Creep of Slag Blended Cement Concrete with and Without Activator

H. T. Thanh, M. J. Tapas, J. Chandler, and V. Sirivivatnanon

Abstract Partly replacing Portland cement (PC) with lower carbon footprint cementitious materials such as ground granulated blast furnace slag (slag) is considered as a practical method for reducing CO_2 emissions in the cement concrete industry. To mitigate the slow reactivity of slag in a cementitious system and enhance early-age strength, the addition of a chemical activator is a solution. However, the effect of the activator on creep behaviour of slag-blended cement concretes remains unclear. This work presents the effect of sodium sulfate (Na_2SO_4) activator on the compressive creep of PC concrete blended with 50 and 70 wt% slag. Four concrete mixes (with and without 2.5% Na_2SO_4 activator) containing 395 kg of cementitious material were prepared. The creep strain measurements were conducted on 150 × 300 mm cylindrical specimens for 140 days under sustained compressive load. The results showed that the 70% slag concrete had lower creep strain than 50% slag-blended cement concrete. The presence of Na_2SO_4 helped reduce the creep strain of 50% slag concrete but slightly increased that of 70% slag-blended cement concrete. In addition, the applicability of the predictive model in AS3600:2018 for the creep behaviour of high slag content concrete was assessed.

Keywords Activator · Compressive creep · Slag concrete

1 Introduction

Cement-based materials have an essential role in civil infrastructure worldwide. However, the production of clinker, the major constituent of Portland cement (PC), accounts for ≈7% of global CO_2 emissions [1], which has a destructive impact on

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environmental sustainability. Reducing the clinker to cement ratio by partly replacing PC with lower carbon footprint cementitious materials such as ground granulated blast furnace slag (GGBSF or slag) is considered a practical technique for reducing CO_2 emissions in the cement industry sector. The direct cumulative CO_2 emissions reduction by this method is estimated to reach almost 37% by 2050 [2]. Using slag in cement concrete also enhances its compressive and flexural strengths at later ages and improves the durability properties of concrete [3, 4].

As a pozzolanic-hydraulic activity or latent hydraulic behaviour, slag only provides additional surface area to enhance PC hydration by filler effect in the early days of hydration, without chemical reaction [5]. Hence, at high levels of slag replacement, the slow reactivity and dissolution of slag in the cementitious system causes slower strength gain at early ages. To mitigate this, adding an activator such as sodium sulfate (Na_2SO_4) is adopted [6, 7]. This addition accelerates slag's reactivity and enhances the early strength. However, in the presence of Na_2SO_4, a decrease in the compressive strength growth rate and increased capillary porosity at a later age have been reported [8, 9].

Creep of concrete is a time-dependent property that significantly affects the performance of concrete structures. Generally, creep in concrete includes basic and drying creeps. Under constant stress, gel particles slide and consolidate as water molecules rearrange in capillary pore structures, and microcracks form in the interfacial transition zones between the aggregate and cement paste. These phenomena primarily govern the basic creep of concrete [10]. In terms of creep of cement concrete using slag as a cement replacement, only a few conducted studies are reported. Khatri et al. [11] and Shariq et al. [10] concluded that creep of slag-blended cement concrete increased when the slag replacement increased. In addition, the creep strains were higher in slag cement concrete compared with plain concrete [10]. However, the creep behaviour of high slag-blended cement concretes with the presence of an activator has not yet been reported.

To understand the effect of Na_2SO_4 activator on the creep behaviour of slag-blended cement concrete, we conducted experiments on compressive creep. In this study, four mixes were cast with 50 and 70 wt% slag replacement. A dose of 2.5 wt% by total binder of Na_2SO_4 activator was used for activating two of the four slag-blended cement concrete mixes. The measurement data were analyzed and compared with the obtained values from the predictive model in AS3600:2018 to assess the capability of model prediction for creep behavior of high slag-blended cement concrete.

Table 1 Concrete mix proportions and properties

Mix ID	W/B	Cement (kg/m^3)	Slag (kg/m^3)	Aggregate (kg/m^3)	Sand (kg/m^3)	HRWR mL/m^3	Slump (mm)	f_c 28 days (MPa)	MoE (GPa)
M1_50	0.54	197.5	197.5	1035	850	1685	140	43.0	36.3
M2_50A	0.51	197.5	197.5	1035	850	2130	120	43.0	44.6
M3_70	0.52	118.5	276.5	1035	850	1685	110	38.0	35.8
M4_70A	0.52	118.5	276.5	1035	850	2130	130	35.5	35.7

f_c, compressive strength; HRWR, high-range water reducer; MoE, modulus of elasticity

2 Experiments

2.1 Mixture Proportions and Properties

The four concrete mixes containing 395 kg of cementitious material were prepared using shrinkage limited (SL) cement and slag provided by Boral Cement (Maldon, Australia). The mix proportions and mix IDs are shown in Table 1. In the mix ID, the numbers 50 and 70 signify the replacement percentage of slag, and the letter A denotes the use of 2.5% Na_2SO_4 activator for that mix.

Four cylinders of 150 × 300 mm and seven cylinders of 100 × 200 mm were cast for each concrete mix. Of the four 150 × 300 mm cylinders, two were used for the creep test, and two were used as control samples for measuring free drying shrinkage strain. The compressive strength test and the determination of elastic modulus were conducted on the 100 × 200 mm cylinders. The average results of these two tests are shown in Table 1.

2.2 Creep Test Setup

Before the testing day, demountable mechanical gauge (DEMEC) points were attached with 200 mm gauge length in three-gauge lines that were uniformly drawn around the perimeter of each cylinder. The DEMEC strain gauge is used for measuring creep/shrinkage strains of specimens. The vertical alignment of specimens and creep rigs were carefully checked with water level instruments before applying load. Figure 1a shows the creep rig used to perform compressive creep tests, and Fig. 1b presents the controlled samples for free drying shrinkage measurements.

One creep rig was used to test two mixes of the same replacement percentage of slag with and without activator. The loading started at 28 days, and the applied load was set at 40% of the average 28 day compressive strength of the concretes. Because two mixes were tested within a creep rig, the load was applied at 40% of the lower strength mix. The tests were conducted in a controlled environment (23 ± 2 °C and

(a) (b)

Fig. 1 **a** Creep rigs and loaded samples, **b** control samples

relative humidity 50%). During the testing period, the applied load was monitored by a pressure gauge and maintained at a value not less than 5% of its initial value.

The referenced readings were obtained just before applying load. The creep/shrinkage strains were recorded immediately after loading, 2 and 6 h for the first loading day, daily for the first week, weekly until 2 months, and then monthly. Here we report the findings after sustained load had been applied for 140 days. The creep strains of each mix were averaged from two specimens and three-gauge lines of each specimen.

3 Creep Model in AS3600:2018

As creep of concrete is a time-dependent behavior, using an empirical model to predict the creep strain of concrete is a practical and useful approach for designing concrete structures. From the viewpoint of building construction, it is not practical to perform a long-term creep test for every concrete mix. In AS3600:2018, the predictive creep strain of a sample bearing constant sustained stress σ_o at any time t can be generally expressed as:

$$\varepsilon_{cc}(t) = \varphi_{cc}\left(t, t_{load}, f_c', t_h, E_{env}, \varphi_{cc.b}\right)\frac{\sigma_o}{E_c} \tag{1}$$

where φ_{cc} is the time-dependent creep coefficient function depending on the loading time t_{load}, characteristic compressive strength f_c' at 28 days, hypothetical thickness of sample t_{h} and the exposure environmental condition E_{env}. The basic creep coefficient $\varphi_{cc.b}$ and elastic modulus E_{c} of a sample loaded at 28 days can be determined based on the characteristic compressive strength f_c'. Assuming that we only know the 28 day compressive strength of the four mixes described in Sect. 2.1, the characteristic compressive strength f_c' was selected equal to 30 MPa and 35 MPa for 50% and 70% slag-blended cement concretes, respectively. Hence, in the predictive model, the values of $E_{\mathrm{c}} = 29.1$ GPa and $\varphi_{cc.b} = 3.6$ were used for 50% slag-blended cement concretes, and $E_{\mathrm{c}} = 31.1$ GPa and $\varphi_{cc.b} = 3.2$ were used for 70% slag-blended cement concretes. In addition, the interior environment ($E_{\mathrm{env}} = 0.65$), which was nearest to the test environment, was also selected.

4 Results and Discussion

4.1 Total Deformation

The total deformation due to elastic, creep, and shrinkage strains of the four mixes are plotted in Figs. 2 and 3. It can be observed that the presence of Na_2SO_4 significantly reduced the creep and shrinkage strains of the 50% slag-blended cement concrete. A similar trend can also be observed with the shrinkage of 70% slag-blended cement concrete, but the total deformation of the loaded samples is comparable. A significant difference in deformation at initial loading due to the higher elastic modulus in the activated mix was also notable in the 50% slag-blended cement concrete mixes. The creep strain rate of the two mixes was, however, almost identical.

In addition, it can be seen that the 70% slag-blended cement concrete exhibited lower creep strain than the 50% slag-blended cement concrete. At 140 days, the creep strains of the 50% slag-blended cement concretes was ≈1400 µm/m, while those of 70% slag-blended cement concretes were only slightly greater than 1000 µm/m. This finding contradicts the reports in [10].

4.2 Creep Strain Measurement and Model Prediction

The creep strains (including instantaneous elastic strain) were obtained by subtracting the shrinkage strain from the total deformation of the loaded specimens. The development of creep strains of the four tested mixes are shown in Figs. 4 and 5. Although

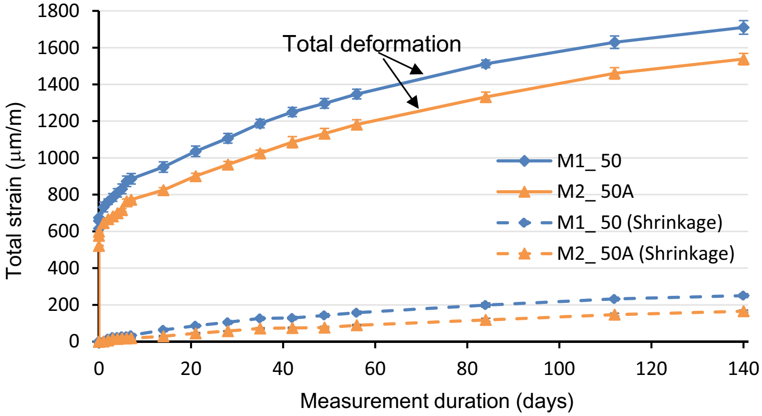

Fig. 2 Total deformation including creep and shrinkage strains of 50% slag-blended cement concrete, with and without Na_2SO_4

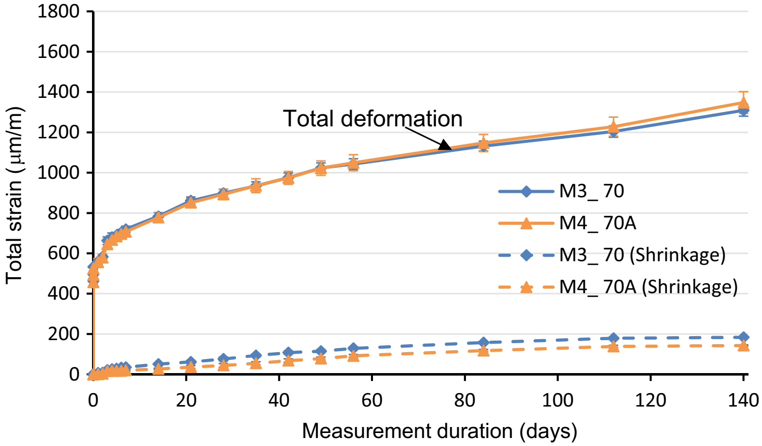

Fig. 3 Total deformation including creep and shrinkage strains of 70% slag-blended cement concrete, with and without Na_2SO_4

the presence of Na_2SO_4 appeared to slightly reduce the creep strains of 50% slag-blended cement concrete, an increase, though within measurement error range, in that of 70% slag-blended cement concrete was observed.

The predictive results from the creep model in AS3600:2018 are also plotted in Figs. 4 and 5. It can be seen that the predictive values from the model are lower than the measured values for all mixes. Except for the initial deformation or instantaneous elastic strain, the model underestimated the development of creep strain for both 50 and 70 wt% slag replacement cement concretes.

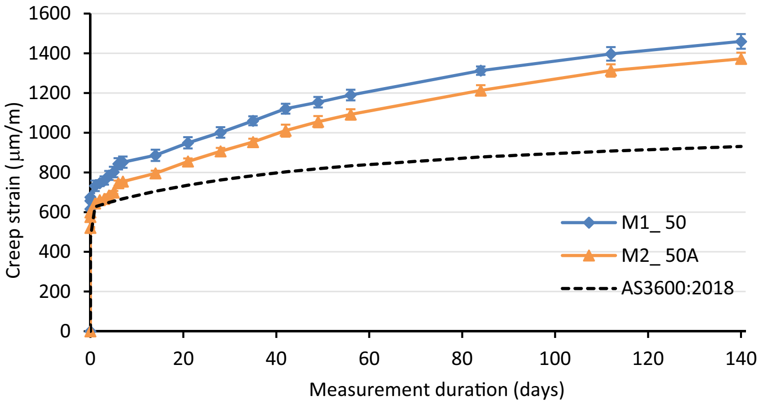

Fig. 4 Creep strain of concretes with 50 wt% slag replacement and predictive results

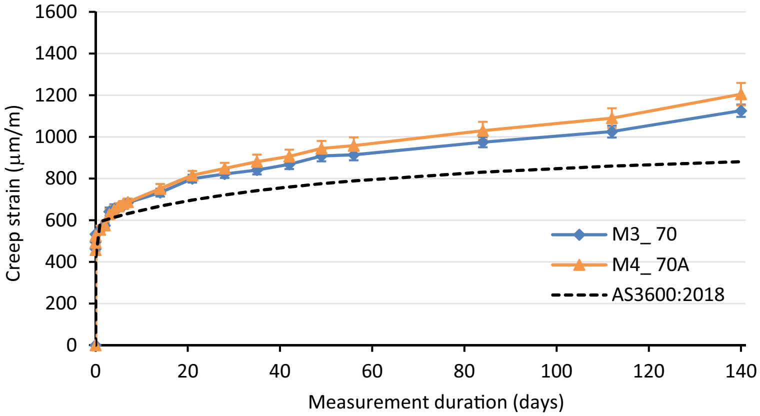

Fig. 5 Creep strain of the concrete with 70 wt% slag replacement and predictive results

5 Conclusions

From the results of 140 day compressive creep testing of PC concrete blended with 50 and 70 wt% slag, the main findings can be summarized as:

(1) 70% slag-blended cement concrete had lower creep strain than 50% slag-blended cement concrete, which suggested that increasing the slag content improved creep performance
(2) adding 2.5% Na_2SO_4 activator had negligible effects on the creep strain of slag-blended cement concretes
(3) the activator slightly decreased the shrinkage strain of slag-blended cement concretes

(4) the predictive model in AS3600:2018 underestimated the creep strain of high slag concretes regardless of the presence of Na_2SO_4.

The monitoring of long-term creep behavior of these slag-cement concretes is ongoing, and the results will be reported in the future.

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