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Influence of concrete age on stress–strain behavior of FRP-confined normal- and high-strength concrete

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HIGHLIGHTS

- Influence of concrete age on compressive behavior of FRP-confined concrete was investigated.
- Transition zone of stress–strain curve of FRP-confined concrete changes with concrete age.
- Dilation behavior of FRP-confined concrete changes with concrete age.
- Strength and strain enhancements decrease slightly with an increase in concrete age.
- Hoop rupture strain of FRP jacket also decreases with an increase in concrete age.

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ABSTRACT

The potential applications of fiber reinforced polymer (FRP) composites as concrete confinement in retrofitting existing concrete columns and in the construction of new high-performance composite columns have received significant research attention. In practical applications, the ages of concrete in retrofitted columns are significantly different from those of newly constructed columns. Without a full understanding on the influence of concrete age on their compressive behaviors, the validity of existing experimental findings, which are based the age of concrete at the time of testing, remains ambiguous when the design application lapses in time. This paper presents the results of an experimental study on the influence of concrete age on the compressive behavior of FRP-confined normal-strength (NSC) and high-strength concrete (HSC). The first part of the paper presents the results of 18 FRP-confined and 18 unconfined concrete specimens tested at 7 and 28 days. To extend the investigation with specimens with concrete ages up to 900 days, existing test results of FRP-confined concrete was assembled from the review of the literature. Based on observations from both short- and long-term influences of concrete age on compressive behavior of FRP-confined concrete, a number of important findings were drawn and are presented in the second part of the paper. It was observed that, at a same level of FRP confinement and unconfined concrete strength, the stress–strain behavior of FRP-confined concrete changes with concrete age. This difference is particularly pronounced at the transition zone of the stress–strain curves. It is found that, in the short-term, the ultimate condition of FRP-confined concrete is not significantly affected by the age of concrete. However, in the long-term, slight decreases in the compressive strength and the ultimate axial strain are observed with an increase in concrete age.

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1. Introduction

Understanding the influence of concrete age on the compressive behavior of FRP-confined concrete in newly constructed and retrofitted existing columns is of vital importance. A number of existing studies have investigated time-related issues affecting the compressive behavior of FRP-confined concrete under various environmental exposures [1–6] and sustained loading [7–12]. However, none of these studies directly investigated the influence of concrete age on the stress–strain behavior of FRP-confined concrete. To gain an insight into the possible changes in the behavior of FRP-confined concrete members throughout their service lives, influence of concrete age on the stress–strain behavior of FRP-confined concrete needs to be understood. To this end, the experimental program reported in the present study investigated the axial compressive behaviors of 18 FRP-confined and 18 unconfined NSC and HSC specimens tested at 7 or 28 days of concrete age.

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The specimens were prepared such that concretes at different ages attained the same unconfined strength at the day of testing and they were confined with the same amount of FRP. To extend the observation range of concrete age up to 900 days, the results of the present study were analyzed together with those from several groups of specimens assembled from the published literature.

2. Experimental program

2.1. Test specimens and materials

18 FRP-confined and 18 unconfined concrete cylinders were prepared. All of the specimens were 152.5 mm in diameter and 305 mm in height. The influence of concrete age on the mechanical properties of the confined and unconfined specimens was investigated using six separate batches of concrete mixes. The mixes were designed such that, in each comparison pair, companion specimens tested at 7 and 28 days developed the same test-day unconfined concrete strength. The mix proportions of each batch of concrete is given in Table 1. Crushed bluestone gravel of 7 mm maximum size and graded sand were used as the aggregates. The specimens were manufactured using concrete mixes of two different grades, namely HSC and NSC. The HSC specimens in Batches 1–4 had an average strength of 73.0 MPa and the NSC specimens in Batches 5 and 6 had an average strength of 33.9 MPa. To establish the final w/c ratios used in Batches 1–6, a large number of trial batches were prepared and tested. The summary of the axial compression test results of the unconfined specimens are given in Table 2, which provides the peak stress (f'_{co}) and corresponding axial strain (ε_{co}) of the specimens. The axial strain corresponding to the peak stress of unconfined concrete (ε_{co}) was not recorded during the compression tests, and values reported in Table 2 were calculated using the expression proposed by Lim and Ozbakkaloglu [13].

$$\varepsilon_{co} = \frac{f'^{\,0.225k_d}_{co}}{1000} k_s k_a \quad (1)$$

where f'_{co} is in MPa, and k_d, k_s, and k_a, respectively, are the coefficients to allow for concrete density, specimens size and specimen aspect ratio. Each of these coefficients becomes unity for a specimen with concrete density of 2400 kg/m^3, diameter of 152 mm and height of 305 mm, as was the case for the control cylinders of the present study.

A total of 18 FRP tubes were prepared using a manual wet lay-up process by wrapping epoxy resin impregnated unidirectional fiber sheets around precision-cut high-density Styrafoam templates, which were removed prior to concrete casting. The FRP tubes were prepared using a single continuous fiber sheet and had a single 150-mm long overlap region. The material properties of the aramid and S-glass fiber sheets used to manufacture the FRP tubes are provided in Table 3. The table reports both the manufacturer-supplied fiber properties and the tensile tested FRP composite properties. The tensile properties of the FRP made from these fiber sheets were determined from flat coupon tests, where the loading was applied in accordance with ASTM D3039 [14].

The FRP tubes of the 12 specimens were manufactured using S-glass FRP (GFRP), and the tubes of the remaining six specimens were manufactured with aramid FRP (AFRP). The specimens with AFRP tubes and six of the specimens with GFRP tubes were cast with HSC, whereas the remaining six GFRP tube encased specimens were manufactures using NSC. The tubes of NSC and HSC specimens had two and four layers of FRP, respectively. These FRP layer arrangements were determined based on the understanding that the confinement demand of concrete increases with its strength [15–18]. Three nominally identical specimens were tested for each unique specimen configuration. The FRP-confined specimens were tested on the same day with their companion unconfined specimens, through which the test-day unconfined concrete strengths (f'_{co}) reported in Table 2 were established.

Table 1
Mix proportions of concrete specimens tested at different ages.

Designated study	AFRP tube-encased HSC		GFRP tube-encased HSC		GFRP tube-encased NSC	
Batch	B1	B2	B3	B4	B5	B6
Cement (kg/m^3)	550	520	550	520	380	380
Sand (kg/m^3)	710	710	710	710	710	710
Gravel (kg/m^3)	1065	1065	1065	1065	1065	1065
Water (kg/m^3)	133	137	133	137	213	243
Superplasticiser (kg/m^3)	20	20	20	20	0	0
Water–cementitious binder ratio	0.270	0.294	0.270	0.294	0.560	0.640
Slump height (m)	>0.250	>0.250	>0.250	>0.250	0.065	0.190
Concrete age at testing (day)	7	28	7	28	7	28

Table 2
Compression test results of unconfined specimens.

Specimen	Concrete batch	Age (day)	w/c ratio (%)	Avg. f'_{co} (MPa)	Avg. ε_{co} [a] (%)
A0-U73-D7	B1	7	0.27	72.0	0.26
A0-U73-D28	B2	28	0.29	74.9	0.26
G0-U73-D7	B3	7	0.27	70.8	0.26
G0-U73-D28	B4	28	0.29	74.1	0.26
G0-U34-D7	B5	7	0.56	33.0	0.22
G0-U34-D28	B6	28	0.64	34.7	0.22

[a] Axial strains were not recorded experimentally. Values determined using expression given by Lim and Ozbakkaloglu [13].

2.2. Specimen designation

The specimens in Tables 2 and 4 were labeled as follows: the first letter A, G or C represents the type of FRP (i.e., AFRP, GFRP or CFRP) and it is followed by the number of FRP layer; the second letter U is followed by the unconfined concrete strength in MPa; and the third letter D is followed by the age of concrete in days at the day of testing. Finally, the last number in the specimen designation (i.e., 1, 2 or 3) was used to make the distinction between three nominally identical specimens. For instance, A4-C73-D7-2 represents the second of the three nominally identical specimens, which were tested at 7 days of concrete age were and cast from a concrete mix with a 73 MPa unconfined concrete strength in an FRP tube manufactured with 4 layers of aramid fibers.

2.3. Instrumentation and testing

The specimens were tested under axial compression using a 5000-kN capacity universal testing machine. During the initial elastic stage of the behavior, the loading was applied with the load control set at 5 kN per second, whereas displacement control operated at 0.004 mm per second beyond the initiation of transition region until specimen failure. Prior to testing, all specimens were ground at both ends to ensure uniform distribution of the applied pressure, and load was applied directly to the concrete core using precision-cut high-strength steel plates with a 150 mm diameter.

The hoop strains of the specimens were measured using 12 unidirectional strain gauges placed at the mid-height around the circumference of specimens outside the overlap region. As illustrated in Fig. 1, the axial strains of the confined specimens were measured using two different methods: (i) four linear variable displacement transformers (LVDTs) mounted at each corner of the steel loading platens with a gauge length of 305 mm; and (ii) four LVDTs placed at the mid-height at a gauge length of 175 mm at 90° spacing along the circumference of specimens. The readings from the mid-height LVDTs were used to correct the full-height LVDT measurements at the early stages of loading, where additional displacements due to closure of the gaps in the setup were also recorded by the full-height LVDTs.

3. Test results and discussion

3.1. Failure mode

The typical failure modes of the FRP-confined specimens tested at 7 and 28 days are illustrated in Figs. 2–4. As can be seen from the photos, all of the specimens failed by the rupture of the FRP jackets. As illustrated in Figs. 2(a) and 3(a), heterogenic microcrack formations were observed in the concretes of the 7-day old AFRP- and GFRP-confined HSC specimens at failure. On the other hand, as evident from Figs. 2(b) and 3(b), the concrete in the companion 28-day old specimens exhibited larger cracks that were more localized. In the GFRP-confined NSC specimens shown in Fig. 4(a) and (b), the change in the concrete cracking pattern from microcrack to macrocrack with an increase in concrete age are also evident, however the change is not as pronounced as those seen in the HSC specimens. The observed variations in the cracking patterns of concretes of same compressive strength suggest that the concrete brittleness increases with its age. This change in concrete brittleness with concrete age is more pronounced in higher strength concrete.

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