Research Article

Short-Term Gradation Loading Creep Properties and Failure Characteristics of High-Strength Fly Ash Concrete for Underground Engineering

Bing Li ¹, Lianying Zhang ¹, Hai Pu ^{2,3}, Xianbiao Mao ^{2,3}, Peitao Qiu ¹,
Zhong Zhao ¹ and Chao Ma ¹

¹School of Civil Engineering, Xuzhou Institute of Technology, Xuzhou 221008, Jiangsu, China

²State Key Laboratory of Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou 221008, Jiangsu, China

³School of Mechanics and Civil Engineering, China University of Mining & Technology, Xuzhou 221008, Jiangsu, China

Correspondence should be addressed to Lianying Zhang; zhanglianying@126.com

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In order to study the short-term creep deformation of high-strength concrete with varying fly ash replacement ratios, concrete samples with 0, 20, 35, and 50 wt% fly ash were tested using an electrohydraulic servocontrolled creep testing system and characterized using scanning electron microscopy after fracturing. Three different creep deformation behaviors were observed over time under different stress levels, namely, decelerating, isokinetic, and accelerating creep, where the creep rate increased with increasing stress. Failure of the samples occurred once isokinetic creep was achieved. The peak stress of the concrete samples exhibited a parabolic trend with increasing fly ash content, where the peak stress in the 0, 20, 35, and 50 wt% samples during short-term gradation loading creep testing was 13.08%, 7.94%, 15.14%, and 14.50% lower, respectively, than the peak stress measured in conventional uniaxial compression testing. The accumulated creep of the samples was reported and can be used as a reference for future studies on the long-term creep characteristics of concrete. The macro- and microscopic failure modes of the fly ash concrete during short-term gradation loading creep under uniaxial compression were brittle cleavage fracturing.

1. Introduction

The rapid rise in the global population and economy has led to the depletion of shallow underground resources, and deeper exploration has inevitably increased. In turn, sudden disasters related to underground construction have become more frequent. The deeper underground space is a complicated environment associated with high ground stress, high ground temperature, and high karst water pressure, which pose significant challenges to engineering personnel and scientific researchers [1–3]. For example, deep coal is an important underground resource utilized in various countries, but accidents occur frequently during its mining due to the associated environment, lithology, exploitation, and transformation. Mine walls and roadway supports to control

rocks in coal mines should be improved. This development should encompass deep underground geomechanical testing technology, data on the physical and mechanical properties of the rocks, low stress and mining-induced stress field distribution laws, and the deformation and destruction mechanisms of the surrounding rocks. Further, control, support, and reinforcement technologies should be considered [4–7].

Concrete is one of the most widely used building materials, where applications have extended beyond conventional buildings to underground, aquatic, and marine structures. This broad spectrum of applicability is associated with a range of qualitative changes in concrete materials, where factors such as high stress, high corrosion, and high or low temperature play a role. Continued research and

practical implementation have contributed to the development of novel concrete materials with high strength and high or ultrahigh performance, such as fly ash concrete, slag concrete, and fiber concrete [8–13]. The development of concrete materials and technologies has led to advancements in deep underground space engineering. These scientific and technological research achievements are particularly relevant to mine sidewalls and roadway supports [14–19]. However, the concrete materials used in deep underground engineering must be further improved.

This study aimed to evaluate the short-term creep deformation of high-strength concrete with varying fly ash replacement ratios using the gradation loading test method. The creep mechanical properties and failure characteristics of the concrete samples were determined by analyzing the creep-time curves, peak strength, creep rate, and accumulated creep measurements, as well as macroscopic and microscopic observations after failure. These findings are expected to provide insights that support further engineering applications.

2. Experimental Program

2.1. Materials. The cementitious materials used in the experiment were Portland cement and fly ash supplied by two local companies, where the chemical compositions are given in Table 1. River sand was used as the fine aggregate, which had a fineness modulus of 2.8 and an apparent density of 2769 kg/m^3 . Crushed limestone was used as the coarse aggregate, which had a particle size of 5 to 20 mm and an apparent density of 2719 kg/m^3 . The polycarboxylate superplasticizer was provided by Zhejiang Wulong Chemical Co. Ltd (China).

2.2. Samples. Concrete samples ($100 \times 100 \times 300 \text{ mm}$) were produced according to the mixing ratios given in Table 2, where the fly ash replacement level (m) was either 0, 20, 35, or 50 wt%. A maintenance period of over 90 days was used. Three samples of cement with each fly ash replacement ratio were prepared for the uniaxial compression test and the gradation loading creep test.

2.3. Characterization. The strain gauge was mounted in a procedure that involved of patching, grinding, cleaning, and pasting steps (Figure 1). A strain gauge was mounted to each sample on its two symmetrical sides. Uniaxial compression testing was conducted before the stepwise creep loading test to determine the conventional uniaxial compressive peak strength of concrete with each fly ash replacement ratio (Table 3). An electrohydraulic servocontrolled compression testing machine was used (Changchun Kexin YAS-5000) (Figure 2). The gradation loading test method was used to evaluate creep deformation, where the specimen was loaded at a rate of 3 kN/s to 30% of its uniaxial compressive peak strength, held for 30 min, and unloaded. Stepwise compression was followed where the load was increased by 10% of the uniaxial compressive peak strength, held for 30 min, and unloaded. The process was repeated until the specimen

failed. The strain and stress were measured using the strain gauges and pressure sensors.

Scanning electron microscopy (SEM) was used to observe fragments of the concrete samples ($10 \times 10 \times 10 \text{ mm}$) at a consistent distance (about 10 mm) from the concrete surface (Figure 3). Analysis was conducted using the TESCAN VGEA3 SEM test system provided by the Civil Structure Laboratory of Xuzhou Institute of Engineering. Before observation, the samples were dried and sprayed with gold (SBC-12 Ion Sputter Coater).

3. Results and Discussion

3.1. Creep Deformation under Gradation Loading. The creep-time (ε - t) curves of concrete with varying fly ash replacement ratios under increasing stress revealed slightly different behavior between the three samples for each fly ash replacement ratio (Figure 4). This indicated that the results are associated with a certain level of discreteness. The creep deformation exhibited three trends at the different stress levels over time, namely, decelerating, isokinetic, and accelerating creep. Decelerating creep was predominantly observed at low stress levels, while isokinetic and accelerating creep became dominant under higher stress just before sample failure.

3.2. Uniaxial Compressive Peak Strength. The conventional uniaxial compression peak stress (σ_{c0}), creep peak stress (σ_c), and drop ratio ($r = (\sigma_{c0} - \sigma_c)/\sigma_{c0}$) of the fly ash concrete with varying replacement ratios (m) are given in Table 2 and Figure 5. The uniaxial compression peak stress values initially increased and subsequently decreased with increasing fly ash replacement. Thus, the trend was fitted according to a parabola, namely, $\sigma_{c0} = -154.47 m^2 + 68.83 m + 58.06$, where MPa is the unit of σ_{c0} . Specifically, $\sigma_{c0} = 58.1 \text{ MPa}$ at $m = 0 \text{ wt\%}$; $\sigma_{c0} = 65.5 \text{ MPa}$ at $m = 20 \text{ wt\%}$ (12.74% increase from $m = 0 \text{ wt\%}$); $\sigma_{c0} = 63.4 \text{ MPa}$ at $m = 35 \text{ wt\%}$ (9.12% increase from $m = 0 \text{ wt\%}$); and $\sigma_{c0} = 53.8 \text{ MPa}$ at $m = 50 \text{ wt\%}$ (7.40% decrease from $m = 0 \text{ wt\%}$). Thus, the maximum uniaxial compression peak stress was achieved in concrete with a fly ash replacement ratio between 20 and 35 wt%, where the fitted parabola indicated the value was 22.3 wt%.

The creep peak stress exhibited a similar parabolic trend with increasing fly ash replacement ratio and was fitted as $\sigma_c = -165.66 m^2 + 71.64 m + 50.93$, where MPa is the unit of σ_c . Specifically, $\sigma_c = 50.5 \text{ MPa}$ at $m = 0 \text{ wt\%}$; $\sigma_{c0} = 60.3 \text{ MPa}$ at $m = 20 \text{ wt\%}$ (19.41% increase from $m = 0 \text{ wt\%}$); $\sigma_{c0} = 53.8 \text{ MPa}$ at $m = 35 \text{ wt\%}$ (6.53% increase from $m = 0 \text{ wt\%}$); and $\sigma_{c0} = 46.0 \text{ MPa}$ at $m = 50 \text{ wt\%}$ (8.91 % increase from $m = 0 \text{ wt\%}$). Thus, the maximum creep peak stress was achieved at a fly ash replacement ratio between 20 and 35 wt %, namely, 21.6 wt% according to the fitted parabolic model. The conventional uniaxial compression peak stress and creep peak stress values exhibited very similar parabolic trends. Thus, optimization of the fly ash concrete for a large conventional uniaxial compression peak stress would simultaneously lead to a large creep peak stress.

TABLE 1: Chemical composition of the cementitious materials.

Materials	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	MgO (%)	Na ₂ O (%)	K ₂ O (%)	SO ₃ (%)
Cement	21.6	4.13	4.57	64.44	1.06	0.11	0.56	1.74
Fly ash	54.9	25.8	6.9	8.7	1.8	0.3	0.1	0.6

TABLE 2: Mixing ratios of the concrete.

Fly ash content (wt%)	Fly ash (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Stone (kg/m ³)	Water-cement ratio	Water (kg/m ³)
0.0	0.0	453.0	740.0	1112.0	0.32	145.0
20.0	91.0	362.0	740.0	1112.0	0.32	145.0
35.0	159.0	294.0	740.0	1112.0	0.32	145.0
50.0	226.5	226.5	740.0	1112.0	0.32	145.0

FIGURE 1: Mounting of strain gauges on the concrete samples.

TABLE 3: Creep peak stress (σ_c) and conventional uniaxial compression peak stress (σ_{c0}) of concrete with different fly ash replacement ratios (m).

m (wt %)		0	20	35	50
Axial compression test	σ_{c0} (MPa)	58.1	65.5	63.4	53.8
Gradation loading creep test	σ_c (MPa)	50.5	60.3	53.8	46.0
Drop ratio ($r = (\sigma_{c0} - \sigma_c)/\sigma_{c0}$)		13.08%	7.94%	15.14%	14.50%

The drop ratios were 13.08%, 7.94%, 15.14%, and 14.50% at fly ash replacement ratios of 0, 20, 35, and 50 wt%. Thus, creep and fly ash replacement had a dual influence on the conventional uniaxial compression peak stress. Creep caused a reduction in uniaxial compression peak stress, where a fly ash ratio of up to 21.6 wt% fly ash led to an improvement in the uniaxial compression peak stress of concrete. However, even the optimal level of 21.6 wt% did not compensate for the negative influence of creep deformation. When the fly ash replacement ratio was over 21.6 wt %, its positive effect was weakened.

3.3. Creep Rate. Specific samples were selected for the separation of the strain under varied stress levels, namely, sample 1 for 0 wt% fly ash (Figure 4(a)), sample 2 for 20 wt% fly ash (Figure 4(b)), sample 2 for 35 wt% fly ash (Figure 4(c)), and sample 2 for 50 wt% fly ash (Figure 4(d)). The instant strain was deducted from the corresponding stress level to give the creep strain-time ($\epsilon_{cp}-t$) curves (Figure 6). The strain at concrete failure (accelerating creep stage) was not calculated. Overall, the concrete exhibited different creep strain-time curves under different stress levels. Specifically, decelerating creep occurred under low stress, resulting in a relatively small creep value. A rise in stress level led to an increase in the creep value and creep rate. At a certain point, often near the peak stress of the concrete, decelerating and isokinetic creep was observed, where the failure occurred once isokinetic creep began.

The decelerating creep stage (Figure 7(a)) and the subsequent decelerating/isokinetic creep stage (Figure 8(a)) presented in Figure 6 were used for exponential function fitting in Figures 7(b) and 8(b), respectively, based on fitting functions (1) and (2). The creep rate ($d\epsilon_{cp}$) was calculated based on derivatization of the fitting parameters given in

FIGURE 2: Electrohydraulic servocontrolled creep test system with the following components: (1) guide screw, (2) bearing plate, (3) strain gauge, (4) concrete, (5) pressure transducer, (6) oil pump system, (7) cooling tower, (8) electric machinery, (9) track, (10) strain collection device, (11) controller, (12) power device, (13) underground space, and (14) bearing plate.

(a)

(b)

(c)

FIGURE 3: SEM analysis of the concrete samples. (a) Scanning electron microscope. (b) Samples for analysis. (c) Gold spraying equipment.

Tables 4 and 5. The fitted values were very similar to the experimental values:

$$\epsilon_{cp} = C_1 + A_1 e^{-t/B_1}, \quad (1)$$

$$\epsilon_{cp} = C_2 + A_2 t. \quad (2)$$

The creep rate-time ($d\epsilon_{cp}/dt$) curves for Figures 7(a) and 8(a) are given in Figures 9(a) and 9(b), respectively. The decelerating creep stage was associated with a gradual decrease in creep rate over time until reaching a rate of zero. The initial creep rate of the concrete with fly ash was significantly smaller than that with no fly ash replacement. However, this difference between the groups gradually decreased over time. The decelerating/isokinetic creep stage exhibited an initial decrease in creep rate over time that was rapid in the concrete with fly ash replacement ratios of 0 and

50 wt% and relatively slow at 20 and 35 wt%. The concrete samples eventually entered the isokinetic creep stage near the time of failure. The 20 wt% fly ash concrete exhibited the highest creep rate, followed by 35, 50, and 0 wt% (lowest), where the creep rate at 50 and 0 wt% was very similar.

3.4. Accumulated Creep. The accumulated creep (ϵ_{cp+}) was calculated as the creep generated at a specific stress level (σ_{sp}) plus the creep generated at all previous stress levels (Table 6 and Figure 10). The accumulated creep of the concrete mixed with fly ash increased with increasing stress, where two stages were observed. The accumulated creep increased slowly as stress increased below 40 MPa and began to rise sharply as the stress exceeded 40 MPa.

At stress below 40 MPa, the accumulated creep values were smaller in the concrete mixed with fly ash than the

FIGURE 4: Creep-time (ε_{cp} - t) curves of concrete mixed with fly ash replacement ratios of (a) 0, (b) 20, (c) 35, and (d) 50 wt% during gradation loading.

FIGURE 5: Creep peak stress (σ_c) and conventional uniaxial compression peak stress (σ_{c0}) of concrete with different fly ash replacement ratios.

concrete without fly ash. As the stress increased further, significant variations in the accumulated creep were observed among the various fly ash concrete groups, but the values were consistently lower than that of concrete without fly ash.

Fly ash replacement led to lower accumulated creep due to the improved antideformation properties of the concrete, where the degree of improvement was related to the fly ash replacement ratio. Specifically, the maximum improvement was observed at 20 wt% fly ash, after which it began to decrease in the 35 and 50 wt% fly ash concrete. The maximum accumulated creep of the concrete with 20 wt% fly ash was 33% lower than that of the concrete without fly ash. Similar results have been reported by Ghosh and Timusk [20], Huang et al [21]. However, these studies were based on short-term creep testing over a longer time. Therefore, the accumulated creep values presented in this study can be used as a reference for further research on the long-term creep properties of concrete.

3.5. Failure Characteristics. The macroscopic failure modes of fly ash concrete due to short-term gradation loading creep under uniaxial compression are shown in Figure 11.

FIGURE 6: Creep strain-time curves (ϵ_{cp} - t) of concrete with fly ash replacement ratios of (a) 0, (b) 20, (c) 35, and (d) 50 wt% under different stress levels.

The samples were largely intact after gradation loading creep failure and exhibited an obvious fractured surface with a few broken pieces. The failure modes were predominantly either oblique section rupture failure, axial direction separation failure, or combined failure. During gradation loading creep testing, the samples exhibited instant failure characterized by a clear loud sound and a small number of broken pieces. These brittle rupture characteristics led to difficulty in observing the generation and evolution of cracks before failure.

SEM was used to evaluate the microscopic rupture characteristics of the concrete samples with different fly ash replacement ratios (Figure 12). Most of the fly ash particles in the concrete with 20 and 35 wt% fly ash participated in secondary hydration reaction, where the

fracture surface was flat and tight. This microstructure contributed to the superior performance compared to concrete without fly ash. The concrete with 50 wt% fly ash exhibited unhydrated fly ash particles and a relatively rough fracture surface.

SEM was used to evaluate the appearance of the fractures in the concrete with varying fly ash replacement ratios (Figure 13). The concrete with no fly ash replacement exhibited semispherical fracturing along the crystals and step-form fracturing through the crystals. These are brittle fracturing modes. The concrete with 20 wt% fly ash also exhibited brittle step-form fractures through the crystals, while the 35 wt% sample exhibited both stacked-form fracturing through the crystals and secondary cracks through and along the crystals, both with brittle fracture

FIGURE 7: Experimental and fitted creep-stain curves of concrete with various fly ash replacement ratios (m) during the decelerating creep stage.

FIGURE 8: Experimental and fitted creep-stain curves of concrete with various fly ash replacement ratios (m) during the decelerating/isokinetic creep stage.

TABLE 4: Fitting parameters of concrete with various fly ash replacement ratios during the decelerating creep stage.

Parameter	Fly ash content (wt%)			
	0 (stress = 50.5 MPa)	20 (stress = 53.6 MPa)	35 (stress = 49.6 MPa)	50 (stress = 44.9 MPa)
A_1	-44.91	-37.72	-26.76	-35.33
B_1	566.60	746.85	358.96	646.67
C_1	50.57	40.74	31.63	38.02

TABLE 5: Fitting parameters of concrete with various fly ash replacement ratios during the decelerating/isokinetic creep stage.

Parameter	Fly ash content (wt%)			
	0 (stress = 56.1 MPa)	20 (stress = 60.3 MPa)	35 (stress = 55.8 MPa)	50 (stress = 50.5 MPa)
A_1	-16.60	-47.78	-48.36	-52.09
B_1	49.32	456.68	361.45	175.40
C_1	16.60	53.06	53.68	55.35
A_2	0.047	0.018	0.018	0.031
C_2	11.65	31.31	36.79	42.19

FIGURE 9: Creep rate-time ($d\epsilon_{cp}-t$) curves of concrete with various fly ash replacement ratios (m) during the (a) decelerating and (b) decelerating/isokinetic creep stages.

TABLE 6: Accumulated creep (ϵ_{cp+}) of concrete with various fly ash replacement ratios (m) at different stress levels (σ_{sp}).

$m = 0$ wt%	σ_{sp} (MPa)	16.8	22.4	28.0	33.7	39.3	44.9	50.5
	ϵ_{cp+} ($\mu\epsilon$)	9.0	21.6	35.9	56.9	80.8	144.8	207.4
$m = 20$ wt%	σ_{sp} (MPa)	20.1	26.8	33.5	40.2	46.9	53.6	60.3
	ϵ_{cp+} ($\mu\epsilon$)	7.5	17.6	28.3	42.6	62.1	89.5	138.6
$m = 35$ wt%	σ_{sp} (MPa)	18.6	24.8	31.0	37.2	43.4	49.6	55.8
	ϵ_{cp+} ($\mu\epsilon$)	8.6	16.7	26.3	39.9	58.8	80.2	140.5
$m = 50$ wt%	σ_{sp} (MPa)	16.6	22.1	27.6	33.2	38.6	44.2	—
	ϵ_{cp+} ($\mu\epsilon$)	3.8	8.6	14.0	23.5	38.5	96.5	—

FIGURE 10: Accumulated creep-stress ($\epsilon_{cp+}-\sigma_{sp}$) curves of concrete with various fly ash replacement ratios (m).

FIGURE 11: Failure modes of concrete with fly ash replacement ratios of (a) 0, (b) 20, (c) 35, and (d) 50 wt% under creep uniaxial compression.

FIGURE 12: Microscopic rupture characteristics of concrete with fly ash replacement ratios of (a) 0, (b) 20, (c) 35, and (d) 50 wt%.

FIGURE 13: SEM images of the fracture morphologies of concrete with fly ash replacement ratios of (a) 0, (b) 20, (c) 35, and (d) 50 wt%.

characteristics. The concrete with 50 wt% fly ash underwent brittle river-pattern fracturing through the crystals. Thus, all of the fracturing modes in the concrete with and without fly ash replacement were cleavage fractures with brittle characteristics.

4. Conclusions

The mechanical properties of concrete related to short-term gradation loading creep were evaluated at various fly ash replacement levels (0, 20, 35, and 50 wt%) after 90 days of curing. Creep has exhibited three main behaviors with time under different stress levels, namely, decelerating, isokinetic, and accelerating creep. The creep rate of the concrete increased with increasing stress levels, where the failure occurred once isokinetic creep was reached.

The peak stress of the concrete with fly ash replacement during short-term gradation loading creep testing exhibited a similar parabolic trend to that observed during conventional uniaxial compression testing. The peak stress of the concrete with 0, 20, 35, and 50 wt% fly ash during short-term gradation loading creep testing was 13.08%, 7.94%, 15.14%, and 14.50% lower, respectively, than the peak stress recorded during conventional uniaxial compression testing. The accumulated creep values reported in this study can be used as a reference value for further studies on the long-term creep characteristics of concrete.

The microscopic failure characteristics of the fly ash concrete during short-term gradation loading creep under uniaxial compression were attributed to cleavage fractures with brittle fracture characteristics, which was reflected in the macroscopic failure form.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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