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Age-dependent properties of fiber-reinforced concrete for thin concrete overlays

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HIGHLIGHTS

- Testing to investigate the age-dependent properties of macro-FRC.
- Compressive strength, modulus of rupture, shrinkage, and thermal expansion not affected by fibers.
- Fracture energy increases with age for all fiber types.
- Residual strength increases with age among deflection-hardening FRC.
- Residual strength ratio decreases with age for all types of FRC.

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ABSTRACT

This study aims to investigate the age-dependent changes in flexural and fracture properties of fiber-reinforced concrete (FRC) used in the design of thin overlay pavements. Total four different types of steel or polypropylene macro-fibers with different dimensions and different fiber volume contents (0%, 0.5%, and 1.0%) were selected and investigated. No significant changes in compressive strength, free drying shrinkage, coefficient of thermal expansion, and modulus of rupture versus age were identified. Steel FRCs were observed to have a constant or increased residual strength as a function of age while different types or contents of polypropylene FRCs showed varied trends in residual strength versus age. Fracture energy for all FRCs was observed to increase versus age. Residual strength ratio for all FRCs decreased as a function of age, but with only two replicates per age and FRC type, values were highly variable so no trends were statistically verified at this time. A standard test age is recommended due to the changing residual strength ratio parameter used in thin FRC overlay design.

1. Introduction

Fibers have been widely utilized as reinforcement in various concrete infrastructure including concrete overlays [1,2], bridge decks [3], high-rise buildings [4], and marine concrete structures [5,6]. Many experimental studies have been carried out to investigate how fibers added to concrete will improve toughness, cracking resistance, and interfacial bond [7–16]. There are some existing testing procedures to evaluate the flexural performance of fiber-reinforced concrete (FRC) such as ASTM C1609 [17], JSCE-SF 4 [18], BS EN14651 [19], and RILEM TC 162-TDF [20].

The design of FRC overlays utilizes a residual strength ratio (R_{150}) which is measured based on the post-cracking flexural stress carried by of the FRC normalized by the flexural strength at first cracking (*MOR*). Reported FRC property measurements have been typically undertaken at 28 days age. The 28 days strength is considered close to the material's final strength and generally accepted for the structural design of various concrete structures including concrete overlays. However, it is well known that the concrete strength does not stop at 28 days, but still increases for many months thereafter. As such, the residual strength ratio may in fact decrease with age since the flexural strength in the denominator is expected to increase. Alternatively, if the residual strength of the FRC correspondingly increases with age besides the flexural strength, the residual strength ratio can be consistent or increased as time goes by. In this regard, understanding the age-dependent FRC properties is crucial for predicting cracking or improving the design of FRC overlays.

Altoubat et al. [21] proposed the following Eq. (1) to determine effective modulus of rupture, MOR_{eff} for FRC overlay design.

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$$MOR_{eff} = MOR(1 + R_{150}) \quad (1)$$

In Eq. (1), R_{150} is FRC residual strength ratio; this can be zero in plain concrete pavement design. The stress ratio used to for fatigue prediction of concrete pavements, SR_{total}, is estimated by dividing the total tensile stress from traffic and environment loading, σ_{total}, by MOR_{eff} as shown in Eq. (2) [21].

$$SR_{total} = \frac{\sigma_{total}}{MOR_{eff}} \quad (2)$$

In FRC overlay design, it is preferred that the MOR_{eff} increase with time to provide more resistance against continued traffic loads.

The fiber effect on compressive and flexural strengths has been investigated by past researchers [14,22–30]. Among the previous studies, steel fiber-reinforced concrete (SFRC) at 1–2% fiber volume fraction has been claimed to increase compressive strength due to dowel-like resistance of the added fibers, which bridge internal defects in the event that failure is initiated [14,22,30]. On the other hand, some researchers pointed out polypropylene fibers can reduce the compressive strength as a function of increasing fiber volume content [23–26,29]. This reduction in compressive strength is speculated to be due to compaction or mixing difficulties with high contents of the polypropylene fibers. In terms of flexural properties, polypropylene fiber-reinforced concrete (PFRC) has been found to improve the post-cracking flexural toughness of concrete while not having significant influence on the measured peak flexural strength compared to plain concrete [24,27–29]. Micro-fiber-reinforced concrete samples were noted to have a reduced free drying shrinkage as compared to macro-FRC and plain concrete [31]. Researchers have found that the effect of macro-fibers on free drying shrinkage is negligible at low fiber volume contents [32,33]. Yet, Zhang et al. [34] reported steel macro-FRC at higher volume contents more than 1% exhibited reduced free drying shrinkage compared to plain concrete. Another important parameter of concrete that is used in pavement design is the coefficient of thermal expansion (CTE). The CTE is presumed to be strongly influenced by aggregate type and the quantity of coarse aggregate [35]. While it is not expected that the CTE changes with ages less than 28 days [36,37], it too will be studied to determine if the CTE might change with the addition of fibers.

Some experimental studies have been carried out to investigate other age-dependent FRC properties [38–41]. An earlier study by Bernard [38] which tested FRC at different ages found that SFRC and PFRC exhibited a decreased or constant residual strength ratio between 7 and 90 days as represented in Fig. 1. Bordelon [39] also reported a reduction of residual strength ratio of PFRC between 7 and 28 days. Conversely to flexural tests, a wedge-split fracture test by Hodicky et al. [40] found that tensile strength and fracture energy of SFRC were both increased with age. On a microstructure level, the fiber-to-cement interfacial bond between 0.5 and 28 days, as determined from a pull-out test, was found by researchers to only increase within the first 2 days, but have no significant change from 7 to 28 days [41].

The objective of this study was to investigate the age-dependent changes in mechanical properties of FRC which can be utilized for FRC overlay design. A standard flexural beam and wedge-splitting fracture test were conducted on FRC samples at the ages between 3 and 90 days. The general concrete properties of compressive strength, free drying shrinkage, and coefficient of thermal expansion are not expected to change due to the fiber content, but were also tested for confirmation in this study.

2. Research significance

While the residual strength ratio used in FRC overlay design is presumed to be measured at 28 days age, the age-dependency of flexural and fracture properties of FRC have not been well integrated in test requirements. It is expected that FRC exhibits age-dependent changes in residual strength ratio, and thus it is critical for a pavement engineer to select the desired age of testing so that the residual strength ratio can be ultimately linked with the long-term performance of FRC overlays. Understanding age-dependent changes in residual strength or residual strength ratio can then provide engineers tips to determine optimum fiber type and volume content. For these reasons, an experimental program was set up and a comprehensive experimental campaign was conducted to investigate the effects of different fiber types and volume contents on age-dependent properties of FRC. The first crack load, second peak, or maximum peak load were measured, and both residual strength and residual strength ratio were calculated according to ASTM and JSCE methods.

3. Experimental investigation

3.1. Mixture design and test variables

Fig. 2 and Table 1 show the selected fibers and material properties used in this study, respectively. All of selected fibers are commonly used in concrete overlays or thin shell structures. The nomenclature for this paper labels the fibers as short steel hooked (SS), long steel hooked (LS), short polypropylene (SP), and long polypropylene (LP) based on the comparative fiber length and fiber type. This study focuses more on the age-dependent changes in flexural or fracture properties of FRCs, rather than the effect of fiber length or fiber type. For example, the direct comparison between the two PFRCs can be meaningless since these two polypropylene

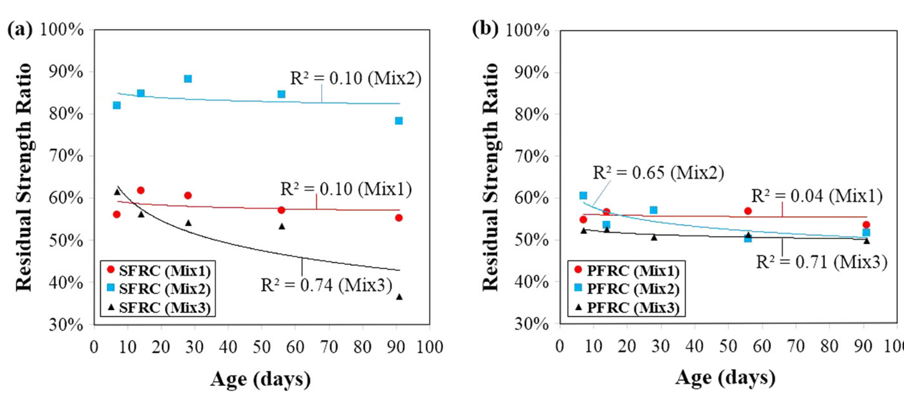

Fig. 1. Age-dependent changes in residual strength ratio for (a): SFRC and (b): PFRC [38].