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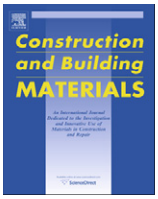

Creep of FRP-wrapped concrete columns with or without fly ash under axial load

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ABSTRACT

This paper presents an experimental work on the long-term deformation properties of four FRP-wrapped concrete columns (FWCCs) with low-volume fly ash (FA) as admixture, and a theoretical study on the creep of FWCCs with or without FA in the concrete mix. Theoretically, considering the creep of concrete under triaxial stresses and the interaction between concrete core and fiber reinforced polymer (FRP) wraps, an analytical model, based on the Model B3 or modified Model B3 for the creep of concrete without or with FA, and the power law for the creep of FRP, is developed to study the creep of FWCC. Validations against creep data from literatures and the experimental results in this paper show the model works well. Additionally, the influences of various parameters on the creep of FWCC are investigated. The creep of FWCC with FA is shown to be less than that of FWCC without FA. And the composition and compressive strength of concrete are demonstrated to affect the creep of FWCC obviously.

1. Introduction

Wrapping fiber reinforced polymer (FRP) laminates around concrete columns has been used in structures (such as Shinmiya Bridge in Japan and Lunensche Gasse Bridge in Germany given by the report of ACI Committee 440) as a strengthening and retrofitting approach [1,2]. This structural technique can improve both strength and ductility of columns, and it is very feasible for construction. Since concrete and the polymer-based material both show obvious time-dependent deformation characteristics, and they affect each other in the long-term deformation process, the creep of this hybrid column is a complex phenomenon. A complete understanding on its creep characteristic is necessary for the analysis and design of structural systems involving FRP-wrapped concrete columns (FWCCs).

As to this problem, Naguib [3] and Naguib and Mirmiran [4] measured the creep of two FWCCs under sustained axial loads for 80 days, and modeled it with the double power law creep function for concrete in the framework of rate of flow method. Tao and Yu [5] and Yu et al. [6] conducted tests on the behaviour of 12 FRP-wrapped concrete short columns under sustained loads for 160 days, and analyzed their creep by the ACI 209 model for the creep of concrete cores. However, the experimental and theoretical work on this issue is still scant: firstly, the time for the creep of FWCCs in the two sets of experiment mentioned above is not long enough, accordingly the creep is not fully developed when the tests are completed; secondly, there is no creep data of concrete columns wrapped with aramid FRP (AFRP) laminates, while the wrapping materials used in Naguib's [3,4] and Yu's [5,6] tests are glass FRP (GFRP) and carbon FRP (CFRP), respectively; thirdly, although the composition and compressive strength of concrete core may have an evident influence on the creep of FWCC, Naguib's [3,4] and Yu's [5,6] models cannot take them into account efficiently.

On the other hand, environmental problems, resource saving and economic benefit make a common use of fly ash (FA), a by-product cementitious material, to replace a part of cement in concrete in recent decades [7,8]. Besides desirable workability as well as social and economic profitability, FA contributes to the properties of concrete in terms of long-term strength and durability [9–12]. Additionally, the effect of FA on the shrinkage and creep of concrete has been studied by some researchers. Zhao et al. [13,14] observed the specific creep of high performance concrete (HPC) incorporated with 12% and 30% and without FA under the stress/strength ratio of 33%, and concluded that the specific creep of HPCs with 12% and 30% FA after 1 year are 0.76 and 0.465 times of that of HPC without FA respectively. Test results obtained by Luo et al. [15], Zou et al. [16] and Qin et al. [17] also indicated that the concrete with small percentage (10–40%) of FA has higher long-term compressive strength and elastic modulus, and lower shrinkage and creep than those of the control concrete without FA. However, only some experimental data are given for the shrinkage and creep of the concrete containing FA as a partial replacement of cement, and there is no predictive formula on this issue at present.

Since FA is commonly used as a concrete admixture to improve the performance of concrete and attain the environmental and economic benefit now, this paper presents a theoretical study on the creep of FWCCs with or without FA and experimental work

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on the long-term deformation properties of four FWCCs with low-volume FA. For FWCCs without FA, a creep model based on Bažant's Model B3 [18] for the creep of plain concrete and Findley's power law [19] for the creep of FRP is proposed and validated against experimental data from the literatures. For FWCCs with FA, Model B3 is modified depending on the creep data of concrete with FA [20,21] and based on the modified Model B3 a creep model for the hybrid columns is proposed. The proposed model for FWCC considers the state of triaxial stresses of the concrete core, and the interaction between the concrete core and FRP wraps, and can analyze the influences of various parameters on the creep of FWCC, such as the water/binder ratio (*w*/*b*), the aggregate/binder ratio (*a*/*b*), and the compressive strength of concrete.

2. Materials and experiments

2.1. Specimen design

Four cylindrical FWCCs with FA as the admixture were tested in the laboratory for the research of long-term deformation. Two of them were used to perform the creep study, and parallel shrinkage test was carried out on the other two specimens. The diameters and heights of concrete cores are all 150 mm and 450 mm respectively. All concrete cores of the four specimens, classified into two groups according to the different designed cube compressive strengths of 45 MPa and 50 MPa, were wrapped with two layers of unidirectional AFRP laminates. Three 100 mm cubes for each group were prepared to measure the actual compressive strength of concrete. The summary of the specimen test matrix is given in Table 1.

2.2. Materials and mix proportions

The cementitious materials of concrete core used in the test were ordinary Portland cement and FA. The replacement of FA was kept at the level of 15% of the weight of cement. The *w*/*b* for FWCC-45 and FWCC-50 were 0.39 and 0.36 respectively. River sand was used as fine aggregate and crushed granite stone with a maximum size of 40 mm was used as coarse aggregate. The composition and compressive strength of concrete are shown in Table 2. And the physical and chemical properties of FA are given in Table 3.

The AFRP laminate was used for jacketing, and epoxy resin was used as adhesive. The properties of AFRP are listed in Table 4.

2.3. Experimental methods

The materials of concrete were mixed uniformly, and then cast into the steel moulds by vibration. One day after casting, the concrete cylinders were demolded and cured in a controlled environment of 20 ± 2 °C and relative humidity >95% for 28 days. Before jacketing, the surfaces of columns were repaired and cleaned to get a sound concrete substrate. Then epoxy adhesive mix was applied to the surfaces evenly as a sealant. When the adhesive on the columns was dried, epoxy resin was mixed in proportion. Then the saturating resin was applied uniformly to all prepared surfaces of the concrete columns, and the AFRP laminates were impregnated with the resin in a separate process. Subsequently, the AFRP laminates were wrapped around the columns in a wet lay-up process, with main fibers orientated in the hoop direction of the columns. Effective joints were attained by overlapping the laminates 150 mm in length.

For measuring the axial deformation, each specimen was instrumented at its mid-height with an embedded vibrating wire strain gage (DI-25) in the axial direction. At the age of 28 days, the creep specimens FWCC-45 and FWCC-50 were subjected to sustained axial stresses of 8.48 MPa and 9.43 MPa respectively, which corresponded to the stress-strength ratio of 30%, for a load duration of 312 days. The centering of the specimens was necessary to avoid eccentric loading. Shrinkage was tested parallel to the creep. All the creep and shrinkage specimens were kept in a controlled temperature of 20 °C throughout the test duration. Creep rupture of the AFRP laminates did not occur in the test.

Table 1
Specimen test matrix.

Specimens	Designed cube compressive strength of concrete core (MPa)	Test objective	No. of specimens
FWCC-45	45	Creep	1
FWCC-50	50	Creep	1
FWCC-45	45	Shrinkage	1
FWCC-50	50	Shrinkage	1

Table 2
Composition and compressive strength of concrete.

Contents		Values	
Designed cube compressive strength (MPa)		45	50
Measured 28-day cube compressive strength $f_{cu,28}$ (MPa)		47.3	51.1
Composition (kg/m^3)	Cement	230	247
	FA	40.5	43.5
	Water	105	105
	Sand	765	759
	Coarse aggregate	1360	1349

Table 3
Physical and chemical properties of FA.

Properties		Values
Ignition loss (%)		1.2
45-μm Sieve residual quantity (%)		12
Percentage of flow (%)		92
Chemical composition (%)	SO_3	0.4
	SiO_2	54.7
	Al_2O_3	24.3
	Fe_2O_3	9.6
	CaO	4.6
	MgO	2.2

Table 4
Properties of AFRP laminate.

Properties	Values
Elastic modulus (MPa)	118,000
Ultimate tensile strain	0.017
Thickness per layer (mm)	0.286

3. Modeling the creep of FWCC

3.1. The creep of concrete

The Model B3 [18] for predicting concrete creep and shrinkage is based on the solidification theory. Various parameters such as the cement content, water/cement ratio, aggregate/cement ratio and compressive strength of concrete are all taken into account in the Model B3. And the model, which is calibrated by the creep data in the RILEM experimental data bank, has been evaluated to be more proper than the model ACI 209 and model CEB 90 [18]. In the B3 Model, the creep compliance function of concrete under uniaxial constant stress can be calculated as

$$J(t,t') = q_1 + C_0(t,t') + C_d(t,t',t_0) \tag{1}$$

where $J(t, t')$ = compliance function, which is taken as elastic plus creep strain caused by a unit uniaxial constant stress (10^{-6}/MPa); q_1 = instantaneous strain due to unit stress; $C_0(t, t')$ = compliance function for basic creep (10^{-6}/MPa); $C_d(t, t', t_0)$ = additional compliance function due to simultaneous drying (10^{-6}/MPa); t = target time, representing the age of concrete (d); t' = age at loading (d); and t_0 = age when drying begins (d). For FWCC, the concrete core only has basic creep, because the sealing provided by FRP protects the concrete core from migration and loss of moisture, and considerably reduces its shrinkage and drying creep [4]. The compliance function for basic creep can be calculated as

$$C_0(t,t') = q_2 Q(t,t') + q_3 \ln[1 + (t-t')^n] + q_4 \ln\left(\frac{t}{t'}\right) \tag{2}$$

where q_2, q_3, and q_4 = aging viscoelastic compliance, non-aging viscoelastic compliance, and flow compliance concerning the composi-