related to loading paths and is no less than UCS.
3.2.2 Strain–time curve

The strain–time curve under step-by-step load is shown in Fig. 7(a). The instantaneous strain and creep strain under various SSRs are shown in Table 3. Specimen A was destroyed during the final-step loading process, specimens B, C, D and E were destroyed in the final creep stage, but specimen D was destroyed after 1 min when the test entered the creep process. The axial deformation of the CGBM sample has the following characteristics:

The instantaneous strain at the first step was relatively large because of the compaction of the micropores, and then, the instantaneous strain decreased with the increase in the SSR except for the loading steps that changed from a 10% UCS increment to a 20% UCS increment. The instantaneous strain of the last step of the three groups of B, C, and E was only about 146 με, which means that the backfill column hardens during the step-by-step loading process, and the stiffness increases. However, the instantaneous strain of the last step of the groups of A and D with 20% UCS increment was over 390 με which was larger than twice the instantaneous strain produced by 10% UCS increment, indicating that the step-by-step loading increment has a great influence on the internal damage of the backfill column.

As the SSR increased, the creep strain decreased first and then increased. Under the high SSR, the creep strain was greater than the instantaneous strain, indicating the obvious rheological characteristics of the CGBM column. In addition, the difference between the creep strain and the instantaneous strain at each step increased with the increase in the SSR. For some 20% UCS increment steps, the creep strain was less than the instantaneous strain. It means that the 20% UCS increment produced more microcracks at the instantaneous loading process, which caused damage to the backfill column.

Except for group A which represents that the hydraulic support moves a long distance each time, resulting in a large loading increment at each step, the creep failure strengths of the other 4 groups were all larger than the UCS. It means that, under the small increment step-by-step load, the unconfined cemented gangue backfill column will show the axial creep hardening characteristic, which is beneficial for the stability of the backfill column.

Fig. 7(b) shows the creep strain–time curves during the creep instability stage. The creep
instability of the CGBM samples had three typical creep stages: attenuation creep, stable creep, and accelerated creep. Before entering the creep accelerated stage, the creep strain rate of the different loading paths in the stable creep stage was almost the same, for example, the creep strain rates of samples B, C, and E were ranged from 0.173 με/s to 0.195 με/s, and the average strain rate was 0.187 με/s. This creep strain rate could be defined as the critical value of the creep instability of the backfill column under step-by-step load, that is, once it reaches this creep rate, the backfill column is considered to enter the creep acceleration stage.

![Fig. 7. (a) Strain–time curve under step-by-step load. (b) Strain–time curve during the creep instability process.](image)

Table 3 The axial strain development under step-by-step load.

| SSR | A / (με) | B / (με) | C / (με) | D / (με) | E / (με) |
|-----|----------|----------|----------|----------|----------|
|     | Instantaneous strain | Creep strain | Instantaneous strain | Creep strain | Instantaneous strain | Creep strain |
| 0.4 | 3418.61 | 667.39 | 2862.79 | 406.51 | 2127.29 | 231.35 | 2804.53 | 443.84 | 2464.07 | 363.44 |
| 0.5 | 235.87 | 257.19 | 238.74 | 242.84 | 289.10 | 312.42 | 294.67 | 313.45 | 296.21 | 310.69 |
| 0.6 | 761.33 | 931.97 | 211.66 | 279.35 | 442.61 | 254.73 | 209.61 | 269.50 | 528.75 | 326.93 |
| 0.7 | 189.51 | 296.16 | 169.82 | 162.44 | 460.25 | 498.39 | 416.35 | 392.56 | 265.81 |
| 0.8 | 517.26 | 2099.40 | 171.05 | 332.67 | 460.25 | 498.39 | 416.35 | 392.56 | 265.81 |
| 0.9 | 158.75 | 347.85 | 401.99 | 277.71 | 158.75 | 265.81 |
| 1.0 | 153.41 | 361.39 | 150.13 | 228.48 | 383.54 | 831.89 | 149.31 | 381.08 |
| 1.1 | 148.49 | 460.24 | 143.16 | 523.01 |
| 1.2 | 146.85 | 337.18 | 911.87 | 396.25 | 144.82 |
| 1.3 | 146.44 | - |

### 3.2.3 Instantaneous deformation modulus

The ratio of the axial instantaneous stress increment to the axial instantaneous strain increment under each loading step was defined as the instantaneous deformation modulus (IDM) (Fan et al. 2005). Fig. 8 shows the relationship between IDM and SSR. The IDM showed an upward trend as a whole, but was affected by the loading increment and paths. Group A and
Group E were applied with 20% UCS increment before 0.8 UCS, and their IDM growth rate was basically the same, but after over 0.8 UCS, group A still loaded 20% UCS increment and destroyed, while the IDM of group E using the 10% UCS increment increased gradually until 1.1 UCS. Group B and D were both applied with 10% UCS increment before 0.6 UCS, and the growth rate of IDM remained the same, but after 0.6 UCS, the group D was applied with a 20% UCS increment and the IDM decreased rapidly; however, the IDM of group B increased continuously with 10% UCS increment. Before 0.7 UCS, the increase of IDM of Group C was consistent with group B and D, and even at 0.7 UCS, the IDM of group C was greater than that of group B and D, but the IDM dropped rapidly when the SSR increased from 0.7 to 0.9, and then when it was loaded with 10% UCS increment, the IDM increased again. The IDM has the following characteristics:

SSR ≤ 0.6, comparing the group B, although the group E was loaded uniformly with a 20% UCS increment when SSR was less than 0.8, the IDM of the two groups was the same in the later period, which means that the IDM of the backfill column does not be affected by the loading increment in the low-stress stage. However, loading in a 10% UCS increment made the backfill column more compact than the 20% UCS increment. 0.6 < SSR ≤ 0.8, the IDM of the backfill column was affected by the loading increment. An increase of 20% UCS, by contrast with a 10% UCS increment, would cause the internal microcracks of the backfill column to continue to grow and damage inside the backfill column. 0.8 < SSR, the IDM of the backfill column was more sensitive to the step-by-step loading increment, that is, the large increment could cause more damage. For example, the IDM of the backfill column with 20% UCS as the load increment was much lower than that of the 10% UCS. In the low-stress levels, the IDM increased gradually, which showed the creep hardening property and the backfill column hardened; in the medium-stress level, creep hardening and damage competed with each other and continued to develop. In the high-stress level, the IDM had a decreasing trend, which means that the damage in the backfill column accumulated continuously, and the viscosity coefficient decreased.
The backfill column has the axial creep hardening property. The degree of creep hardening can be expressed by the increment of the IDM under unit stress (MPa), that is, the IDM growth rate \( \dot{E}(\sigma) \) (Chen et al. 2016b), calculated as follows:

\[
\dot{E}(\sigma) = \frac{E_{\text{max}} - E_{\text{min}}}{\sigma_{\text{max}} - \sigma_{\text{min}}} 
\]

Where \( E_{\text{max}} \) is the maximum value of the IDM (MPa) during the step-by-step loading creep process, \( E_{\text{min}} \) is the IDM (MPa) at the first stress level, \( \sigma_{\text{max}} \) (MPa) and \( \sigma_{\text{min}} \) (MPa) are the corresponding stress of \( E_{\text{max}} \) and \( E_{\text{min}} \), respectively.

The degree of creep hardening of groups B (0.678×10^5%) and E (0.772×10^5%) are much higher than that of groups C (0.553×10^5%) and D (0.385×10^5%), which means that the 20% UCS increment can cause more damage inside of the backfill column after 0.6 UCS. More new microcracks are created in the instantaneous loading process and the original cracks expand obviously. The creep hardening degree of the CPB in the results of Chen et al. (2016b) is 1.2×10^5%, which is much larger than the CGBM and proves that the porosity of the CPB is higher. The IDM growth rate in the results of Fan et al. (2005) of red sandstone is 0.593×10^5%, which is consistent with the CGBM.

### 3.2.4 Relationship between creep strain and SSR

Fig. 9(a) shows the creep strain of each SSR under respectively unit stress under step-by-step load. It can be seen that the unit creep strain showed a trend of decrease first and then increase, but the turning point was related to the step-by-step loading paths. Fig. 9(b) shows the accumulation of creep strain. It can be seen that the accumulation of creep strain increased with the increase in SSR, and the growth rate increased gradually. There is an obvious turning point...
in the curve under various loading paths. Except for group A, the turning points were between 0.9 SSR and 1.0 SSR, which means that there is a stress threshold of the backfill column. When the stress value was less than the stress threshold, the creep rate would decay gradually; when the stress value was greater than the stress threshold, the creep rate at the stable stage was almost constant or even entered the creep failure stage.

![Fig. 9.](a) Specific creep strain at different stress–strength ratios; (b) Accumulation of creep strain.

### 3.3 Lateral deformation under step-by-step load

#### 3.3.1 Relationship between lateral strain and SSR

Table 4 shows the instantaneous strain and creep strain at axial and lateral (axial compressive strain is set to a positive value) of group B in the entire step-by-step loading process. Fig. 10 shows the instantaneous strain and creep strain at axial and lateral of the backfill column at various SSRs. The lateral deformation has the following characteristics:

As the SSR increased, the lateral instantaneous strain decreased first and then increased, while the axial instantaneous strain decreased continuously. When the SSR exceeded 1.1, the lateral instantaneous strain increased sharply, showing a large increase in damage. The lateral instantaneous strain and lateral creep strain at each side of various positions of the backfill column were different.

When SSR was less than 0.6, the lateral creep strain at different places was negative, which means that the cracks produced during the instantaneous loading step closed gradually during the creep process. In other words, the lateral position of the backfill column shrunk during the creeping process. As the SSR increased (SSR ≥ 0.6), the lateral creep strain increased continuously, which means that the cracks expanded during the creep process. The creep strain of the axial was larger than that of the lateral, but in the later step-by-step loading process, the
lateral creep strain developed faster than the axial. For example, when the SSR was 0.6, the axial creep strain and the lateral creep strain (Middle Left) accounted for 1.32% and 3.9% of the total strain, respectively; and when the SSR was 1.1, the axial creep strain accounted for 4.31%, and lateral creep strain accounted for 5.26%; however, when the SSR reached 1.2, axial creep strain accounted for 9.59% and lateral creep strain accounted for 23.09%.

Fig. 10(a) shows that the instantaneous strain of axial tended to stabilize after the first loading step; however, the increase of SSR had a great influence on the development of lateral instantaneous strain after the first loading step. The turning point of lateral instantaneous strain was around 0.9 SSR, while the turning point of axial instantaneous strain was around 1.0 SSR, which means that the stress threshold of axial direction was greater than that of the lateral direction. Fig. 10(b) shows that the turning point of lateral creep strain and axial creep strain was 0.9 SSR. When the stress value was lower than the stress threshold, the creep strain tended to a certain value, showing the characteristics of attenuation creep; when the load was higher than the stress threshold, the creep strain increased with time, showing the characteristics of a stable creep and even an accelerated creep.

**Table 4** The axial strain and lateral strain of group B under step-by-step load.

| Position | Axial (με) IS | Top R (με) IS | Middle R (με) IS | Bottom R (με) IS | Top L (με) IS | Middle L (με) IS | Bottom L (με) IS |
|----------|---------------|---------------|-----------------|-----------------|---------------|-----------------|-----------------|
| SSR      | IS CS         | IS CS         | IS CS           | IS CS           | IS CS         | IS CS           | IS CS           |
| 0.4      | 2939.49 122.65 | 113 -27 125 -19.23 | 104 -16 147 -86 | 184 -26 159 -42 |
| 0.5      | 260.06 191.15  | 18 -3 20.19 -9.62 | 18 -5 39 -37   | 46 -8 34 -19   |
| 0.6      | 209.20 84.50  | 25 3 25 9.62 20 10 | 46 7 52 14 35 5 |
| 0.7      | 196.89 100.90  | 32 39 34.61 23.08 | 22 29 45 15 54 34 | 32 18 |
| 0.8      | 192.38 161.61  | 48 29 48.08 31.73 | 27 25 53 18 69 34 | 39 20 |
| 0.9      | 173.10 166.95  | 54 23 52.88 32.70 | 30 22 45 24 60 36 | 34 15 |
| 1.0      | 167.36 199.35  | 68 9 86.53 58.66 | 49 26 33 12 79 57 | 40 16 |
| 1.1      | 168.59 275.65  | 50 15 107.69 64.42 | 62 24 25 16 92 69 | 47 21 |
| 1.2      | 173.21 613.65  | 56 64 184.62 166.34 | 131 247 6 35 163 303 | 155 140 |

Notes: IS and CS represents the instantaneous strain and creep strain, respectively. R and L represent the right side and left side of the test sample, respectively.
3.3.2 Instantaneous Poisson’s ratio and accumulation of lateral strain

The ratio of the lateral strain to the axial strain under the unit stress increment was defined as the instantaneous Poisson’s ratio (Fan et al. 2005). The instantaneous Poisson’s ratio of the backfill column was calculated by using the lateral instantaneous strain in the middle of the left and right positions. Fig. 11(a) shows the relationship between the instantaneous Poisson’s ratio and the SSR. It can be seen that the instantaneous Poisson’s ratio of the backfill showed a concave upward trend with the increase in SSR, and it was much greater than the value of the Poisson’s ratio in the conventional test (Sun et al. 2019). There is a turning point at 0.9 SSR, and the instantaneous Poisson’s ratio increased sharply after 0.9 SSR. During the step-by-step loading process, the axial instantaneous strain decreased with the increase in SSR; however, after the first loading step, the lateral instantaneous strain increased with the increase in SSR. It means that the cemented gangue backfill column showed axial creep hardening property and lateral creep softening property as a whole during the step-by-step loading process. With the increase of creep time and SSR, the microcracks expanded during the creep process and the damage accumulated at the same time, and the plastic deformation of the lateral was higher than that of the axial, which shows the obvious expansion phenomenon.

Fig. 11(b) shows the accumulation of lateral strain on the left and right side of group B under the step-by-step load. The lateral deformation at the middle positions on the left side and right side of specimen B increased gradually with the increase in SSR and was greater than the deformation at the other positions on the same side. Besides, with the increase of SSR, the lateral expanding rate increased significantly. When the lateral localized deformation reached the limit, the corresponding position was damaged, producing macrocracks on the surface and
the specimen lost its bearing capacity instantly (Sun et al. 2019). In the actual engineering, the
top and bottom of the backfill column had a hoop effect due to the friction of the roof; therefore,
it had a certain protective effect on the ends of the backfill column (Du et al. 2019a). However,
in the middle of the unconfined backfill column was subjected to tensile stress, it was easy to
produce macrocracks, which led to sudden instability of the backfill column. Thus, it is
necessary to set the around constraint in the middle part of the backfill column to restrict the
lateral deformation, such as the use of stirrups. The expansion of the backfill column because
of the production of cracks makes the stirrups tensile, and then the stirrups restrict conversely
the continuous expansion of the backfill column, increasing the stability of the backfill column
(Du et al. 2019b).

3.4 Instability of the backfill column

3.4.1 Development of cracks under step-by-step load

With the increase of SSR, the lateral of the backfill column expanded outwards
continuously. The non-uniform lateral deformation led to excessive localized deformation at a
certain position of the backfill column, which mainly occurred in the middle places. The tensile
stress on the surface exceeded the limit of CGBM and caused macrocracks, which led to the
reduction of the actual bearing area, and the increase of the actual stress. Therefore, the damage
of the backfill column intensified suddenly, and the backfill column underwent creep failure.
The evolution of damage of the backfill column under step-by-step load associates with the
development of cracks, which could be divided into 4 stages according to the above analyses,
as shown in Fig. 12. In compression, the orientation of microcracks is preferred to be parallel
to the loading direction (Rossi et al. 2012). The density of microcracks generated during the
creep process depends on the propagation of the microcracks created during the instantaneous loading process (initial microcracks), but also on the creation of new microcracks.

When SSR is less than 0.6 (Fig. 12(a)). The backfill column is in the elastic stage. After the initial instantaneous loading step, microcracks are produced in the interfacial transition zone (ITZ) (Al-Mufti et al. 2016), and a small number of microcracks are generated in the mortar. However, during the constant load stage, most microcracks in the mortar can close, and partial microcracks in the ITZ can close at the same time; thus, the entire backfill column is stable.

When SSR is 0.6 – 0.9 (Fig. 12(b)). The backfill column enters the plastic stage. After the static loading steps, new cracks can be generated in the ITZ and the mortar, and the existing cracks can expand. There is a competition between the creation of new microcracks during the sustained load and the closure of the previous microcracks created during the instantaneous loading. In the creep stage, some microcracks can close, a small part of the microcracks can expand, if there is no external dynamic disturbance (Sun et al. 2018), the backfill column stabilizes gradually during the creep process.

When SSR is greater than 0.9 (Fig. 12(c)). After the instantaneous loading step, more new cracks are produced in the ITZ and mortar of the backfill column, and the existing cracks can expand. The density of microcracks increases significantly. During the creep process, more cracks can expand and a few cracks can close. As active microcracks (opened) that were created during the sustained loading are more numerous than the closed ones, localization of the new microcracks can occur at the macrocrack front tip, hence leading to macrocrack propagation (Rossi et al. 2012). Consequently, the cracks in mortar and ITZ tend to connect to form larger macrocracks, but it will take a long time for creep instability to occur and depends on the stress level.

If the stress increases on this basis, as shown in Fig. 12(d), the backfill column will enter the creep failure stage rapidly. During the instantaneous loading process, a large number of new cracks can be created in the ITZ and the mortar, and the existing cracks can extend significantly during the creep process. The elastic strain energy accumulated during the instantaneous loading process is larger than the energy that the expansion of cracks needs. When the cracks
in the ITZ and the cracks in the mortar are connected, meantime, tension cracks appear on the surface of the backfill column, and macroscrews form inside the backfill column, the macrocracks penetrate each other. As shown in Fig. 13, there are many obvious tensile cracks on the surface of the sample because of the Poisson's effect, accompanied by shear and peeling failure. Compared to the uniaxial compression test, the creep failure under step by step was more quickly and intensely. There’s no residual bearing stage of the creep failure, and the backfill column loses the bearing capacity immediately (Ran et al. 2021).

Fig. 12. Schematic description of the production of cracks and cracking processes.

Fig. 13. Failure forms of the CGBM samples.

3.4.2 Effects of step-by-step loading increment and paths on the cracking

The bearing capacity of the backfill column was affected by the increment during the step-by-step loading process. The main reason is that the 20% UCS increment will affect the generation and expansion of cracks in the backfill column, that is, under the condition of large
increment, the internal cracks of the backfill column will develop more fully during the static loading process. When entering the creeping stage, the localized stress concentration caused at the static loading process will redistribute and homogenize, forming a state of coexistence of crack closure and crack development.

The effect of loading increment on the cracking also depends on the stress level. Under low-stress levels, microcracks are created in the backfill column at the static loading, because the length of the crack is relatively short, most of the microcracks can close during the creep process; thus, the loading increment will not affect its internal crack system. Under medium and high-stress levels, for the uniform step-by-step load, the 20% UCS loading increment can cause more microcracks in the backfill column during the static loading process, and cracks can expand more fully during the loading process. Consequently, compared with the 10% UCS loading increment, greater irreversible damage is produced in the backfill column. Although some microcracks can close during the creep process, more microcracks expand gradually and connect under constant pressure. For the alternate loading path, the 20% UCS increment still causes more obvious damage, but when the next level of 10% UCS increment is applied, the damage will not increase rapidly. Consequently, the crack system inside the backfill column is more stable compared with the 20% UCS increment uniform load.

Therefore, the step-by-step loading test can be used to study the failure process of the backfill column during the advancement of the coal mining face. In addition, the failure process of the backfill column can be influenced by the step-by-step loading paths. In order to avoid the instability of the goaf, the design of moving distance and cycle of the hydraulic support should match the bearing capacity of the backfill column.

4 Constitutive model of the creep strain under step-by-step load

4.1 Establishment of the model

Through the combination of the various rheological elements, which can characterize the basic properties of materials, such as elasticity, viscoelasticity, viscosity or damage, a comprehensive performance of materials could be depicted (Han et al. 2017). The strain development at each step of the CGBM column under step-by-step load can be divided into
three stages, instantaneous strain, recoverable viscoelastic strain, and the uncoverable viscous strain caused by the generation of microcracks under high-stress levels. Therefore, a creep model for the backfill column under step-by-step load can be established by assembling the following rheological components. As shown in Fig. 14, the constitutive model is connected by the Maxwell model, Kelvin model, and the Bingham model.

As stated, the backfill column would be damaged under a relatively high-stress level and its creep strain presents nonlinearly. In the model, the Bingham model was used to feature the nonlinear aspect of the creep. If the stress exceeds $\sigma_{VP}$ of the Saint-Venant body, which signifies damage, Bingham model takes its effect, or else its strain is zero. The instantaneous deformation modulus of the backfill column under step-by-step load increased gradually; thus, the value of the Maxwell model’s spring body was determined by the IDM. According to the experimental data, as shown in Fig. 8, groups B and E are set as examples, the IDM of the backfill column under step-by-step load was fitted.

\[
E_i = -2.67 + 11.39 \times SSR - 5.34 \times SSR^2 \quad (R^2 = 0.951 \text{ group B}) \quad (2)
\]

\[
E_i = -0.00137 - 0.0137 \times SSR + 0.224 \times SSR^2 - 0.126 \times SSR^3 \quad (R^2 = 0.965 \text{ group E}) \quad (3)
\]

Where $E_i$ is the elastic modulus of the Maxwell model, and $SSR$ is the stress–strength ratio.

As shown in Fig. 7(b), the creep strain rate is almost a constant before entering the accelerated creep stage, which means that this creep strain rate could be regarded as the trigger of the creep model whether to start the accelerated stage. To describe the accelerated creep strain at the failure stage, a nonlinear dashpot with a creep strain rate trigger was connected to the viscoelastic-plastic model to construct the creep model, as shown in Fig. 14. The creep strain rate-triggered nonlinear dashpot has a rigid body when the creep strain rate is less than $\dot{\varepsilon}_a$ and does not work. When the creep strain rate is greater than $\dot{\varepsilon}_a$, the nonlinear dashpot is triggered; its constitutive relation is given by (4) (Qi et al. 2012).

\[
\begin{cases}
\sigma = \eta_{nl} \dot{\varepsilon} \quad (\varepsilon > \varepsilon_a) \\
\dot{\varepsilon}_{nl} = 0 \quad (\varepsilon \leq \varepsilon_a)
\end{cases}
\]

Where $\eta_{nl}$ is the viscosity coefficient of the nonlinear dashpot, $\dot{\varepsilon}$ is the creep strain rate, $\varepsilon_a$ is the creep strain rate.
is the trigger value of the nonlinear dashpot.

Fig. 14. Modified viscoelastic-plastic model for the creep of CGBM.

The axial strain of the CGBM column at each step could be obtained by

\[
\varepsilon_n(t) = \begin{cases} 
\frac{\sigma}{E_{1n}} + \frac{\sigma - \varepsilon}{\eta_{1n}} + \frac{\sigma - \varepsilon}{E_{2n}}(1-e^{-\frac{\varepsilon}{\eta_{2n}}}) & \text{if } \sigma < \sigma_{vp}, \quad \varepsilon < \varepsilon_a \\
\frac{\sigma}{E_{1n}} + \frac{\sigma - \varepsilon}{\eta_{1n}} + \frac{\sigma - \varepsilon}{E_{2n}}(1-e^{-\frac{\varepsilon}{\eta_{2n}}}) + \frac{\sigma - \sigma_{vp}}{\eta_{3n}}t & \text{if } \sigma \geq \sigma_{vp}, \quad \varepsilon \leq \varepsilon_a \\
\frac{\sigma}{E_{1n}} + \frac{\sigma - \varepsilon}{\eta_{1n}} + \frac{\sigma - \varepsilon}{E_{2n}}(1-e^{-\frac{\varepsilon}{\eta_{2n}}}) + \frac{\sigma - \sigma_{vp}}{\eta_{3n}}t + \frac{\sigma}{2\eta_{id}}t^2 & \text{if } \sigma \geq \sigma_{vp}, \quad \varepsilon > \varepsilon_a
\end{cases}
\]

(5)

Where \( \varepsilon_n(t) \) is the strain at each step, and \( n \) represents the step number; \( \sigma \) is the stress loading on the test sample; \( t \) means the creep loading time at each step; \( E_{1n} \) and \( E_{2n} \) are the elastic parameters of the spring element; \( \eta_{1n}, \eta_{2n} \) and \( \eta_{3n} \) are the viscosity coefficients of the Newton dashpot; \( \sigma_{vp} \) is critical stress to trigger the Saint Venant body, and it is activated when the SSR is over the 0.6; \( \tau = t - t_{\varepsilon > \varepsilon_a} \) and \( t_{\varepsilon > \varepsilon_a} \) is the time for the start of accelerated creep stage.

To describe the complete axial deformation process of backfill column under step-by-step load, the total strain was accumulated and can be expressed as

\[
\varepsilon_{total} = \sum_{1}^{n} \varepsilon_n(t)
\]

(6)

Where \( \varepsilon_{total} \) is the total axial strain; \( n \) represents the step number.

4.2 Determination of the parameters for the constitutive model

The parameters of samples B and E in the viscoelastic-plastic model were fitted, and the fitting results are shown in Table 5. The calculated results and measured data were compared, as shown in Fig. 15. The results of the two groups were highly consistent. It shows that the nonlinear creep model established in this paper is reasonable and reliable. Thus, the nonlinear creep constitutive model can accurately depict the axial strain development of the backfill
column under step-by-step load.

### Table 5 Parameter fitting results of samples B and E.

| Sample | Stress (MPa) | SSR     | $E_1$ (GPa) | $\eta_1$ (MPa · h) | $E_2$ (MPa) | $\eta_2$ (MPa · h) | $\eta_3$ (MPa · h) | $\eta_4$ (MPa · h$^2$) | $R$-square |
|--------|--------------|---------|-------------|--------------------|-------------|--------------------|--------------------|----------------------|------------|
| B      | 2.02         | 0.4     | 0.69        | 58524.902          | 8216.675    | 844.839            | -                  | -                    | 0.9994     |
|        | 2.52         | 0.5     | 2.11        | 101656.551         | 17838.637   | 4376.277           | -                  | -                    | 0.9729     |
|        | 3.02         | 0.6     | 2.37        | 125538.527         | 18080.891   | 4805.288           | -                  | -                    | 0.9858     |
|        | 3.52         | 0.7     | 2.65        | 130629.873         | 20939.243   | 6700.095           | -9.63e22           | -                    | 0.9910     |
|        | 4.025        | 0.8     | 2.94        | 112494.902         | 25147.119   | 10460.961          | -5.27e26           | -                    | 0.9952     |
|        | 4.528        | 0.9     | 3.17        | 133037.883         | 24546.043   | 14754.544          | 4.46e20            | -                    | 0.9972     |
|        | 5.03         | 1.0     | 3.28        | 156570.82          | 24025.577   | 15825.899          | 1.57e27            | -                    | 0.9968     |
|        | 5.53         | 1.1     | 3.4         | 151209.82          | 19520.561   | 16785.725          | 1.15e22            | -                    | 0.9984     |
|        | 6.04         | 1.2     | 3.42        | 10351.7587         | 1.64e24     | 2.26e5             | -3.13e19           | -                    | 0.9878     |

| Sample | Stress (MPa) | SSR     | $E_1$ (GPa) | $\eta_1$ (MPa · h) | $E_2$ (MPa) | $\eta_2$ (MPa · h) | $\eta_3$ (MPa · h) | $\eta_4$ (MPa · h$^2$) | $R$-square |
|--------|--------------|---------|-------------|--------------------|-------------|--------------------|--------------------|----------------------|------------|
| E      | 2.013        | 0.4     | 0.777       | 59632.399          | 9431.944    | 1364.912           | -                  | -                    | 0.9645     |
|        | 3.019        | 0.6     | 1.899       | 110674.062         | 14921.977   | 1736.174           | -                  | -                    | 0.9628     |
|        | 4.024        | 0.8     | 2.409       | 127934.897         | 16063.746   | 2721.757           | 3.46e27            | -                    | 0.9665     |
|        | 4.526        | 0.9     | 3.166       | 144153.869         | 46665.205   | 20798.086          | 3.64e5             | -                    | 0.9966     |
|        | 5.029        | 1.0     | 3.376       | 101077.646         | 36418.481   | 17430.376          | 4.44e27            | -                    | 0.9968     |
|        | 5.532        | 1.1     | 3.521       | 92944.718          | 23458.735   | 14750.221          | 4.77e21            | -                    | 0.9975     |
|        | 6.034        | 1.2     | 3.476       | 7524.703           | -7.21e12    | 4.40e11            | 1.01e20            | 28326.812       | 0.9201     |

**Fig. 15.** Comparison of the experimental and simulation results of samples (a) B and (b) E.

### 5 Conclusions

In this study, five step-by-step loading paths are used to simulate the loading history of the roof loading to the backfill columns. The deformation and instability properties of the CGBM column under step-by-step load were analyzed, and the following conclusions were drawn:

1. As SSR increases, the axial instantaneous strain decreases gradually, the axial creep strain decreases first and then increases. In the high SSR, the axial creep strain is greater than the axial instantaneous strain, and the difference between the creep strain and the instantaneous strain at each step increases with the increase in SSR. The lateral instantaneous strain decreases first and then increases, while the lateral creep strain increases continuously. When SSR is less
than 0.6, the lateral positions of the backfill column shrink during the creeping process. In the high-stress levels, lateral creep strain develops faster than axial creep strain, and the stress threshold of axial is larger than that of lateral.

(2) The backfill column shows the axial creep hardening and lateral creep softening properties during the step-by-step loading process. The ultimate stress and its corresponding strain of the backfill column under step-by-step load are greater than those of the uniaxial compression test. The instantaneous deformation modulus shows an upward trend on the whole, but it is affected by the step-by-step loading increment and paths. The instantaneous Poisson’s ratio exhibits a concave upward trend and is larger than that in the conventional test.

(3) The ultimate bearing capacity of the backfill column under step-by-step loading is related to the step-by-step loading increment and paths, small increment uniform loading ≥ large to small increment uniform loading ≥ small to large increment uniform loading > large increment uniform loading ≥ uniaxial compression. The development of cracks of the backfill column under step-by-step load could be divided into 4 stages according to the SSR. The non-uniformity of the lateral deformation of the backfill column leads to the excessive localized deformation that mostly occurs at the middle of the backfill column and produces macroscopic cracks, which causes the overall instability.

(4) The CGBM column has obvious rheological characteristics, and the creep strain of the backfill column has nonlinear characteristics. Under different step-by-step loading paths, the axial creep strain rate is nearly a constant before entering the accelerated creep stage. A nonlinear creep constitutive model with a creep strain rate trigger was established to express the development of the axial strain of the backfill column under the step-by-step load.

In this research, the small size sample was tested, in the future, the large size sample will be tested, and the damage will be monitored using acoustic emission and ultrasonic equipment during the step-by-step loading process.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.
Author contribution

Yuxia Guo: conceptualization, funding acquisition, methodology, and writing-review and editing. Hongyu Ran: Experiment, investigation and writing-original draft. Guorui Feng: investigation, supervision, funding acquisition, and writing-review and editing. Xianjie Du: writing-review and editing. Yonghui Zhao: experiment and investigation. Wenshuo Xie: experiment and investigation.

Funding

This work is supported by the National Natural Science Foundation of China (51974192), Shanxi province postgraduate education innovation project (2020SY567), Distinguished Youth Funds of National Natural Science Foundation of China (51925402), Shanxi Science and Technology Major Project (20201102004), and the Applied Basic Research Project of Shanxi Province (201801D121092).

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Competing interest The authors declare no competing interests

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Figures

Figure 1

Schematic diagram of the unconfined backfill columns in constructional backfill mining: (a) layout of the unconfined backfill column, (b) load on the unconfined backfill column.

Figure 2

Morphology of raw material and test samples.
Figure 3

Particle size distribution of fly ash (a) and coal gangue aggregate (b).

Figure 4

Testing machine and the distribution of strain gauges.
Figure 5

Strain–time curve and stress–time curve under uniaxial compression.
Figure 6

Stress–strain curve under step-by-step load and uniaxial compression.

Figure 7

(a) Strain–time curve under step-by-step load. (b) Strain–time curve during the creep instability process.
Figure 8
Development of instantaneous deformation modulus.

Figure 9
(a) Specific creep strain at different stress–strength ratios; (b) Accumulation of creep strain.
Figure 10

Development of (a) instantaneous strain and (b) creep strain of group B under step-by-step load.

Figure 11

(a) Curve of instantaneous Poisson's ratio; (b) Accumulation of the lateral strain of sample B.
Figure 12

Schematic description of the production of cracks and cracking processes.
Figure 13

Failure forms of the CGBM samples.

The diagram shows a stress-strain relationship with the following components:

- Maxwell (\( \eta_1 \))
- Kelvin (\( E_2 \))
- Bingham (\( \eta_3 \), \( \sigma_{vp} \))
- Nonlinear (\( \eta_{nl} \), \( \varepsilon_a \))

The equations for the stress-strain relationship (\( \varepsilon(t) \)) are:

- Maxwell: \( \varepsilon_1 = \frac{\sigma}{E_1} + \eta_1 \cdot \dot{\varepsilon}_1 \)
- Kelvin: \( \varepsilon_2 = \frac{\sigma}{E_2} + \eta_2 \cdot \dot{\varepsilon}_2 \)
- Bingham: \( \varepsilon_3 = \frac{\sigma - \sigma_{vp}}{\eta_3} + \eta_3 \cdot \dot{\varepsilon}_3 \)
- Nonlinear: \( \varepsilon_4 = \frac{\sigma - \sigma_{vp}}{\eta_{nl}} + \eta_{nl} \cdot \dot{\varepsilon}_4 \)

Where \( \sigma \) is the stress, \( \sigma_{vp} \) is the yield stress, and \( \varepsilon(t) \) is the strain at time \( t \).
Figure 14

Modified viscoelastic-plastic model for the creep of CGBM.

Figure 15

Comparison of the experimental and simulation results of samples (a) B and (b) E.