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Shear Behaviour of High-Strength Self-Compacting Concrete (HSSCC) RC Beam with 12.5% Metakaolin and Variations of Silica Fume

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Abstract. High-Strength Self-Consolidating Concrete (HSSCC) is a type of concrete that possesses superior mechanical properties and can self-settle without the need for vibration assistance. Numerous advancements have been implemented to enhance the properties of HSSCC. In prior experimental work, the authors investigated the mechanical characteristics of HSCC with 12.5% metakaolin and 0-15% silica fume as a partial cement substitute. Since metakaolin and silica fume have smaller particle sizes than cement, they can fill voids between aggregate and enhance the concrete's compactness. Further structural study is necessary to provide a more complete knowledge of the impact of partially substituting cement with metakaolin and silica fume. Using the Response 2000 program, this investigation analyzes the shear behavior of reinforced HSSCC beams. Laboratory-determined material mechanical properties were utilized as simulation input data. In this investigation, the maximum strength, deflection, and crack development of five beam models produced with varying material mechanical properties were investigated and compared.

1 Introduction

High-strength self-compacting concrete (HSSCC) is a type of concrete that possesses high strength and the ability to flow on its own without the need for external compaction. The high strength is essential for structures that bear significant loads, such as long-span bridges and high-rise buildings. The use of high-strength concrete can also reduce the dimensions and weight of structures while enhancing their durability against aggressive environmental attacks. On the other hand, the self-flowing capability of fresh concrete without the need for external compaction is necessary to overcome issues commonly encountered in the construction site, such as difficulties in compacting concrete in hard-to-reach areas or complex shapes. The utilization of this type of concrete can also achieve uniform density and distribution without potential air gaps that could weaken the concrete structure. In densely

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populated project locations, this concrete type is often chosen as a construction material to reduce noise levels at the construction site.

Research related to Self-Compacting Concrete (SCC) has been underway for several decades [1]. In the early stages of its discovery, the mechanical properties of Self-Compacting Concrete were not yet sufficiently developed. Further research was conducted to formulate concrete mixes with the ability to self-flow without significant loss of strength [2]. In the 2000s, SCC began to be commercially applied in numerous construction projects worldwide. Several countries have also developed standards for this type of concrete. Organizations such as the American Concrete Institute (ACI) and the European Committee for Standardization (CEN) have issued guidelines and standards regarding SCC to regulate materials and testing methods. Ongoing efforts are being made to develop new materials and technologies to enhance the performance and efficiency of SCC. Research on fillers, additives, and mixing methods continues to be conducted to optimize the characteristics of SCC [3,4].

Metakaolin is a pozzolanic material produced through the processing and calcination (high-temperature heating) of kaolin, a type of white clay rich in the mineral kaolinite. The calcination process removes a significant portion of the crystal water from kaolin, transforming it into metakaolin, which possesses more chemically reactive properties. Metakaolin is used as an additive in the production of concrete and other construction materials to enhance their properties. The reactive particles of metakaolin fill voids within the concrete structure and interact with cement hydration products, forming strong products that reinforce the concrete matrix. Metakaolin can assist in controlling concrete cracks and shrinkage by reducing alkali-silica reactions and alkali-aggregate expansion, thereby diminishing the risk of detrimental cracking. Furthermore, the use of metakaolin in concrete has been found to enhance its durability by increasing its resistance to the ingress of aggressive chemical compounds, including salts and acidic solutions. The application of this technique enhances the durability of the concrete by increasing its resistance to chemical degradation and corrosion [5].

Silica fume, alternatively referred to as microsilica, is a byproduct generated during the production of silicon or ferrosilicon through reduction processes in the metallurgical industry. Silica fume consists of small nano-sized particles primarily composed of silica (SiO2) and possesses highly reactive chemical properties with an exceptionally high specific surface area. Generally, silica fume is used as an additive in concrete or cement mixes to enhance several mechanical and physical properties of concrete, such as compressive strength, wear resistance, chemical resistance, and resistance to water penetration. When introduced into concrete mixes, the small silica fume particles interact with the calcium hydroxide produced during cement hydration, forming stronger and denser products. This results in concrete that is more durable and stronger compared to concrete without the addition of silica fume [6–8]. The combination of metakaolin and silica fume can provide concrete with higher strength, better environmental resistance, and superior mechanical performance [7,8].

Shear failure and flexural failure are common modes of failure in reinforced concrete structures. Shear failure occurs when the shear forces exceed the shear capacity of the structure. This can be caused by design errors, excessive loads, low material quality, and insufficient capacity of the provided shear reinforcement. Shear failure is brittle in nature and happens suddenly. Therefore, shear failure in reinforced concrete structures is generally avoided by enhancing the shear capacity of the structure beyond its flexural capacity [9]. However, for specific structures dominated by shear behavior (such as transfer beams, pile caps, and tunnel roof slab), changing the failure mode is challenging [10]. Regarding the use of Self-Compacting Concrete (SCC), some researchers have raised doubts about its field application. The aggregate size used in SCC is relatively smaller compared to conventional concrete. This reduction can diminish the contribution of aggregate interlocking in providing overall shear capacity to beams. This was evidenced by the experiments of Lin and Chen [11], who applied two different coarse aggregate contents in SCC mixtures. SCC with a higher coarse aggregate content exhibited shear strength nearly equivalent to conventional concrete. Conversely, SCC with a lower coarse aggregate content tended to have a smaller shear capacity compared to conventional concrete beams.

Research on the shear behavior of HSSCC reinforced structures using silica fume and metakaolin is still limited [12,13]. Therefore, further research is necessary to provide a more comprehensive understanding of this field of study. This research was conducted to numerically assess the shear performance of reinforced HSSCC beams containing 12.5% metakaolin and different proportions of silica fume. The numerical modeling was accomplished with the RESPONSE 2000 software, which relied on the mechanical parameters of concrete derived from prior investigations undertaken by the author [14,15].

2 Experimental Work

In the previous study, the authors [14,15] conducted mix design and tested the mechanical properties of HSSCC with a metakaolin content of 12.5% and varying levels of silica fume. Table 1 shows the mix design used in the production of HSSCC. The concrete mixture consists of fine aggregate, coarse aggregate, binder, superplasticizer, and water. The concrete binder itself consists of cement, metakaolin, and silica fume, with their total weight kept constant in 1 m^3 of the concrete mix. Based on research conducted by Joseph et.al [16]. and Wibowo et.al. [17], the optimum value of metakaolin as a substitute material for cement is 12.5% of the total binder. This optimum content was used in this study. The silica fume content was varied from 0%, 9%, 11%, 13%, to 15%.

Table 1. Mix design of HSSCC.

Specimen	**Coarse aggregate (kg/m^3)**	**Fine aggregate (kg/m^3)**	**Cement (kg/m^3)**	**Meta-kaolin (kg/m^3)**	**Silica fume (kg/m^3)**	**Water (l/m^3)**	**Superplas-ticizer (l/m^3)**
HSSCC-SF0%	777.9	915.3	525	75	0	150	9
HSSCC-SF9%	769.8	905.7	471	75	54	150	9
HSSCC-SF11%	767.9	903.6	459	75	66	150	9
HSSCC-SF13%	766.1	901.5	447	75	78	150	9
HSSCC-SF15%	764.3	899.3	435	75	90	150	9

Table 2. Mechanical properties of HSSCC.

Specimen	**Compressive strength, f'c (Mpa)**	**Splitting tensile strength, f_{ct_sp} (Mpa)**	**Modulus rupture, f_{ctf} (Mpa)**	**Elastic modulus, E (Mpa)**
HSSCC-SF0%	41.99	3.93	6.8	19907
HSSCC-SF9%	55.39	4.76	7.66	25443
HSSCC-SF11%	67.75	5.78	7.97	29571
HSSCC-SF13%	61.80	5.27	7.82	26616
HSSCC-SF15%	58.03	4.94	7.69	26161

The results of fresh concrete tests, including slump flow test, L-box test, and V-funnel test, indicate that the fresh concrete characteristics met the criteria of the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) for self-compacting concrete. Detailed results of the fresh concrete tests can be found in the previous study [14,15]. Table 2 presents the mechanical properties of concrete tested in the laboratory, including compressive strength, split tensile strength, modulus of rupture, and modulus of elasticity. Generally, the mechanical properties of the material increased with the addition of silica fume. Within the range of silica fume variations studied, the optimum value for adding silica fume was found to be 11%. The mechanical properties of the material decreased after surpassing the optimum content, although they remained higher than the values of mechanical properties of concrete without any added silica fume. The addition of silica fume increased the compressive strength, modulus of elasticity, split tensile strength, and modulus of rupture by up to 61%, 49%, 47%, and 17%, respectively, as shown in Figure 1.

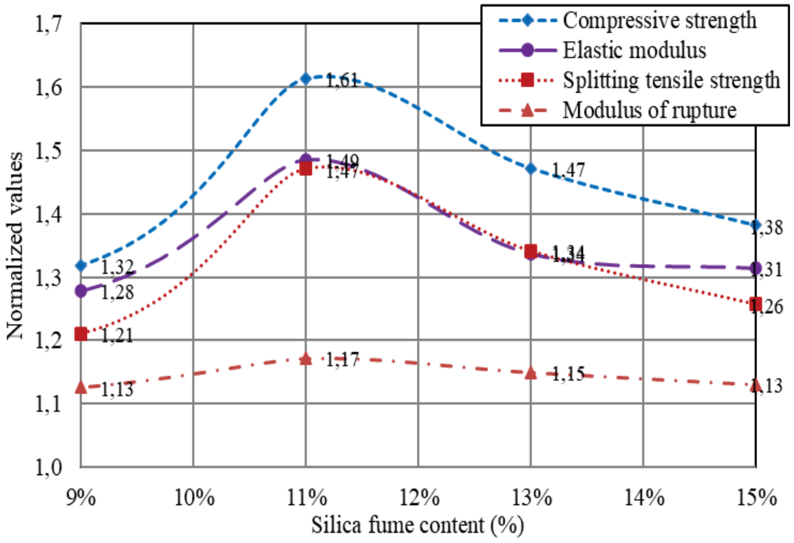

Fig. 1. The effect of silica fume content on the mechanical properties of HSSCC.

3 Numerical Simulation

Modeling and numerical analysis were carried out utilizing the RESPONSE 2000 software, a user-friendly cross-sectional analysis program developed by Prof. Bentz from the University of Toronto. This software is intended to determine the strength and ductility of a cross-section of reinforced concrete under shear, moment, and axial stress. The simulations employed the Modified Compression Field Theory (MCFT) proposed by Collins and Vecchio [18]. The validation of the numerical analysis results against experimental data has been carried out in several studies, including Bentz [19]and Metwally et. al. [20].

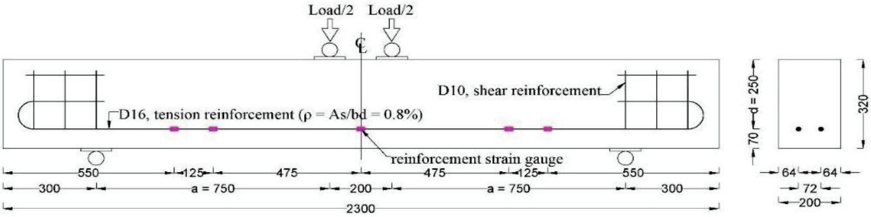

Fig. 2. Outline of RC beam.

For this simulation, beam specimens from the study by Saifullah et al. [21,22]were used, as illustrated in Figure 2. The beams had a width of 200 mm, height of 320 mm, length of 2300 mm, and a shear span-to-effective depth ratio of 3.0. High-strength steel reinforcement (fy = 1062 MPa) with a reinforcement ratio of 0.8% was placed at the bottom of the beam as tension reinforcement. Shear reinforcement was not placed along the shear span to ensure a shear failure mode. Mechanical properties data obtained from concrete testing in the laboratory, such as compressive strength and tensile strength, were used as the primary input for the program. Direct tensile testing was not conducted in the laboratory, so the concrete's tensile strength value was taken as 90% of the split tensile strength or approximately 50-60% of the modulus of rupture value [23]. In shear capacity calculations using MCFT, the maximum aggregate size plays a crucial role. The model incorporates a 12 mm maximum aggregate size to illustrate the diminished role of aggregate interlocking in the shear transfer of HSSCC beams. The chemical effects of the concrete mix on the flexural strength of the beam were not considered in this simulation.

4 Behaviour of RC Beam

Figure 3 illustrates the load-deflection relationship at the midspan of reinforced concrete beams with varying levels of silica fume. During the initial loading, the load-deflection relationship is linearly elastic. Although all beams have nearly the same initial stiffness, each beam has a different elastic limit, greatly influenced by the concrete's tensile strength. The first flexural crack occurred in beams with silica fume contents of 0%, 9%, 11%, 13%, and 15% at loads of 19.4 kN, 25.8 kN, 29.2 kN, 27.7 kN, and 26.5 kN, respectively. The deflection at the first flexural crack for beams with silica fume contents of 9%, 11%, 13%, and 15% was 0.4 mm, while the control beam without added silica fume exhibited a smaller deflection of 0.3 mm. The addition of silica fume increased the flexural crack capacity of the beams.

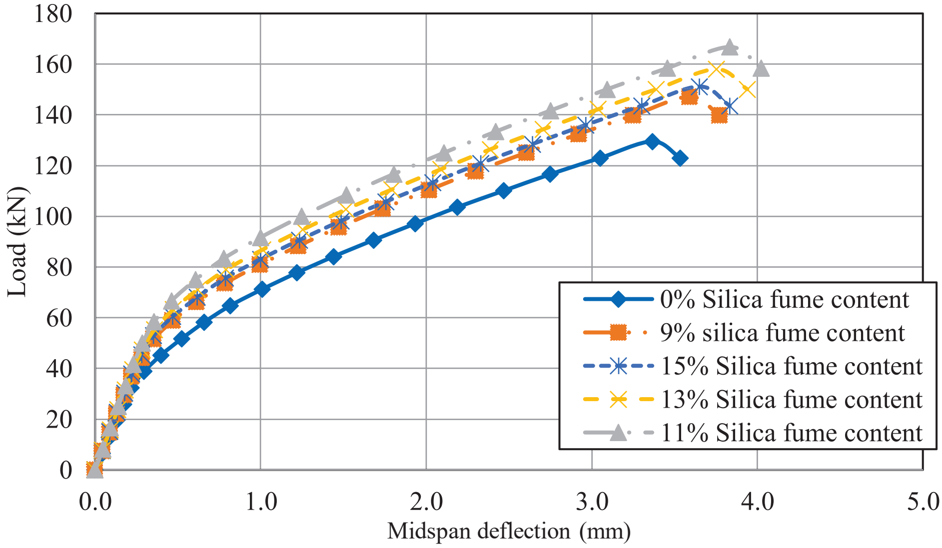

Fig. 3. Load-midpsan deflection of HSSCC RC beam with variation of silica fume content.

As the load increased, flexural cracks started to distribute uniformly along the beam's shear span and propagated towards the compression region at the top of the beam. The initiation of diagonal shear cracks was triggered by these flexural cracks. Shear failure of the beams occurred at loads of 129.52 kN, 147.20 kN, 166.77 kN, 158.02 kN, and 151.18 kN for beams with silica fume contents of 0%, 9%, 11%, 13%, and 15%, respectively. Based on longitudinal reinforcement strain checks at the ultimate condition, it was found that the strain in the longitudinal reinforcement was still lower than the yielding strain. This indicates that the beams experienced shear failure without longitudinal reinforcement yielding. On the other hand, the beams have a shear span-to-effective depth ratio falling within the range categorized as slender beams. Hence, the ultimate value also indicates the presence of significant diagonal cracking. The maximum deflection values for beams with silica fume contents of 0%, 9%, 11%, 13%, and 15% were 3.37 mm, 3.59 mm, 3.83 mm, 3.75 mm, and 3.65 mm, respectively. The addition of silica fume also increased the ultimate capacity and ductility of the beams. Detailed values of the first flexural crack load, deflection at first flexural crack load, ultimate load, deflection at ultimate load, and maximum crack width for each beam can be found in Table 3.

Table 3. Load, deflection, and maximum crack width at the initial cracking and ultimate stages.

Specimen	**Initial cracking load**		**Ultimate load**		
	Pcr (kN)	**Dcr (mm)**	**Pu(kN)**	**Du (mm)**	**Max. w_{cr} (mm)**
HSSCC-SF0%	19.4	0.3	129.52	3.37	0.94
HSSCC-SF9%	25.8	0.4	147.20	3.59	1.03
HSSCC-SF11%	29.2	0.4	166.77	3.83	1.14
HSSCC-SF13%	27.7	0.4	158.02	3.75	1.1
HSSCC-SF15%	26.5	0.4	151.18	3.65	1.06

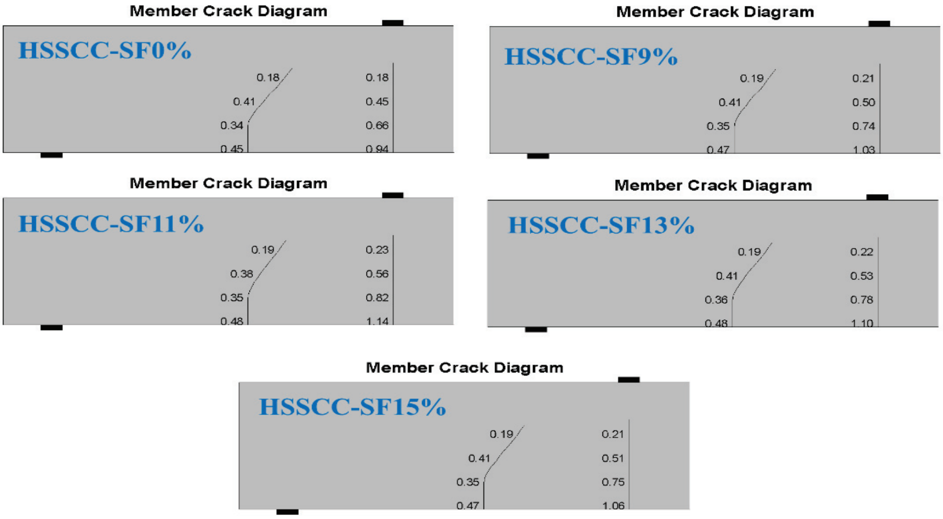

Fig. 4. Crack patterns of the HSSCC beams at the ultimate stage (E3S) (E3S) (E3S).

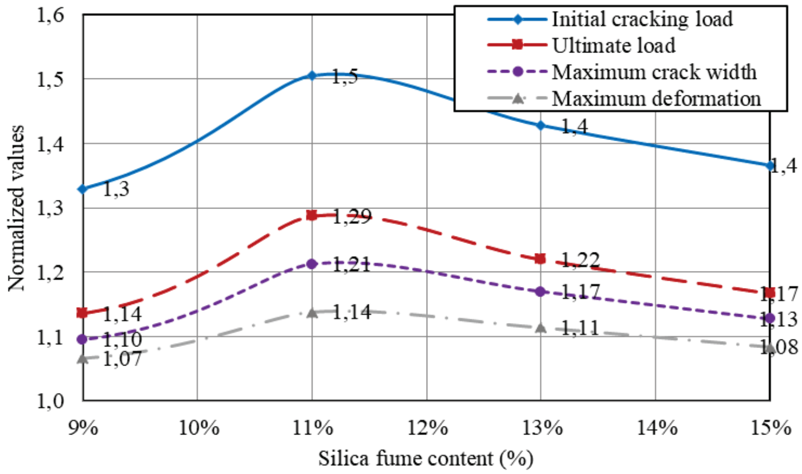

Fig. 5. The impact of silica fume content on the performance of HSSCC beams.

Figure 4 displays the crack patterns of HSSCC reinforced beams with different levels of silica fume at the ultimate load condition. As seen in the figure, the crack patterns for all beams are identical. The only difference lies in the maximum crack width each beam can sustain before failure. The influence of varying silica fume content on several key beam parameters, such as first flexural crack load, ultimate load, maximum crack width, and maximum deflection, can be easily identified through Figure 5. The values of these parameters have been normalized with similar parameters from control reinforced concrete beam specimens without added silica fume. Overall, the addition of silica fume enhances the performance of HSSCC reinforced beams. Among the key parameters studied, the ultimate load parameter of the beams is most affected by the addition of silica fume. The maximum values of the parameters occurred in beams with a silica fume content of 11%. Adding silica fume at the optimum content increased the first flexural crack load, ultimate load, maximum crack width, and maximum deflection of the beams by 50%, 29%, 21%, and 14%, respectively.

5 Conclusion

The present study investigates the shear behavior of HSSCC reinforced beams with 12.5% metakaolin and different levels of silica fume ranging from 0-15% as a partial replacement for cement. Using 12.5% metakaolin and roughly 11% silica fume can potentially increase the shear strength of these reinforced HSSCC beams by as much as 30%. Additionally, some improvements are observed in the beam's performance concerning the initial flexural crack load, maximum crack width, and deformation.

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