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STRENGTH DEVELOPMENT AND COEFFICIENT OF THERMAL EXPANSION OF HIGH-STRENGTH CONCRETE USING SILICA FUME

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Abstract. Silica fume as a partial replacement for cement in high-strength concrete has been the focus of numerous studies. However, the impact of substituting cement with silica fume in concrete mixtures on the mechanical and thermal properties of high-strength concrete remains insufficiently explored. Silica fume, characterized by its high pozzolanic activity and ultra-fine particles, is incorporated into concrete mixtures to enhance their mechanical properties and durability. The research examines the influence of varying silica fume content on the compressive strength and CTE of high-strength concrete. In the present study, concrete specimens with a water-cement ratio of 0.32 were prepared, with 5%, 10%, and 15% of the cement replaced by silica fume. Experimental results demonstrate that silica fume significantly improves compressive strength, particularly at early ages, starting from 7 days. However, the CTE of these mixtures is not significantly affected, with the average values varying slightly, ranging from 8.95 to 9.93 × 10^{-6}/°C. This study contributes to further clarifying the role of silica fume in concrete mixtures and its effect on the CTE.

Keywords: Strength development, Silica fume, Coefficient of thermal expansion, High-Strength Concrete.

1. INTRODUCTION

Currently, in the field of bridge construction, high-strength concrete (HSC) is widely used for projects that require large spans and fast construction times. The use of this material enables more slender structures, thereby reducing the dead load. HSC typically uses a high cement content in its mix, resulting in greater heat release during the cement hydration process compared to conventional concrete mixtures [1,2]. For bridge projects, controlling the temperature of the concrete during the construction phase is crucial to ensure that thermal cracks do not develop, which could affect the structure's functionality and long-term durability.

One solution to reduce the temperature in concrete is to partially replace the cement content in the mix with alternative materials while maintaining or improving the concrete's properties. In recent years, concrete incorporating silica fume as a mineral admixture has become popular in bridge construction worldwide, including in Vietnam. When used in appropriate amounts (about 5-15% of the cement content), silica fume enhances concrete strength, increases the density of the concrete mass, and reduces water and chloride permeability, Thereby improving resistance to water penetration and corrosion, as well as enhancing durability due to pozzolanic reactions[3]. Advanced concretes, such as High-Strength Concrete (HSC) [3], High-Performance Concrete (HPC), and Ultra-High-Performance Concrete (UHPC) [4], all utilize silica fume in reasonable amounts to achieve higher strength and better performance than normal concrete.

Thermal stress in concrete structure not only depends on the temperature difference between the core and the surface of the structure but also on the coefficient of thermal expansion (CTE) of concrete. CTE helps to understand and predict volume changes in the concrete mass due to temperature variations. Factors affecting CTE include mix proportions, water/cement ratio, type of aggregate, type of cement, and the moisture condition of the concrete [5,6]. The cement paste in concrete typically has a higher CTE than the aggregate, but the CTE of concrete largely depends on the aggregate since it makes up a significant portion of the mix. The CTE of concrete remains relatively stable from a few hours after pouring until 28 days. Therefore, Specific studies on the CTE of concrete when silica fume is used as a cement replacement in the mix are necessary.

Several recent studies on the CTE used for concrete pavements have been conducted, focusing on the impact of coarse aggregates such as quartzite, limestone, basalt, granite, and gravel on the concrete's CTE [5]. According to Neville [7], the CTE of ordinary concrete depends on factors such as hydrated cement paste, aggregate, curing conditions (air curing, water curing, etc.), and typically ranges from $6.1\times10^{\wedge-6}$/°C to $13.1\times10^{\wedge-6}$/°C. According to recent research in Viet Nam by Ngo [8] on concrete mixes used for cement concrete pavements, concrete using quartzite aggregate at 28 days has a CTE of $11.18\times10^{\wedge-6}$/°C, while concrete using limestone aggregate at 28 days has a CTE of $7.41\times10^{\wedge-6}$/°C. These studies affirm that concrete strength has little impact on the CTE. Some studies suggest that humidity, particularly the environmental humidity during the concrete curing process, affects the CTE during the hardening and strength development stages [5]. However, most of these studies focus on concrete used in pavements, with limited research on concrete using in structural components in bridge construction in Viet Nam.

The objective of this experimental study is to determine and assess the compressive strength and the coefficient of thermal expansion (CTE) of high-strength concrete (HSC) when replacing 5-15% of cement with silica fume, following the ACI 211.4R-08 standard [9]. The study aims to evaluate the impact of silica fume replacement on the coefficient of thermal expansion and the strength of high-strength concrete.

2. MATERIAL AND PROCEDURE TEST

2.1. Material

High-strength concrete (HSC) used in this study consists of the following main aggregate components with technical specifications: But Sơn PC40 cement; Coarse aggregate is crushed limestone from Phu Ly, Hà Nam with a maximum size (D_{max}) of 12.5 mm, yellow sand; silica fume; and the superplasticizer Sika Viscocrete 151. The silica fume used in the study is Sikacrete PP1 from Sika according to the ASTM C1240-15 standard. The particle size ranges from 0.1 to 0.2 µm, with a specific gravity of 0.2 g/cm³ (Figure 1). Meanwhile, the cement used in the study is PC40 with a common average particle size of 5-30 µm.

Figure 1. SikaCrete PP1 from Sika.

The concrete mix design was prepared according to the ACI 211.4R-08 standard [8] with the target of producing concrete with a strength of 50 MPa. The concrete mix composition is summarized in Table 1 below:

Table 1. Concrete mix proportions for 1m³.

Items	% substitution of cement	W/CKD	water (litre)	Cement (kg)	Silica Fume (kg)	Coarse aggregate (kg)	Sand (kg)	Superplasticizer (kg)
SF00	0%	0.32	169	530	0	1098.2	620.4	5.5
SF05	5%	0.32	169	503.5	26.5	1098.2	611.8	5.5
SF10	10%	0.32	169	477	53	1098.2	603.2	5.5
SF15	15%	0.32	169	450.5	79.5	1098.2	594.6	5.5

In this article, SF00 refers to the concrete mix without silica fume, using 530 kg/m³ of cement. The mixes SF05, SF10, and SF15 correspond to concrete mixes where cement is replaced by 5%, 10%, and 15% silica fume, respectively. Because, the specific gravity of cement and silica fume differ, we adjusted the sand content in the mix accordingly, while the quantities of the other components were kept unchanged.

2.2. Experimental Testing of Concrete Strength Using Silica Fume (SF)

To evaluate the effect of replacing cement with silica fume, cylindrical specimens with dimensions of 150×300 mm were prepared. The samples were then cured under laboratory conditions, and compressive strength tests were conducted at 1, 2, 3, 7, and 28 days of age according to ASTM C39/C39M-21 [10]. Figure 2 illustrates the test performed on an SF15 sample at 3 days of age.

Figure 2. Test of compressible strength in SF15 specimen at 3 days of age.

2.3. Experimental measurement of the thermal expansion coefficient of Silica fume concrete

Experiment to measure the coefficient of thermal expansion (CTE) determines the CTE of cylindrical concrete specimens, maintained under saturated conditions, by measuring the change in specimen length due to specified temperature changes. This principle is detailed in the AASHTO 336T standard [11]. The measured length change will be adjusted for any variations in the length of the measuring device, and the CTE is then calculated by dividing the adjusted length change by the temperature change and subsequently by the specimen length, as described in the following calculation section.

If the change in the length of the device varies linearly with temperature, the adjustment factor C_f is defined as:

$$C_f = \Delta L_f / L_{cs} / \Delta T \tag{1}$$

where:

ΔL_f: the change in the length of the measuring device during temperature changes; L_{cs}: the length of the calibration specimen at room temperature; ΔT: the measured temperature change, °C ; C_f : the correction factor accounting for the change in the length of the measuring device with temperature mm^{-6}/mm/ºC

Calculation of the CTE for a specimen undergoing expansion or contraction as follows

$$CTE = (\Delta L_a / L_o)/\Delta T \tag{2}$$

where: ΔL_a: the variation of actual length of the specimen with changing of temperature, mm ; L_0 the measured length change of the specimen during temperature variation

$$\Delta L_a = \Delta L_s + \Delta L_f \tag{3}$$

where:

ΔL_s: the measured length change of the specimen during temperature changes

ΔL_f : the change in the length of the measuring device during temperature changes

The concrete samples were measured for thermal expansion coefficient at the Transport Science and Technology Center, University of Transport and Communications according to AASHTO 336T standards. The thermal expansion coefficient (CTE) test was calibrated according to AASHTO 336T [10]. The CTE value and test date must be marked on the test samples. Test samples are cast into cylinders with a nominal diameter of 100 mm. Two test samples are required for each mix.

a) b)

Figure 3. Thermal expansion coefficient measuring device: a) general view of device; b) Sample immersion tank for measurement.

3. RESULTS AND DISCUSSION

3.1. Effect of silica fume on the strength development of concrete

The results of the compressive strength tests for the mixes are summarized in Table 2 and illustrated in Figure 4. Concrete mixtures at 1 day of age have a compressive strength reaching over 50% of the average compressive strength at 28 days (R28), and the compressive strength at 3 days reaches over 75% of R28. Specifically, the SF concrete mixtures (SF05, SF10, and SF15) have a compressive strength at 7 days reaching over 80% of R28. This indicates that SF concrete mixtures have a significant advantage in achieving early-age compressive strength, particularly in the period from 3 to 7 days of age. The maximum and minimum deviations in the compression strength test among the three specimens are 5.98% and 0.33%, respectively.

Table 2. Compressive Strength by Age (MPa).

Age (day)	**SF00**	**SF05**	**SF10**	**SF15**	**Number of specimens**
1	38.54	39.26	39.13	41.24	3
2	49.02	50.53	50.72	50.23	3
3	51.23	53.52	55.80	56.62	3
7	52.45	60.44	61.03	62.63	3
28	66.26	69.06	73.34	71.65	3

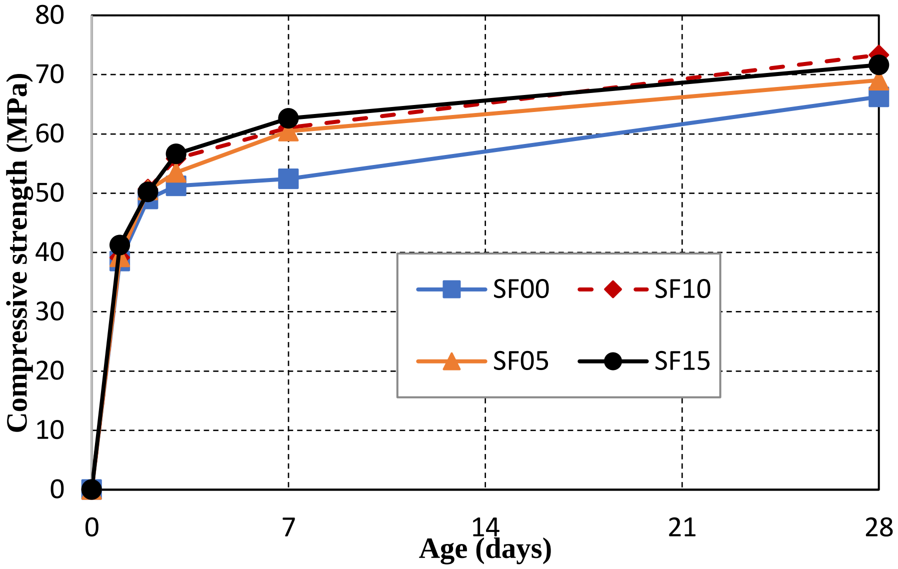
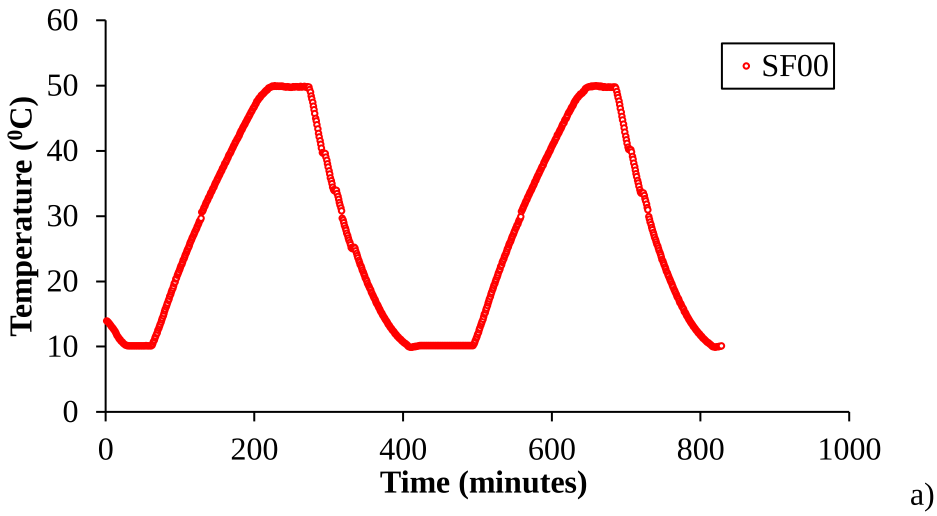


Figure 4. Compressive strength by age of SF concrete mixtures (MPa).



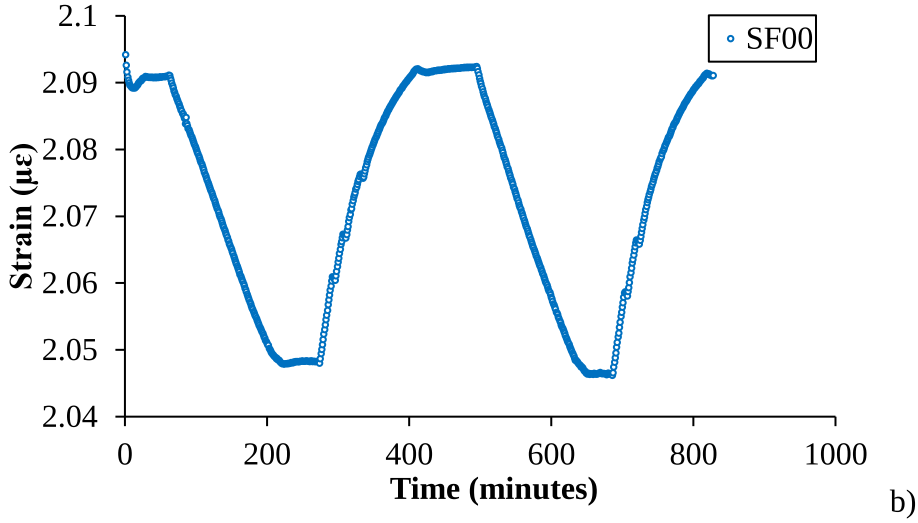
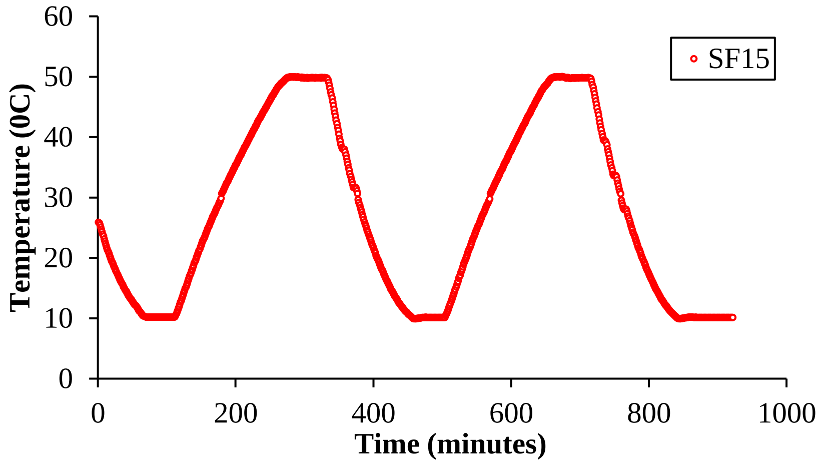


Figure 5. Illustration of the measured results for the SF00 sample: a) Temperature change over time; b) Strain monitoring over time.

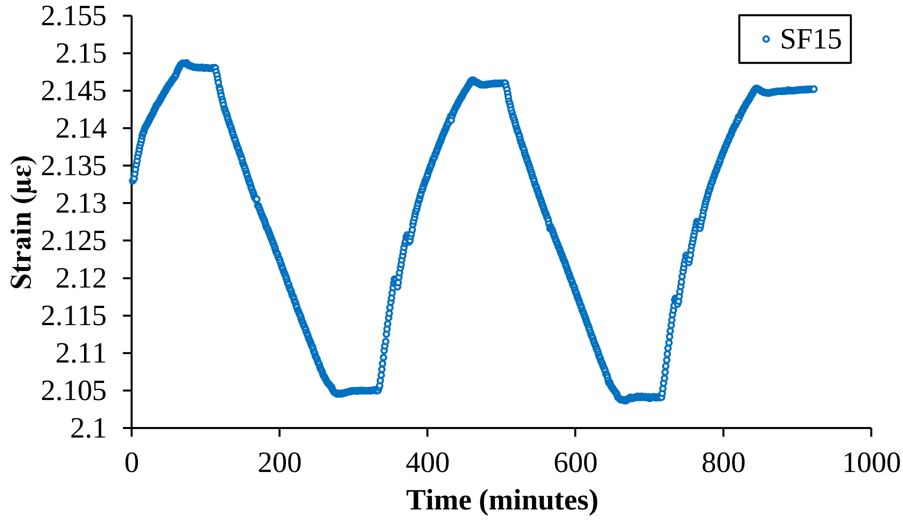
Figure 4 also shows that replacing cement with silica fume at a content of 5% in the concrete mixture helps improve the compressive strength of the concrete. The control sample has a compressive strength of 66.26 MPa at the age of 28 days, while the samples with replacement contents of 5%, 10%, and 15% have compressive strengths of 69.06 MPa, 73.34 MPa, and 71.65 MPa, respectively. Silica fume is approximately 50-200 times smaller than cement particles, as demonstrated in Section 2.1. Thus, silica fume can fill the voids in the cement paste and increase the density of the concrete, thereby enhancing its strength. Furthermore, the pozzolanic reactions between silica fume and calcium hydroxide contribute to accelerating the strength development of concrete, especially at early ages. This finding is consistent with previous studies by García [3], Mazloom et al. [12], and Judita et al. [13].In this study, the experimental results did not show significant differences in strength when 10% or 15% of the cement was replaced with silica fume.

3.2. Effect of silica fume on the thermal expansion coefficient of concrete

The results of the sample measurements are recorded over time as described in Figure 5 and Figure 6. The temperature is initially maintained at 10°C, then gradually increased to 50°C and stabilized at that temperature before being reduced back to 10°C. This cycle is repeated several times, and the data is recorded to determine the thermal expansion coefficient of HSC.



a)



b)

Figure 6. Illustration of the measured results for the SF15 sample: a) Temperature change over time; b) Strain monitoring over time.

The strain of the sample during a single cycle of temperature increases and decrease, starting from 10°C and gradually rising to 50°C for four concrete mixtures over time, is described as shown in Figure 7. Figure 7 shows that during the heating process, the strain and the slope of the strain curves for the samples are quite similar. When maintaining a constant temperature and then cooling, the strain fluctuates but not significantly, and the strain curves remain relatively similar.

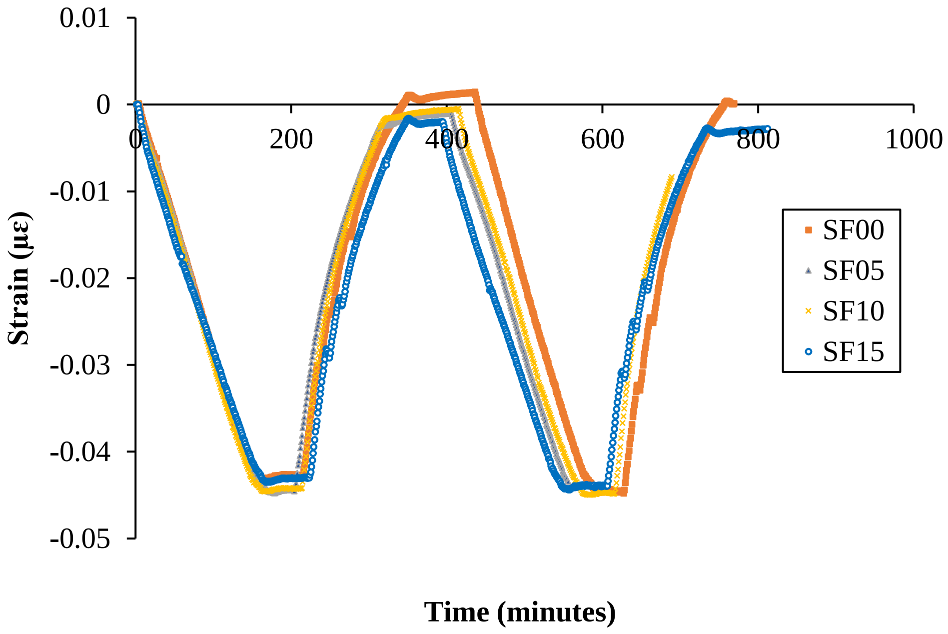


Figure 7. Relative strain of the sample over time along with the temperature increase and decrease cycle over time.

The thermal expansion coefficients of the four SF concrete mixtures, after measurement, are presented in Table 3 below. The CTE of the four mixtures varies slightly, ranging from 8.95 to 9.93×10^{-6}/°C. The effect of SF content on the CTE of concrete is not clear, which is consistent with previous studies indicating that CTE primarily depends on the type of coarse aggregate [5] [15]. According to ACI 363R-10 [14], the thermal properties (including the thermal expansion coefficient) of HSC are approximately similar to those of normal concrete. According to ACI 363R-10 [14], the CTE of concrete ranges from 7.1×10^{-6}/°C to 13.1×10^{-6}/°C.

Table 3. Thermal expansion coefficient (CTE) of silica fume concrete mixtures (10^{-6}/°C).

Mixture	**CTE (10^{-6}/°C)**
SF00	8.95
SF05	9.25
SF10	9.22
SF15	9.93

This result is quite consistent with precedent studies, where the thermal expansion coefficient mainly depends on the coarse aggregate [5]. Replacing cement with silica fume in the mixture essentially does not change the thermal expansion coefficient [15]. Reducing the amount of cement in the concrete mixture helps minimize the potential for thermal cracking in the concrete structure.

4. CONCLUSION

The paper presents ex perimental research results determining the development of strength and the thermal expansion coefficient (CTE) of high-strength concrete mixtures when replacing cement in the mixture with 5-15% silica fume content. Some conclusions drawn from the study are as follows:

- Replacing 5-15% of cement with silica fume in high-strength concrete mixtures significantly enhances concrete strength at 7 days, with further improvement observed at 28 days. The strength increases substantially with a 5% silica fume replacement due to the pozzolanic reaction, followed by a more moderate increase as the replacement content is raised to 10% and 15%.
- The experimental results show that replacing cement with 5-15% silica fume results in minor variations in the CTE, with measured values ranging from 8.95 to 9.93×10^$^{-6}$/°C. This is generally consistent with previous studies, which indicate that the CTE primarily depends on the coarse aggregate in the mixture.

Future research will focus on evaluating the impact of silica fume replacement on the thermal parameters of concrete and assessing the influence of aggregate parameters on the CTE of concrete.

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