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Flexural performance of reinforced self-consolidating concrete beams containing hybrid fibers

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HIGHLIGHTS

- Effects of hybrid fibers on flexural performance of SCC beams were investigated.
- Macro PP fiber was employed in this study.
- A new calculation model for predicting ultimate bearing capacity of SCC beams was proposed.

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ABSTRACT

Flexural performances of twelve reinforced self-consolidating concrete (SCC) beams containing steel fiber, macro polypropylene fiber, micro polypropylene fiber, and their combinations were studied at room temperature. The major test variables were fiber types, fiber contents and longitudinal reinforcement ratios. Cracking load, yielding load, ultimate load, mid-span deflection, longitudinal reinforcement strain and crack pattern of the reinforced SCC beams were investigated. It was found that the addition of mono steel fiber and hybrid fibers enhanced the ultimate bearing capacity but reduced the mid-span deflection of reinforced SCC beams. With the increase in fiber content, the longitudinal reinforcement strain, crack width and crack spacing decreased significantly. The hybrid use of steel fiber and micro polypropylene fiber did not have a further beneficial effect on the flexural performance of SCC beams at room temperature. Compared to micro polypropylene fiber, the macro polypropylene fiber displayed a more significant effect on the structural behavior of SCC beams. A calculation method for ultimate bearing capacity of flexural SCC beams at room temperature was proposed, which takes into consideration the effects of hybrid fibers. Comparisons were drawn between the predicted results of this proposed model and other previous models with experimental data in this study and previous literature. The results indicate that the proposed model can reasonably estimate the ultimate bearing capacity of SCC beams containing hybrid fibers subjected to flexural loading at room temperature.

1. Introduction

The demands of the construction industry for stronger and more ductile concrete structures have been successfully met by the use of high-strength concrete and dense steel reinforcement. However, more fluid fresh concrete mixture is needed for the highly congested reinforced concrete elements to improve their constructability. Self-consolidating concrete (SCC), a flowing concrete which gives a slump value of over 200 mm and a slump-flow value of more than 600 mm, has been developed in recent years as a possible solution as it is highly cohesive and can be placed and compacted without external vibration [1–5]. Although SCC has excellent workability, it is still a brittle material with poor tensile performance. The use of randomly distributed short and discrete fibers is one of the most effective ways to improve the tensile properties and cracking behaviors of SCC. There are a variety of commercialized fibers used in SCC (steel fiber, synthetic fiber, etc.) and their feasibility has been clearly documented [6–11]. Usually, steel fibers are used for structural purpose and synthetic fibers (e.g. micro polypropylene fiber) are employed for non-structural applications (shrinkage resistance, fire resistance, etc.).

It is recognized that fire usually poses serious damage to concrete structures. Spalling of concrete during fire exposure will further aggravate these damages, especially for high strength concrete

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Nomenclature

ρ_s	longitudinal reinforcement ratio
ρ_{sv}	stirrup reinforcement ratio
SF	steel fiber
PPF	polypropylene fiber
P_{cr}	cracking load
$P_{y,b}$	yielding load
$P_{u,b}$	ultimate load
$\delta_{u,b}$	deflection of simply supported beam at ultimate load
σ_f	tensile stress of fibers
α	fraction ratio of fibers which currently bridging the crack
V_f	volume fraction of fibers
$V_{f,st}$	volume fraction of steel fiber
$V_{f,sy}$	volume fraction of macro PP fiber
f_1	coefficient of friction between fiber and concrete matrix sheared over crack
f_2	flexural characteristics coefficient
$\bar{\sigma}_f$	average fiber stress for the load-carrying fibers
τ_f	interfacial shear stress between fiber and concrete
$\tau_{f,st}$	interfacial shear stress between steel fiber and concrete
$\tau_{f,sy}$	interfacial shear stress between macro PP fiber and concrete
$\bar{x}$	average shear length of fibers bridging over crack
d_f	diameter of fiber
F_{be}	fiber characteristics coefficient
$F_{be,st}$	characteristics coefficient of steel fiber
$F_{be,sy}$	characteristics coefficient of macro PP fiber
L_f	fiber length
λ	aspect ratio of fiber
λ_{st}	aspect ratio of steel fiber
λ_{sy}	aspect ratio of macro PP fiber
ω	crack width
h	depth of the beam cross section
c	depth of neutral axis of reinforced concrete beam
L_0	span of beam
ε_{cr}	cracking strain of FRC
ε_{tu}	ultimate tensile strain of FRC
f_c	compressive strength of FRC
ε_0	compressive strain corresponding to compressive strength
ε_{cu}	ultimate compressive strain
E_s	elastic modulus of rebar
f_y	yield strength of rebar
ε_s	ultimate tensile strain of longitudinal rebar
A_s	steel reinforcement area
h_0	effective height of beam cross section
x	depth of rectangular compressive stress blocks
b	width of the beam cross section
h	depth of the beam cross section
c	depth of neutral axis of reinforced concrete beam
M_{pre}	predicted moment
M_{exp}	measured moment

(HSC) and SCC due to their high compactness and low permeability [12–15]. Previous studies have confirmed the efficient role of micro polypropylene fibers (micro PP fibers) in reducing the fire spalling risk of SCC [16–19]. However, the hybrid use of steel fibers and micro PP fibers in SCC structural elements exposed to fire is still limited. The hybrid concept of steel and micro PP fibers is that the steel fibers can enhance the structural behavior and the micro PP fibers can improve the fire resistance of SCC structures.

In addition, macro PP fibers for structural application have been produced and widely applied in structural elements, especially for tunnel engineering, due to their excellent corrosion resistance [20–24]. The macro PP fibers usually have a diameter of about 0.7 mm and a length of 45–60 mm. Previous studies demonstrate that the addition of macro PP fibers can significantly improve the mechanical performance of concrete elements. However, relevant research on SCC elements containing hybrid steel and macro PP fiber at both room temperature and high temperature needs further investigation.

In this paper, the flexural performances of SCC beam and a series of reinforced SCC beams (with steel fibers, with steel and micro PP fibers, with steel and macro PP fibers, and with steel, micro and macro PP fibers) before exposure to fire, will be thoroughly studied. Relevant investigation of SCC flexural beams with or without fibers, after exposure to fire, will be discussed in the follow-up papers.

2. Experimental

2.1. Materials

The raw materials used in this study were cement (P·O 52.5R), fly ash, quartz sand (0–5 mm) and crushed stone (5–15 mm). Their basic properties are shown in Table 1.

Mix proportion of SCC without fibers is listed in Table 2 [25]. The amount of superplasticizer (Sika, polycarboxylic acid type, ASTM C494 type F, the highest water reduction is up to 30%) was 1.2 wt% of binder content. Fibers used in this study were steel fiber, micro polypropylene (PP) fiber, macro PP fiber and their combinations. Images and basic properties of different fibers employed in this paper are given in Fig. 1 and Table 3, respectively. Mechanical properties of steel reinforcement bars are shown in Table 4.

2.2. Design of specimen

All SCC beams have the same dimensions, as illustrated in Fig. 2. The cross section dimensions of the beams are $150 \times 150\ mm^2$. Reinforcement ratios and fiber contents of the 12 different beams are presented in Table 5.

2.3. Loading program and measurement

A displacement-controlled procedure was employed by using a hydraulic servo testing machine (maximum load capacity of 10,000 kN). In order to provide a pure flexural zone, a steel distribution girder having 350 mm spacing on the top face of the test beam was employed, as shown in Fig. 3.

The flexural test consisted of two steps, namely a load controlled step and a displacement controlled step, as illustrated in Fig. 4. During the load controlled step, the load increment was 10 kN and the load rate was 0.1 kN/s. After every loading step, the strain of steel rebar and the concrete crack patterns were recorded. When the bottom longitudinal reinforcement bars yielded, the loading process was changed to displacement controlled stage. The displacement rate was kept at 0.5 mm/min until the beam failed. As illustrated in Fig. 3, three linear variable differential transducers (LVDTs) were employed to monitor the displacement of mid-span and loading points. Strain gauges were used to measure the strain of longitudinal reinforcement bars, as illustrated in Fig. 5.