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Impact dynamics and energy dissipation capacity of fibre-reinforced self-compacting concrete plates

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HIGHLIGHTS

- Impact dynamics of SCC and FR-SCC plates were explored by drop-weight tests.
- Dissipation of the FR-SCC plates was 6–14 times higher than that of pure SCC plates.
- Damage effects on impact forces and coefficients of restitution were evaluated.
- Crack growth in FR-SCC plates subjected to impact loading is stabilised by fibres.

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ABSTRACT

Applications of self-compacting concrete (SCC) in mega constructions have become increasingly popular. However, structures constructed with brittle SCC are extremely vulnerable to impact loading. Fibre-reinforced SCC (FR-SCC) could be a viable solution to this problem, since the dynamic cracking in the SCC matrix can be restrained by the dispersed fibres and the overall impact resistance can be enhanced. However, the dynamics and failure mechanisms of FR-SCC subjected to impact loading are seldom explored in the literature. Furthermore, an excessive amount of fibres can deprive SCC of its favourable fluidity and segregation resistance. Hence, the fibre content has to be optimised to strike a balance between impact resistance and fluidity. In this regard, this paper presents a study on the impact dynamics of plates made of one SCC and three fibre-reinforced SCC (FR-SCC) mixes with different fibre content using a drop-weight testing apparatus. The rheological properties of the mixes were also investigated. The kinematic responses, effective impact forces, energy dissipation capacities, momentum transfer, and coefficients of restitution of the plates subjected to impact loading were evaluated and compared to explore the impact mechanisms. On the basis of the experimental results, the relationships between the effective impact forces and coefficients of restitution with the accumulated damage were obtained. The momentum transfer and impact duration remained approximately constant for the FR-SCC plates after being subjected to certain numbers of blows on account of the crack-bridging toughening mechanism. Also, it was found that the impact resistances and the energy dissipation capacities of the FR-SCC plates can be significantly higher than that of pure SCC plates by 6–14 times.
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1. Introduction

Self-compacting concrete (SCC) is a special concrete mixture characterised by high fluid consistency in the fresh stage and being able to consolidate under its own weight without the use of mechanical vibration. Given the characteristics of superior fluidity and self-consolidation, the placement and quality control of SCC are made much easier than in ordinary vibrated concrete (VC). Many technical issues associated with concrete casting for mega-sized structural members and members with closely spaced reinforcing steel bars can be resolved by using SCC. Hence, SCC has become increasingly popular in super high-rise buildings and mega infrastructure constructions worldwide. Nevertheless, the very low fracture toughness of SCC, which can be more brittle than conventional VC with similar compressive strength [1,2], can cause vulnerability of SCC structures to impact and blast loading. It is

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known that extreme dynamic effects of impact loading, such as explosions, sudden rock falls and vehicle strikes can be devastating to structures in a very short span of time. Therefore, the high brittleness of SCC may limit its applications to those structures of great importance that require extra security and safety from blast and impact loading. The risk of catastrophic collapse of existing concrete buildings due to impact/blast can be reduced by retrofitting the critical structural members, such as columns and walls, with FRP wraps or steel jackets [3,4]. However, the total associated cost for applying these retrofitting techniques could be quite high [5] and the continuous function of the buildings is interrupted during the retrofit. Therefore, it would be more cost-effective and reasonable to equip a new protective structure with the ability of impact resistance in the first place when it is being constructed. One of the feasible solutions would be using fibre reinforcement to enhance the fracture toughness and ductility of SCC. The mix of fibres and SCC is commonly referred to as fibre-reinforced SCC (FR-SCC).

The static behaviour of SCC and FR-SCC has been extensively investigated in the literature [6–8], while there are some studies on the impact behaviour of different types of concrete members reinforced with fibres or polymer beads, for instance natural fibre-reinforced cement mortar slabs [9], steel and propylene fibre-reinforced concrete [10,11], ultra-high performance fibre-reinforced concrete plates [12,13], and expanded polystyrene concrete cubes [14]. However, there are limited studies that comprehensively explore the impact dynamics and failure mechanisms of fibre-reinforced SCC. To understand the impact effects on structures, impact tests using drop-weight testing apparatuses [15–19] have been an effective means. The structural dynamic responses can be measured directly during the drop-weight impact tests, and together with the cracking mechanisms can provide a basis for investigating the impact behaviour of structural members with different materials. Nevertheless, while it is expected that fibre reinforcement can enhance the mechanical properties and impact resistance of concrete, it can also reduce the beneficial workability of self-compacting concrete. Although super-plasticizers may be adopted to solve this problem, segregation could result. Nevertheless, an optimum balance of the workability and segregation resistance can be attained by increasing the amount of fine materials or by using viscosity-enhancing agents.

In this regard, this paper presents a rigorous study exploring the impact dynamics and failure mechanisms of SCC and FR-SCC plates. Section 2 presents the material properties and preparation of one pure SCC and three FR-SCC mixes with different fibre content. Slump flow and V-funnel tests were first performed to determine the rheological properties of the mixes in their fresh states. Then, three series of impact tests with different drop-heights of the impact hammer were conducted using the drop-weight testing apparatus as shown in Section 3 on the plate specimens of four different mixes. Section 4 presents and compares the kinematic responses of the specimens, impact forces, and crack propagations recorded during the impact tests. The energy dissipation capacities, momentum transfers and coefficient of restitution were also evaluated in order to explore the impact mechanism of the specimens. The major findings of this study are summarised in Section 5.

2. Specimen preparations

2.1. Materials and mix proportioning

A flat synthetic from polypropylene (PP) fibre, as shown in Fig. 1(a), was used as the fibre reinforcement in this study. The fibres do not interfere with the hydration process of the cement and the pozzolanic reaction of the fly ash in the SCC. It has been demonstrated by other studies (e.g. [20]) that PP fibres can enhance the durability and control the long-term cracking of concrete. Therefore, the fibres are suitable for structural applications. The standard geometric and mechanical properties of the fibres are shown in Table 1. One SCC and three fibre-reinforced SCC (FR-SCC) mixes with different fibre content were prepared. The first mix labelled as F0 was pure SCC without fibre. The other three FR-SCC mixes labelled as F1, F2, and F3 had a fibre content of 2 kg/m^3, 2.5 kg/m^3, and 3 kg/m^3 respectively. A sufficient amount of fibres should be provided to achieve the desired fracture toughening effect on the SCC [21], but the favourable fluidity and segregation resistance can be eliminated by an excessive amount of fibres [22,23]. Hence, it is necessary to optimise the fibre proportions. In this study, the fibre contents in the FR-SCC mixes were determined based on the results of rheological and strength tests. The minimum fibre dosage considered in this study was in accordance with the recommendation of Eurocode 2 [24] that more than 2 kg/m^3 of monofilament fibres can be included in concrete mix as a possible measure to prevent or limit thermal spalling. The minimum dosage of 2 kg/m^3 provides a good safety margin and is widely adopted by engineers.

The adopted materials and mix proportioning of the SCC and FR-SCC are shown in Table 2. The design proportions of Portland cement (42.5), fly ash, water, and fine and coarse aggregates, as per the Turkish design standard for SCC [25], were the same for all mixes, but a higher amount of super-plasticizer (ADVA 375) was provided for mixes with higher fibre content. For the series F2 and F3, V-MAR-3 as the viscosity-enhancing agent (VEA) and a modified amount of ADVA375 were added to prevent segregation of fibres from the matrix while maintaining ideal fluidity and consistency of the SCC.

2.2. Mechanical and rheological properties

For each design mix, three identical plates with the dimensions of $400 \times 400 \times 40$ mm for the impact tests, six $150 \times 150 \times 150$ mm cubes for the compressive strength tests, and three $150 \times 150 \times 600$ mm beams for the 4-point flexural tests were prepared. The fluidity and rheology of the fresh SCC and FR-SCC were evaluated by slump flow and V-funnel tests as per the EFNARC guidelines [26]. Among all four mixes, the pure SCC mix (F0 mix) had the best fluidity in that it had the largest flow diameter of 700 mm in the slump flow test and took the shortest time (V-funnel flow-time) of 7.2 s to completely discharge in the V-funnel test. The fluidity of the mix reduced with increasing fibre content, which was clearly demonstrated by the V-funnel test results. The V-funnel flow-time of FR-SCC with fibre content of 2 kg/m^3 (F1 mix) was 1.4 s longer than for the pure SCC but further increase in the fibre content resulted in a significant reduction of the V-funnel flow-time. The V-funnel flow-times of FR-SCC with fibre content of 2.5 kg/m^3 (F2 mix) and 3.0 kg/m^3 (F3 mix) were 13.8 s and 22.7 s, respectively, almost two times and three times the V-funnel flow-time of pure SCC. The slump flow diameter of the F1 mix was smaller than the F0 mix by 33 mm but the difference between the slump flow diameters of the F1 and F2 mixes was only 10 mm. Because of the higher dosage of super-plasticizer (ADVA 375), the slump flow diameter of the F3 mix was even larger than that of the F2 mix by 5 mm. Nonetheless, it is noted that the fluidity of all fresh SCC and FR-SCC mixes satisfied the ENFARC criteria [26].

The average 7-day and 28-day compressive strengths and the average flexural strength were determined for each mix. It was found that the addition of fibres had a negligible or only slight enhancing effect on the strengths, consistent with other observations in the literature [21]. The flow and strength test results are presented in Table 3. The drop-weight impact tests were performed on the hardened plate specimens after 28 days of curing.

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