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Creep characteristics and instability analysis of concrete specimens with horizontal holes

Yajun Xin[1,2a], Haichun Hao[1b], Xin Lv[1b] and Hongying Ji*[3,4]

[1]School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan, China
[2]The Collaborative Innovation Center of Coal Safety Production of Henan Province, China
[3]Institute of Resource and Environment, Henan Polytechnic University, Jiaozuo, Henan, China
[4]The Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Henan Province, China

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Abstract. Uniaxial compressive strength test and uniaxial compression creep one were produced on four groups of twelve concrete specimens with different hole number by RLW-2000 rock triaxial rheology test system. The relationships between horizontal holes and instantaneous failure stress, the strain, and creep failure stress, the strain, and the relationships between stress level and instantaneous strain, creep strain were studied, and the relationship between horizontal holes and failure mode was determined. The results showed that: with horizontal hole number increasing, compressive strength of the specimens decreased whereas its peak strain increased, while both creep failure strength and its peak strain decreased. The relationships between horizontal holes and compressive strength of the specimens, the peak strain, were represented in quadratic polynomial, the relationships between horizontal holes and creep failure strength, the peak strain were represented in both linear and quadratic polynomial, respectively. Instantaneous strain decreased with stress level increasing, and the more holes in the blocks the less the damping of instantaneous strain were recorded. In the failure stress level, instantaneous strain reversally increased, creep strain showed three stages: decreasing, increasing, and sharp increasing; in same stress level, the less holes the less creep strain rate was recorded. The compressive-shear failure was produced along specimen diagonal line where the master surface of creep failure occurred, the more holes in a block, the higher chances of specimen failure and the more obvious master surface were.

Keywords: horizontal holes; concrete specimen; creep characteristics; strength characteristics; failure mode

1. Introduction

With mining depth increasing, stress concentration in surrounding rock becomes serious in deep gateway, the rheology characteristics of surrounding rock in deep gateway gradually reveals obviously, and gateway stability control has more difficulties. It is a development trend to realize stability of surrounding rock in deep gateway by cooperation support of borehole pressure relief and resistance force. Drilling could damage the stability of surrounding rock, and the number of holes affects directly surrounding rock strength and stress relief. Reasonable hole parameters (number and arrangement) could facilitate the coordination of surrounding rock bearing and stress relief in deep gateway, realize the long-term rheological stability of surrounding rock in deep gateway by borehole pressure relief, and guarantee the safe mine production.

Recently, there are many studies on uniaxial compression mechanics of coal-rock and perforated coal-rock (Wu *et al.* 2010, Zhao *et al.* 2014, Li *et al.* 2011, Li *et al.* 2016, Xin *et al.* 2017, Kamran *et al.* 2015), and the further studies on the construction of mechanical model and deformation evolution of concrete, rock, are also gradually deepening (Zhu *et al.* 2002, Ma *et al.* 2006, Reiko and Richard 2011, Wang *et al.* 2011, Shokrieh *et al.* 2017, Su *et al.* 2017, Emara *et al.* 2017, Emara *et al.* 2018, Zhou *et al.* 2008, Hodhod *et al.* 2018). The study on mechanics property of reserved-hole rock has achieved initial success (André *et al.* 2016, Du *et al.* 2017, Haeri *et al.* 2015, Haeri and Sarfarazi 2016), it was found from damage evolution magnetic-resonance imaging test of hole hard rock under static-dynamic loading that damaged degree of square-hole specimen was more serious than circular-hole one in the same loading (Li *et al.* 2015). The relationship curve between average maximum shear strain on rock surface and axial displacement could reflect well the evolution progress and the laws of rock deformation fracture (Liu and Li 2010). The uniaxial, biaxial, triaxial compression fracture characteristics of rock specimen were obtained by calculating and analyzing 3D damaging progress of hole-rock specimen (Xie *et al.* 2011). Uniaxial compression mechanics property of double-circular-hole rock was generalized and the initial damage produced from inner wall caving, and hole distance and hole angle affected the crack initiation stress level, fillet joint mode and damaging evolution (Zhu *et al.* 2015). Partial compression performance and bearing capacity of reserved-hole active-powder concrete were analyzed, practical calculation

*Corresponding author, Professor
E-mail: jihongying321@163.com
[a]Ph.D.
[b]Postgraduate

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(a) Filling mold (b) Making-hole tube

Fig. 1 Concrete specimen mold

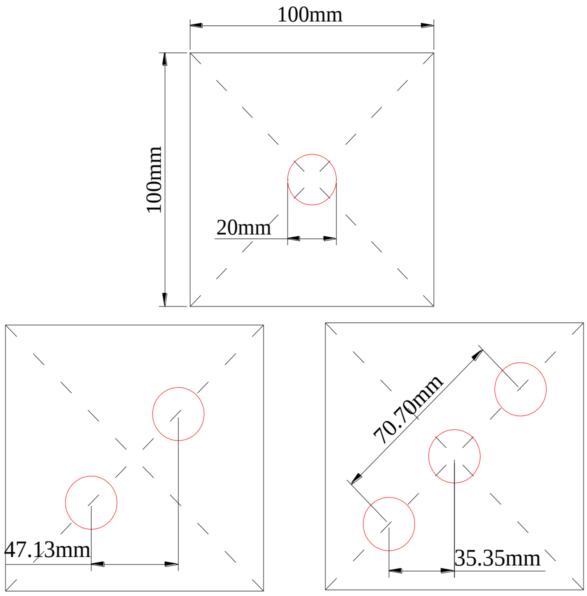


Fig. 2 Distribution of horizontal holes

method of partial compression bearing capacity of reserved-hole active-powder concrete was provided (Zhou and Hu 2014). The laws of strength, deformation, crack evolution on double-circular-hole sandstone with different hole diameter and different hole distribution were studied (Han *et al.* 2017). And the interaction test between round-hole defect and moving crack mode was operated, and increasing round-hole diameter can control effectively crack expanding (Yang *et al.* 2016).

Creep failure of rock depended mostly on time (Zhang *et al.* 2016). Based on single-stage and multi-stage creep test of shale in uniaxial and triaxial, time effect on specimen creep was analyzed, shale failure model in biaxial and triaxial compression was studied, new method of determining rock creep characteristics was provided, non-linear creep model was established, and rock creep model was derived according to variable order score derivative and continuous damage mechanics (Brijes and Priyesh 2015, Shrey and Brijes 2015, Ömer *et al.* 2014, Zhao *et al.* 2018, Tang et al. 2018). To study rock creep characteristics, mechanism deformation model and wavelet neural network reliability method were introduced into creep model (Firme *et al.* 2016, Janusz *et al.* 2016). Hard-rock rheological properties was analyzed from the structural anisotropy, then the concept of brittle creep emerged, and then brittle creep failure and model were studied (Wu *et al.* 2016, Wu *et al.* 2018, Brantut *et al.* 2013, Li and Shao 2016a,b). The relationships between concrete creep and various stresses, temperatures were analyzed, and rheology, strength and durability properties of concrete made from different materials was studied by experiments (Klovanych 2015, Bauchkar and Chore 2018, Mazloom *et al.* 2018). For finding the relationship between rock creep and concrete one, Moon compared rock creep characteristics and concrete ones (Moon 2001), and Rahimi studied the creep behavior of hollow cylindrical salt rock (Rahimi and Hosseini 2015).

It can be seen that, the above studies mainly were about basic mechanical property of reserved-hole specimen and about creep characteristics of rock, while the study on creep failure mechanism of horizontal-hole concrete specimen was lack. Uniaxial compressive strength test and uniaxial compression creep one were produced on four groups of twelve concrete specimens with different hole number by RLW-2000 rock triaxial rheology test system. The relationships between horizontal holes and instantaneous failure stress, the strain, and creep failure stress, were analyzed and the relationship between horizontal holes and failure form was determined. The results can provide reference for the releasing-pressure-hole parameter design (number and arrangement) in deep high-stress gateway.

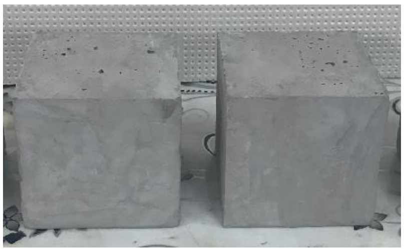
2. Test design

2.1 Specimen making

The conventional rate of cement and water was 3:1 in concrete engineering, so the concrete specimens with horizontal holes were made from GB175-2007 composite portland cement (P·C32.5) and water of the quality rate 3:1, which were mixed and stirred evenly and put in the square standard mode of 100mm×100mm×100mm to form (Fig. 1(a)). The holes in the concrete specimens were reserved by PVC tube. In order to reducing the boundary impact, 1/5 of the size of the square specimen 100mm×100mm (Fig. 1(b)), 20 mm, was selected as the hole diameter. The prefabricated concrete specimens were demoulded after 12 hours, and maintained with water for 28 days, when the prefabricated concrete specimens was the specimens for the test.

The hole number of the concrete specimens was respectively one, two, and three. The hole was in the center of the one-hole specimens; as for two and three holes were evenly distributed across the specimen diagonal leaving the segments equally spaced. Hole arrangements of the specimens were shown in Fig. 2.

Four groups of twelve specimens were operated in the test, including group A, B, C, and D, which were respectively consist of two no-hole specimens (the number A1-A2), four one-hole (the number B1-B4), four two-hole (the number C1-C4), three two-hole (the number D1-D2). Horizontal-hole concrete specimens were shown in Fig. 3. The loading roughness end of the concrete specimens was grinded well to the nonparallelism of less than 0.02 mm.



(a) The group A (no hole)

(b) The group B (one hole)

(c) The group C (two holes)

(d) The group D (three holes)

Fig. 3 Making concrete specimens

Fig. 4 RLW2000 rock triaxial rheology test system

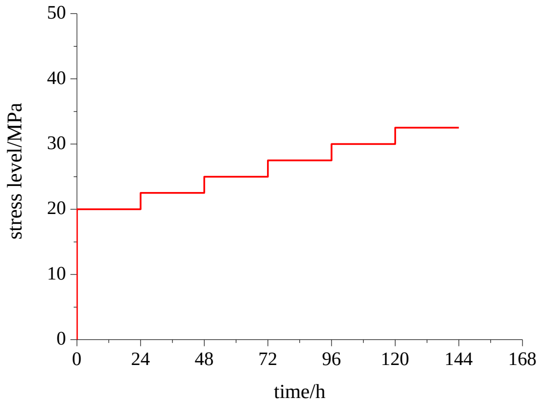


Fig. 5 Specimens load path

2.2 Test method

The test was operated in RLW-2000 rock triaxial rheology test system, which was full-servo controlled by computer (Fig. 4). Creep characteristics and instability mechanism of concrete specimens with different hole number were studied in the displace loading test, and load stress and specimen displace were automatically collected by computer during the test.

2.2.1 Uniaxial compression scheme

The uniaxial compressive strength test was operated at the loading rate 0.01 mm/s on the non-hole concrete specimens A1 and A2, the one-hole concrete specimens B1 and B2, the two-hole concrete specimens C1 and C2 for analyzing their uniaxial compressive strength characteristics and deformation mechanism, meanwhile the reasonable creep test scheme was determined.

2.2.2 Initial stress level

The initial stress level of concrete specimens with holes was roughly determined at 50% of uniaxial compressive strength on non-hole concrete specimens in creep test, which was generally the boundary of high stress level and low stress level. The strength of concrete specimen was degrading with hole number increasing, therefore initial stress level on the concrete specimens with different hole number was adjusted to 20 MPa.

2.2.3 Creep test design

Concrete specimens: For analyzing the effect of hole numbers on creep characteristics of concrete specimens, the uniaxial compressive creep test was operated on the one-hole specimens B3 and B4, the two-hole specimens C3 and C4, and the three-hole specimens D1 and D2.

Loading rate: Displace loading was used in creep test, and the loading rate was same to the one of uniaxial compressive strength 0.01 mm/s.

Test design: According to the results of uniaxial compressive test, the first stress level was determined at 20 MPa, the loading gradient was 2.5 MPa, the loading rate was 0.01 mm/s, and creep time was 24h in every stress level. The specimens were loaded to the first stress level (20 MPa) in displace loading rate 0.01 mm/s, then loaded to the second stress level (22.5 MPa) following creep time 24h, and then loaded to the third stress level (25 MPa) following creep time 24h, in turn, to the last stress level of specimen failure (Fig. 5). Meanwhile, the test phenomena was recorded, and the data was analyzed.

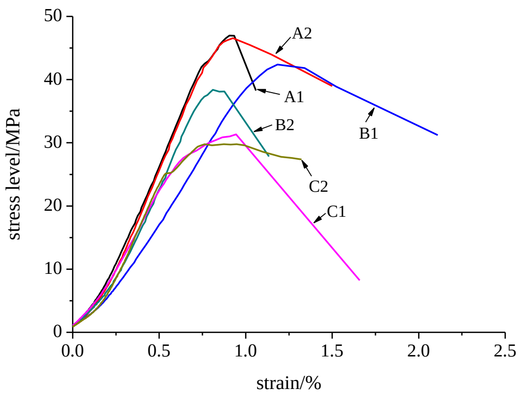


Fig. 6 Uniaxial compression stress-strain curves

3 Test result analysis

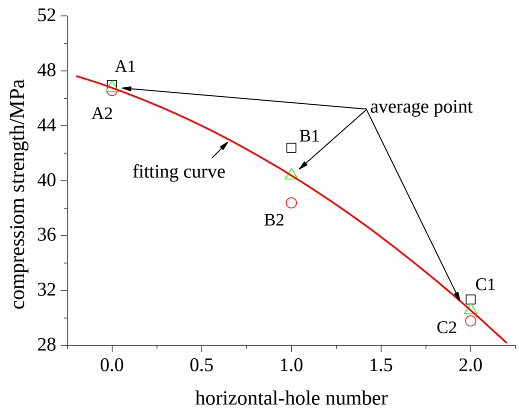
3.1 The relationships between horizontal holes and instantaneous failure stress and strain

Horizontal hole number affects mechanism property of concrete specimens due to the different inner structure. The stress-strain curves of uniaxial compressive strength on non-, one-, two-hole, concrete specimens were shown in Fig. 6, and the data in Table 1.

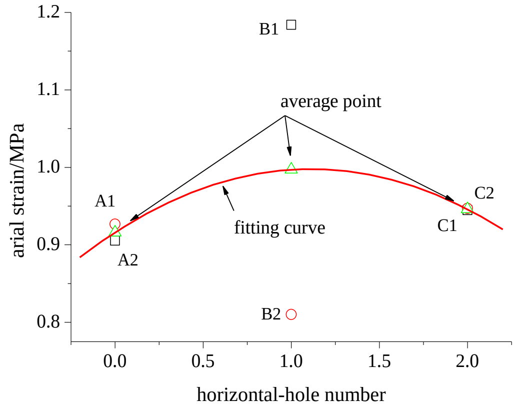
It could be seen from Fig. 6 that, the uniaxial compressive stress-strain curves of horizontal-hole concrete specimens included five stages: original void compaction, linear elastic, elastoplastic transition, plastic, and failure, whose characteristics were obvious. The difference of stress-strain curves on concrete specimens with the same number of hole was less, that was, the curves were roughly coincident. While the difference of stress-strain curves on the one-hole specimens (the specimens B1 and B2) was more, the deviation degrees of peak strength and peak strain was respectively 7.02% and 26.52%, the more discrete was possibly caused during the making and operating of the specimen B2, whose curing conditions were weaker than the others.

Wholly, in the stress-strain curve of horizontal-hole concrete specimens, elastic stage was obvious, mechanism index was stable, and homogeneity was fine, which met creep characteristics of horizontal-hole concrete specimen.

Fig. 7 shows the relationships between horizontal-hole number and uniaxial compression strength, peak strain. From the Fig. 7(a), the number of holes from zero to one, the average instantaneous strength of concrete specimens decreased from 46.7625 MPa to 40.3810 MPa with the damping of 13.65%; as for the number of holes from one to two, the average instantaneous strength of concrete specimens decreased from 40.3810 MPa to 30.5630 MPa with the damping of 24.31%. From the above, with the number of holes increasing, the instantaneous strength of concrete specimen decreased, and the damping increased.



(a) The relationship between horizontal-hole number and uniaxial compression strength



(b) The relationship between horizontal-hole number and peak strain

Fig. 7 The relationships between horizontal-hole number and uniaxial compression strength, its peak strain

The relationship between horizontal-hole number and uniaxial compressive strength of concrete specimens was expressed by the following quadratic polynomial in Eq. (1)

$$\sigma_c = 46.7625 - 4.6634N - 1.7182N^2 \tag{1}$$

Where: σ_c was uniaxial compressive strength of concrete specimen, MPa. N was the number of horizontal holes.

The correlation coefficient was R^2=1.

From the Fig. 7(b), the number of holes from zero to one, the average peak strain of concrete specimens increased from 0.9160% to 0.9971%, the growth of 8.85%; the number of holes from one to two, the average peak strain of concrete specimens decreased from 0.9971% to

Table 1 Uniaxial compression test data

No.	A1	A2	Average	B1	B2	Average	C1	C2	Average
Instantaneous failure strength /MPa	46.959	46.566	46.7625	42.3863	38.3756	40.3810	31.3360	29.7900	30.5630
Peak strain/%	0.9054	0.9266	0.9160	1.1840	0.8101	0.9971	0.9447	0.9471	0.9459
Horizontal-hole number		0			1			2	

Table 2 Creep failure test data

No.	B3	B4	Average	C3	C4	Average	D1	D2	Average
Creep failure strength/MPa	45.00	40.00	42.50	30.00	32.50	31.25	29.93	/	29.93
Peak strain/%	1.4107	1.4509	1.4308	1.0535	1.2329	1.1432	0.8507	/	0.8507
Horizontal-hole number		1			2			3	

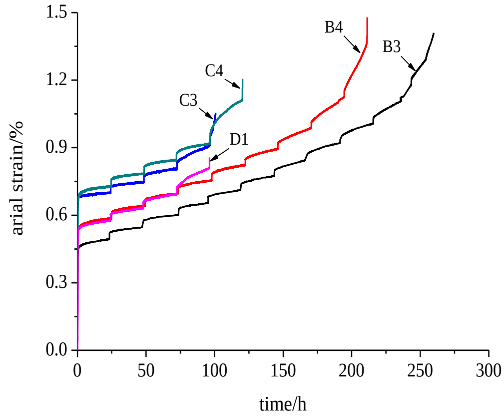


Fig. 8 Creep curves of the horizontal-hole concrete specimens

0.9459%, the damping of 5.13%. From the above, with the number of holes increasing, the peak strain of concrete specimen increased, then decreased, and tended wholly to increase obviously.

The relationship between the number of horizontal holes and axial peak strain of concrete specimens was expressed by quadratic polynomial in Eq. (2)

$$\varepsilon_c = 0.9160 + 0.1472N - 0.0661N^2 \tag{2}$$

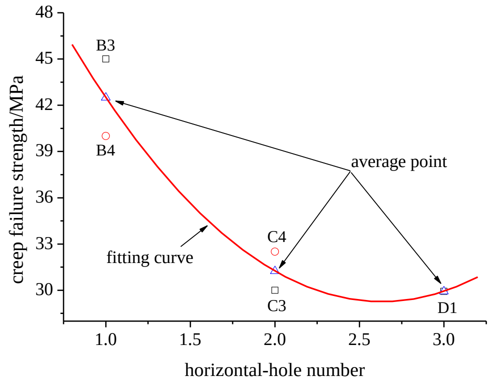
The correlation coefficient was R^2=1.

Generally, with the number of horizontal holes increasing, the compressive strength of concrete specimens decreased, the peak strain increased. If the number of horizontal holes was from zero to two, compressive strength of concrete specimens decreased by 34.64%, and peak strain increasing value was 3.26%. Quadratic polynomial could express the relationships between horizontal holes and compressive strength of concrete specimens and it speak strain.

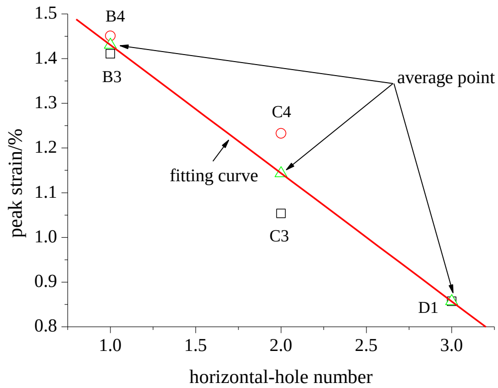
3.2 The relationships between horizontal holes and creep failure stress and the strain

Uniaxial compressive creep test was operated on concrete specimens with different horizontal holes (the specimens B3 and B4 of group B, the specimens C3 and C4 of group C, the specimens D1 and D2 of group D), and the data in Table 2, the specimen D2 wasn’t analyzed because of no saved data during test. Fig. 8 showed creep curves of the horizontal-hole concrete specimens. Instantaneous strain was the change of axial strain on concrete specimens under dynamic loading from one stress level to next stress level; creep strain was the change of axial strain on concrete specimens under invariable load in one stress level, whose value equaled to the initial load in the next stress level.

It could be seen from the Fig. 8 that, with stress level increasing, the instantaneous strain on horizontal-hole concrete specimens decreased, the creep strain increased, and creep characteristics was similar to general rock, including three stages: initial, stability and acceleration creep. The fewer the number of horizontal holes, the more stress level gradients on concrete specimens, the higher creep failure strength, the more creep deformation, and the more acceleration creep characteristics were developed. Vice versa, the less stress level gradients on concrete specimens, the lower creep failure strength, the more plastic creep failure, the less creep strain of the last gradient, and even instantaneous loading failure showed. Generally, creep strain of concrete specimens increased with stress level increasing, and creep strain on concrete specimens with different horizontal-hole arrangement were different.



(a) The relationship between horizontal-hole number and creep failure strength



(b) The relationship between horizontal-hole number and peak strain

Fig. 9 The relationships between horizontal-hole number and creep failure strength, peak strain

Fig. 9(a) shows the relationship between horizontal-hole number and creep failure strength. The number of holes from one to two, the average creep failure strength of concrete specimens decreased from 42.50 MPa to 31.25 MPa, the damping of 26.47%; the number of holes from two to three, the average creep failure strength of concrete specimens decreased from 31.25 MPa to 29.93 MPa, the damping of 4.22%. From the above, with the number of holes increasing, the creep failure strength of concrete specimen decreased, and the damping decreased.

The relationship between the number of horizontal holes and creep failure strength on concrete specimens was expressed by quadratic polynomial in Eq. (3).

$$\sigma_s = 63.6828 - 24.1492N + 4.9664N^2 \tag{3}$$

Where: σ_s was creep failure strength of concrete specimen, MPa. N was the number of horizontal holes.

The correlation coefficient was R^2=1.

Fig. 9(b) showed the relationship between horizontal-hole number and peak creep failure strain. The number of holes from one to two, the average peak strain of concrete specimens decreased from 1.4308% to 1.1432%, the damping of 20.10%; the number of holes from two to three, the average peak strain of concrete specimens decreased from 1.1432% to 0.8507%, the damping of 25.59%. From the above, with the number of holes increasing, the peak creep failure strain of concrete specimen linearly decreased.

The relationship between the number of horizontal holes and axial peak strain on concrete specimens was expressed by linear equation in Eq. (4).

$$\varepsilon_c = 0.7175 - 0.2869N \tag{4}$$

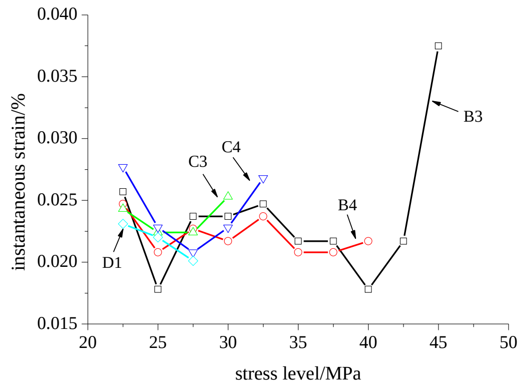
The correlation coefficient was R^2=1.

In general, with the number of horizontal holes increasing, the creep failure strength of concrete specimens and peak strain decreased. With the number of holes decreasing from one to three, the damping of creep failure strength and peak strain was 29.58% and 40.10% respectively. The relationship between the number of horizontal holes and creep failure strength could be expressed by quadratic polynomial, while the relationship between the number of horizontal holes and peak strain by linear.

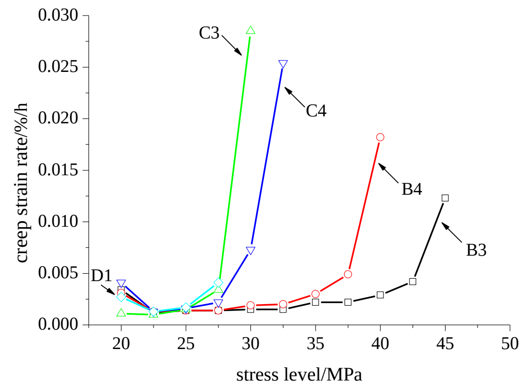
3.3 The relationships between stress level and instantaneous strain, creep strain rate

In order to analyze the relationship between stress level of horizontal-hole concrete specimens and instantaneous strain conveniently, the comparison analysis of instantaneous strains were operated in same stress level (except the instantaneous strain in 20 MPa stress level and instantaneous loading failure), including two cases, one in the last integral stress level stage, the other in the same level.

It could be seen from Fig. 10(a) that, stress level on one-hole concrete specimen B3 increased from 22.5 MPa to 42.5 MPa while instantaneous strain decreased from 0.0257% to 0.0219%, the damping of 14.79%; stress level on one-hole concrete specimen B4 increased from 22.5 MPa to 37.5 MPa while instantaneous strain decreased from 0.0247% to 0.0208%, the damping of 15.79%. Therefore the average damping of instantaneous strain on one-hole concrete specimens B3 and B4 was 15.29% before the last stress level.



(a) The relationship between stress level and instantaneous strain



(b) The relationship between stress level and creep strain rate

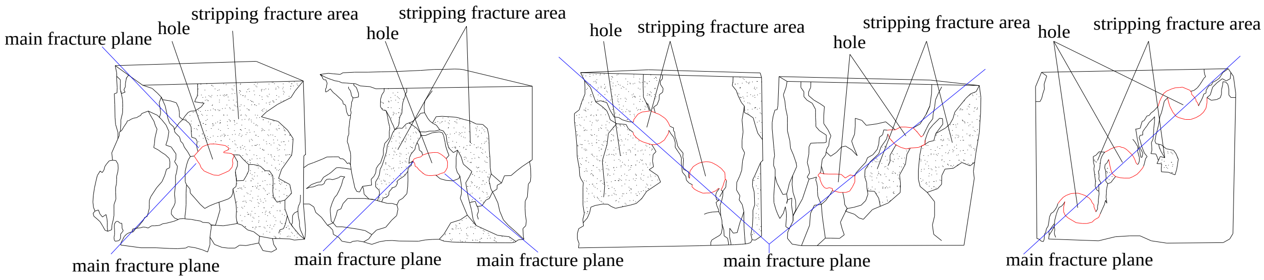
Fig. 10 The relationships between stress level and instantaneous strain, creep strain rate

Stress level on two-hole concrete specimen C3 increased from 22.5 MPa to 27.5 MPa while instantaneous strain decreased from 0.0243% to 0.0224%, the damping of 7.82%; stress level on two-hole concrete specimen C4 increased from 22.5MPa to 30.0MPa while instant aneous strain decreased from 0.0277% to 0.0228%, the damping of 17.69%. Therefore the average damping of instantaneous strain on two-hole concrete specimens C3 and C4 was 12.76% before the last stress level.

Stress level on three-hole concrete specimen D1 increased from 22.5 MPa to 27.5 MPa while instantaneous strain decreased from 0.0231% to 0.0220%, the damping of 4.76%. In the last stress level, instantaneous strain of horizontal-hole concrete specimens increased sharply, the instantaneous strain growth of the one-hole concrete specimens B3 and B4 was 38.57%, the one of the two-hole concrete specimens C3 and C4 was 15.25%, the concrete specimen D1 failed during loading, which wasn't analyzed.

In the same stress level except the last one, instantaneous strain of concrete specimens decreased with stress level increasing, the more the number of holes, the less the damping of instantaneous strain, which was shown by internal compaction and elastic compression produced in concrete specimens. In the last stress level, instantaneous strain of concrete specimens increased sharply, the more the number of holes, the less the growth of instantaneous strain,

(a) Creep fracture morphology in horizontal-hole concrete specimens



(b) The sketch of creep fracture morphology in horizontal-hole concrete specimens

Fig. 11 Creep failure morphology of concrete specimens

which was shown by plastic initial and instability of concrete specimens following elastic compression.

Fig. 10(b) showed the relationship between stress level and creep strain. Stress level on one-hole concrete specimens B3 and B4 increased from 20.0 MPa to 22.5 MPa, the average creep strain rate decreased from 0.0032%/h to 0.0012%/h, creating an average damping of 62.01%. Stress level on one-hole concrete specimen B3 increased from 22.5 MPa to 42.5 MPa, creep strain rate increased from 0.0012%/h to 0.0042%/h, the average growth of 250.00%. The average growth of creep strain rate was 31.25% in every stress level except the last one. Stress level on one-hole concrete specimen B4 increased from 22.5 MPa to 37.5 MPa, creep strain rate increased from 0.0013%/h to 0.0049%/h, the average growth was 276.92%, while the average growth of creep strain rate was 46.15% in every stress level except the last one which was 232.92%.

Stress level on two-hole concrete specimens C3 and C4 increased from 20.0 MPa to 22.5 MPa, the average creep strain rate decreased from 0.0026%/h to 0.0011%/h, creating an average damping of 56.80%. Stress level on two-hole concrete specimen B3 increased from 22.5 MPa to 27.5 MPa, creep strain rate increased from 0.0010%/h to 0.0034%/h, developing an average growth 240.00%, while the average growth of creep strain rate was 120.00% in every stress level except the last one. Stress level on two-hole concrete specimen C4 increased from 22.5 MPa to 30.0 MPa, creep strain rate increased from 0.0013%/h to 0.0073%/h, creating an average growth of 461.54%, while the average growth of creep strain rate was 153.85% in every stress level except the last one which was 493.09%.

Stress level on three-hole concrete specimen D1 increased from 20.0 MPa to 22.5 MPa, creep strain rate decreased from 0.0027%/h to 0.0013%/h, creating an average damping of 107.69%. Stress level on the specimen D1 increased from 22.5 MPa to 27.5 MPa, creep strain rate increased from 0.0013%/h to 0.0017%/h. The growth of creep strain rate of the concrete specimens D1 was 141.18% in the last stress level.

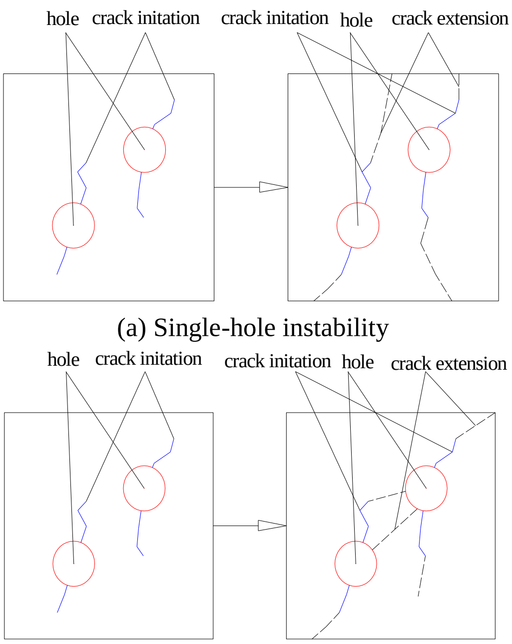
In the whole, the more the number of holes was, the less stress level gradients were. In the same stress level, the less the number of holes, the less creep strain rate, and vice versa. With stress level increasing, creep strain rate of horizontal-hole concrete specimens displayed three stages: decreasing, increasing, and increasing sharply. In the first stress level (20.0 MPa), creep strain rate of horizontal-hole concrete specimens was high, pore continued to close following instantaneous compression. In the second stress level (22.5 MPa), creep strain rate of horizontal-hole concrete specimens began to decrease, pore closing finished and put into elastic stage, and then creep strain rate increased with the increasing stress level. Linear correlation was noticed during which the concrete specimens entered continuous linear elastic stage. In the last stress level, creep strain rate of concrete specimens increased sharply, which indicated possibility of future failure.

3.4 The relationships between horizontal holes and fracture morphology and instability mode

3.4.1 The relationship between horizontal holes and creep fracture morphology

Fig. 11 shows creep fracture morphology in horizontal-hole concrete specimens. It could be seen from Fig. 11 that the concrete specimens failed easily along the weak plane of internal friction angle. The specimens failed with fracture coalescence between holes along diagonal. Wholly, the specimens instability belonged to compressive-shear failure along diagonal fracture plane, the more the number of holes, the easier the fracture morphology of the concrete specimens and the more evident the main fracture plane and vice versa.

One-hole concrete specimens could be subjected to the more stress levels, the fragments was much in the surface, the main fracture plane was not evident, as for compressive-shear morphology was in the specimens, and the crack



(a) Single-hole instability

(b) Coalescence-hole instability

Fig. 12 Instability modes of concrete specimens with horizontal holes

range was large on the surface.

The creep fracture planes was obvious in two-hole concrete specimens, including main and second the fracture plane, which worked during instability progress and were accompanied by cracks.

During instability progress of three-hole concrete specimens, main fracture plane worked mainly by three hole coalescence, which were the main factor of specimen instability. And the more the number of holes, the less the gap between the holes, the easier the hole coalescence and the specimen instability.

3.4.2 The relationship between horizontal holes and creep instability mode

Based on the location and the number of horizontal holes in concrete specimens, creep instability modes were divided into two types: single-hole instability and coalescence-hole instability (Fig. 12).

In one-hole concrete specimens or multi-hole ones, with stress level increasing, the specimens were in plastic stage, and cracks occurred and kept extending. When main fracture plane diffused around a hole and was not coalescence with others, and the specimen became unstable, which was refereed as singe-hole instability (Fig. 12(a)). Therefore, the horizontal-hole concrete specimens B3 and B4 belonged to single-hole instability.

In Coalescence-hole concrete specimens, with stress level increasing, the specimens were in plastic stage, and cracks occurred and kept extending. When main fracture plane diffused around a hole and coalescence with others, and the specimen became unstable, which referred as coalescence-hole instability (Fig. 12(b)). Therefore, the horizontal-hole concrete specimens C3, C4 and D1 belonged to coalescence-hole instability.

4. Discussions

The concrete specimens within same batch were homogeneity, while making process and curing time of the concrete specimens affected its mechanical properties (for example, the strength of concrete specimens increasing with time), making process and curing of concrete specimens should be further strictly controlled in the next test.

Basic creep characteristics of concrete specimens with horizontal holes were shown well in the test, while creep strain was small for the short creep time, 24 hours, in every stress level, which was shorter than the field creep one. Designing long-time creep test will be the focus on further research.

5. Conclusions

- With the increasing number of horizontal holes, uniaxial compressive strength of the specimen decreased while the peak strain increased. Quadratic polynomial could represent the relationships between the number of horizontal holes and the uniaxial compressive strength and its peak strain.
- With increasing number of horizontal holes, both uniaxial creep failure strength of the concrete specimen and the peak strain decreased. The relationships of the number of horizontal holes and uniaxial creep failure strength and its peak strain, could both be represented by quadratic polynomial and linear equation respectively.
- With stress level increasing, instantaneous strain of the concrete specimen decreased, creep strain rate showed three stages: decreasing, increasing, and increasing sharply. In the same stress level, the more the number of holes, the more evident instantaneous strain damping, the larger the creep strain rate.
- Creep failure of the concrete specimen was compressive-shear morphology through main fracture plane along diagonal. The more the number of holes, the simpler the failure morphology of the concrete specimen, and the more evident the main fracture plane. Creep failure modes included singe-hole instability and coalescence-hole one.

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