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# The effect of silica fume and steel fiber on the dynamic mechanical performance of high-strength concrete

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## Abstract

The impact and fatigue performance of high-strength concrete (HSC), silica fume high-strength concrete (SIFUHSC), steel fiber high-strength concrete (SFRHSC), and steel fiber silica fume high-strength concrete (SSFHSC) under the action of repeated dynamic loading were studied. The mechanisms by which silica fume and steel fiber reduce damage were also investigated. The results indicate that steel fiber effectively restrained the initiation and propagation of cracks during the failure of an HSC structure, mitigated the stress concentrations at the tips of cracks, and delayed the damage process under impact and fatigue. Silica fume effectively improved the structure of the interface, eliminated the weakness of the interfacial zone, reduced the number and size of cracks, and enhanced the ability of steel fibers to resist cracking and restrain damage. As a result, the corporation of steel fibers and silica fume can increase greatly the performance of HSC subjected to impact and fatigue. 

*Keywords:* Interfacial transition zone; Fatigue; Silica fume; Fiber reinforcement; High-performance concrete

Both normal-strength concrete and high-strength concrete are brittle, with the degree of brittleness increasing with increasing strength. The dynamic mechanical performance of high-strength concrete (HSC) under impact or fatigue loading has received increasing attention in recent years because of the rapid adoption of higher strength concrete in bridges, pavements, and marine structures, and several researchers have studied the impact or fatigue performance of concrete [1–4].

Many experimental results have indicated that the characteristics and microstructure of both the interfacial zone and the bulk HSC are improved by incorporating silica fume. As well, the addition of steel fibers can effectively restrain the initiation and propagation of crack under stress, and improve the toughness of HSC [5–8].

This paper deals mainly with the impact and fatigue performance of HSC under dynamic loading with the addition of silica fume and steel fibers. Four series of reference HSC mixtures were used: HSC, SIFUHSC (silica fume high-strength concrete), SFRHSC (steel fiber high-strength concrete), and SSFHSC (steel fiber silica fume high-strength concrete).

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## 1. Experimental

### 1.1. Raw materials

The mix proportions and static mechanical properties of the four series of concrete are listed in Table 1. The quantity of reactive $SiO_2$ and the specific area of the silica fume were 94.48% and 24 $m^2/g$, respectively. The steel fibers were rectangular straight fibers made by cutting low-carbon steel sheet. The fiber length ($l_f$), diameter ($d_f$) and aspect ratio ($l_f/d_f$) were 25 mm, 0.417 mm and 60, respectively. The coarse aggregate was crushed granite with continuous grading (5 $\sim$ 20 mm) and maximum size of 20 mm. The fine aggregate was river sand with a fineness modulus of 2.38. The code name of the high-efficiency water-reducing agent was JSM.

### 1.2. Test methods

#### 1.2.1. Impact resistance tests

The impact performance was measured by the freely falling ball method recommended by ACI Committee 544. The $\phi$150 $\times$ 64 mm cylindrical specimens were cast for impact testing. The weight and height of the falling ball were 4.5 kg and 457 mm, respectively. The impact performance was expressed by four indices: the number of blows at initial cracking ($N_1$), the number of blows at rupture ($N_2$), the difference between $N_1$ and $N_2$ ($\Delta N = N_1 - N_2$), and the impact toughness (T).

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Table 1
Mix proportions and static mechanical properties of concrete

| Type of concrete | Cement ($kg/m^3$) | Silica fume ($kg/m^3$) | Steel fiber by volume (%) | w/(c+sf) | Sand ratio (%) | Compressive strength at 28d (MPa) | Flexural strength at 28 days (MPa) |
|---|---|---|---|---|---|---|---|
| HSC | 500 | 0 | 0 | 0.28 | 32 | 80 | 7.0 |
| SIFUHSC | 400 | 100 | 0 | 0.28 | 32 | 100 | 9.0 |
| SFRHSC | 500 | 0 | 1.5 | 0.28 | 36 | 100 | 15.0 |
| SFRSIFUHSC | 400 | 100 | 1.5 | 0.28 | 36 | 120 | 21.0 |

*1.2.2. Flexural fatigue tests*

The 100 × 100 × 400 mm prism specimens were cast for the flexural fatigue tests. The third-point load method was used. The load cycle characteristic value (ρ) was equal to 0.1. The stress ratio (*n*), whose definition is the ratio of flexural fatigue strength to flexural strength, varied from high to low until the fatigue number came to $10^6$. Then, the stress ratio was maintained at this value until the specimens were ruptured under fatigue action. The loading action frequencies were 5 ~ 7 Hz at $n \geqslant 0.8$, and 15 ~ 20 Hz at $n < 0.8$.

*1.2.3. Interface characteristic measurement*

The interface characteristics were determined by the microhardness method. In these measurements, the microhardness was tested layer by layer and point by point from the steel fiber or aggregate surface to a constant microhardness value.

## 2. Results and discussion

*2.1. Impact characteristics of the four series of concrete*

The impact resistance performance of the four series of concrete is shown in Fig. 1. All of the behavior indices of SIFUHSC were increased slightly compared with those of HSC, but they were still of the same order of magnitude. By incorporating steel fibers into HSC, the four indices of SFRHSC compared to those of HSC were increased by 15 times ($N_1$), 17 times ($N_2$), 43 times ($\Delta N$), and 17 times (T), respectively. When silica fume and steel fiber were simultaneously incorporated into HSC, the four indices of SFRSIFUHSC compared with those of HSC were increased by 22 times ($N_1$), 29 times ($N_2$), 123 times ($\Delta N$), and 29 times (T), respectively. Also, the difference between $N_1$ and $N_2$ was increased from 15 to 1853, more than a hundred-fold increase. This indicates that the SSFHSC has a great ability to absorb kinetic energy because of the combined effect of the steel fiber and silica fume. The initiation and propagation of cracks during an impact event were restrained by the combined effect of the steel fibers and silica fume. The SSFHSC could still withstand impact stress and absorb more kinetic energy without leading to concrete damage after the initial cracking. The final damage pattern of SSFHSC was multiple cracking without complete rupture.

*2.2. The fatigue characteristics of four series of concrete*

The fatigue test results, involving 500 fatigue specimens of the four series of concrete, were analyzed by the linear regression analysis. The regression equations relating the stress ratio and the logarithm of fatigue number (lgN) are shown in Eqs. (1–4):

$$n = 1.029\text{–}0.061\ \mathrm{lgN} \qquad \gamma = 0.954,\ S = 0.021 \tag{1}$$

$$n = 1.045\text{–}0.057\ \mathrm{lgN} \qquad \gamma = 0.967,\ S = 0.019 \tag{2}$$

$$n = 1.048\text{–}0.0556\ \mathrm{lgN} \qquad \gamma = 0.973,\ S = 0.02 \tag{3}$$

$$n = 1.0511\text{–}0.0539\ \mathrm{lgN} \qquad \gamma = 0.973,\ S = 0.02 \tag{4}$$

where γ is the relative coefficient and *S* is the regression error.

The stress ratios are shown in Table 2. The stress ratio (each type of concrete could withstand different fatigue numbers) was calculated by subtracting three times the standard deviation from the regression value in order to achieve a 99.7% rate of safety guarantee.

When the fatigue number increased from $10^2$ to $10^6$, the stress ratios for all series of concrete decreased. The magnitude of the decrease was in the order HSC > SIFUHSC > SFRHSC > SSFHSC. This illustrates that the decrease in stress ratio becomes lower with the incorporation of silica

Table 2
The calculating stress ratio according to regression equation

| Type of concrete | The fatigue number | | | | |
|---|---|---|---|---|---|
| | $10^2$ | $10^3$ | $10^4$ | $10^5$ | $10^6$ |
| HSC | 0.844 | 0.783 | 0.722 | 0.661 | 0.600 |
| SIFUHSC | 0.874 | 0.817 | 0.760 | 0.703 | 0.646 |
| SFRHSC | 0.877 | 0.821 | 0.766 | 0.710 | 0.654 |
| SFRSIFUHSC | 0.883 | 0.829 | 0.776 | 0.722 | 0.668 |

Table 3
The flexural fatigue strength (MPa) calculated from the regression equations*

| Type of concrete | The fatigue number | | | | |
|---|---|---|---|---|---|
| | $10^2$ | $10^3$ | $10^4$ | $10^5$ | $10^6$ |
| HSC | 6.05 | 5.56 | 5.00 | 4.44 | 4.20 |
| SIFUHSC | 8.10 | 7.53 | 6.88 | 6.32 | 5.80 |
| SFRHSC | 13.37 | 12.47 | 11.61 | 10.69 | 9.83 |
| SFRSIFUHSC | 18.56 | 17.59 | 16.44 | 15.31 | 14.35 |

* Load cycle characteristics value ρ = 0.1

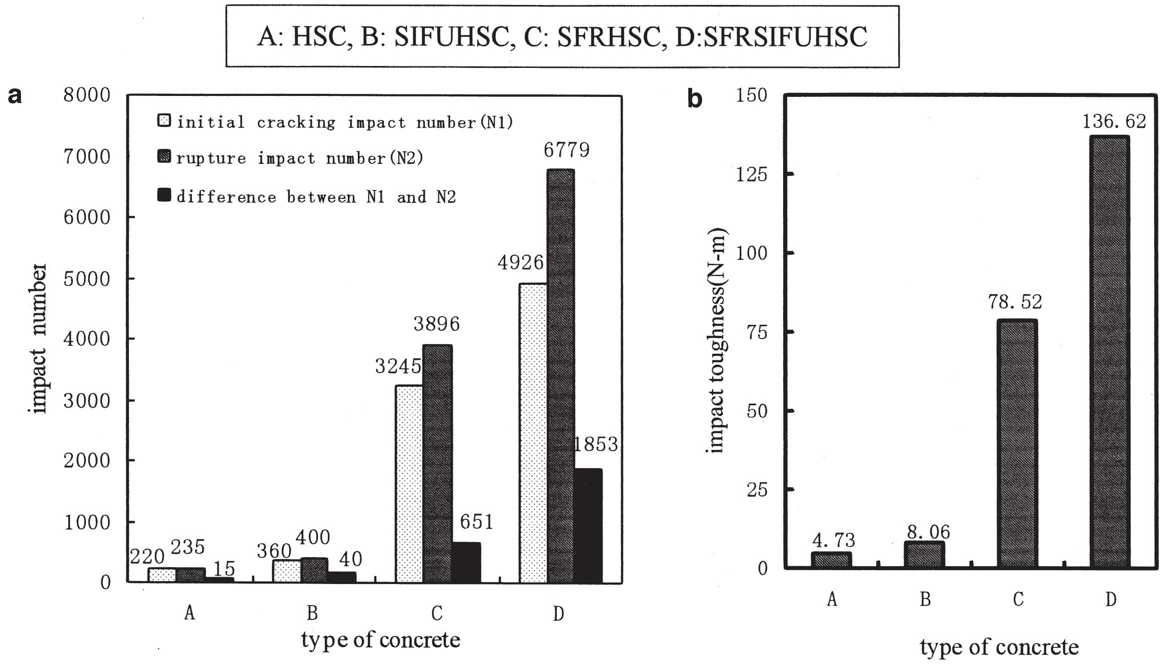


Fig. 1. The impact characteristics of the four series of concrete.

fume, steel fibers, or both. The fatigue capacity was obviously enhanced. Table 3 indicates that the flexural fatigue strength of SIFUHSC and SFRHSC increased by 38% and 134%, respectively, compared to that of HSC when the fatigue number was $10^6$. However, that of the SSFHSC increased by more than a factor of three. That too resulted from the combined effect of silica fume and steel fiber.

### *2.3. The mechanism of the combined effect of silica fume and steel fiber*

The key to increasing the performance of HSC under impact and fatigue is to increase its cracking resistance. This mainly comes from two aspects: a reduction in the number and size of the original cracks and control of the initiation and extension of original cracks. The entire structure of HSC is improved because of the addition of steel fibers. At the crack tip, steel fibers can restrain the extension of the crack, reduce the extent of stress concentration at the tip of crack, change the direction of crack growth, and delay the growth rate of the crack. However, it was still necessary to improve further the interfacial characteristics by incorporating silica fume into the HSC matrix in order to bring the strengthening, toughening, and crack resisting effects of the steel fibers into full play. The interfacial zone is improved because of the filler effect, crystallizing effect, and the pozzolanic effect of the silica fume. From the test results in Table 4, we can see that the microhardness difference between the matrix and the weakest point of the interface decreased on average from about 76 $\sim$ 80 MPa to 0.1 $\sim$ 0.7 MPa when 20% silica fume (replacement of cement) was added to the HSC matrix. This large difference represents a varying process of the interfacial layer, which is from presence to absence and then to stengthening. The thickness of the interfacial layer tends toward zero. The difference between interfacial zone and the matrix are reduced or eliminated completely; this elimination of the harmful effects results from a poor interface. The number and sizes of original cracks at the interface and in the whole structure were decreased, thus produc-

Table 4
The relationship between microhardness and interfacial characteristics

| Type of concrete | The microhardness at the weakest point of interface (MPa) | The microhardness of matrix (MPa) | The microhardness difference between the weakest point of interface and matrix (MPa) | The thickness of interface (μm) | The average bond strength of interface (MPa) |
|---|---|---|---|---|---|
| HSC | 406.2 | 488.6 | 80.4 | 50 | — |
| SIFUHSC | 989.2 | 988.4 | 0.2 | Near zero | — |
| SFRHSC | 410.1 | 486.3 | 76.2 | 50 | 3.52 |
| SFRSIFUHSC | 989.3 | 989.4 | 0.1 | Near zero | 7.63 |

ing an effective interfacial effect. The ability of the steel fibers to resist cracking and restrain damage was significantly increased.

Then, in SSFHSC, the initiation and extension of cracks are faced with a double obstruction: the strengthening by silica fume of the interfacial structure and a consequent improvement in the interfacial effect and the restraint of the propagation of cracks by the steel fibers. Silica fume and steel fibers are particulate and fibrous materials, respectively, with completely different characteristics. They have a synergistic effect that brings the combined effect of particulate and fibrous materials into full play in HSC. Thus every performance index of HSC with regard to impact and fatigue resistance is enhanced considerably.

## 3. Conclusions

1. Silica fume and steel fibers are materials with totally different characteristics. The filler effect, crystallizing effects, and pozzolanic effect of silica fume can reduce the number and size of the original cracks in the interfacial zone and in the bulk of concrete and enhance the interfacial effect. Steel fibers mainly strengthen, toughen, and resist cracking in HSC. Silica fume and steel fiber can restrain HSC damage during the process of impact and fatigue by different, complemental mechanisms.
2. When silica fume or steel fiber is added separately into the HSC matrix, the HSC performance under impact, fatigue, and repeated dynamic loading can be enhanced. The impact indices of SFRHSC can be increased by a factor of two compared with those of HSC. The fatigue strength of SIFUHSC and SFRHSC increase by 38% and 134%, respectively, when the fatigue number is $10^6$. This indicates that the effect of incorporating steel fibers alone is greater than that of incorporating silica fume alone.
3. When silica fume and steel fibers are both incorporated into the HSC matrix, the impact and fatigue resistance performance of HSC can be enhanced considerably. The fatigue strength is increased by a factor of four when the fatigue number is $10^6$. This indicates that the composite effects of silica fume and steel fiber are greater than the sum of the individual effects of silica fume or steel fibers.
4. The test results of HSC interfacial microhardness show that silica fume can improve the interface structure, eliminate weaknesses of the interface, enhance the interfacial bond strength, and reduce the number and size of original cracks. Therefore it can greatly increase the ability of steel fibers to resist cracking and restrain damage to HSC. This indicates further that the combination of silica fume and steel fibers can reduce damage to HSC under impact and fatigue stress by different mechanisms. Then the HSC capacity to resist impact and fatigue can be significantly increased.

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