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Fracture characteristics of high-performance concrete using nano-silica

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Abstract. High-performance concrete (HPC) using nano-silica (NS) has higher mechanical properties and durability than conventional concrete. The highly active silica ultrafine particles have improved the performance of HPC significantly. The fracture characteristics of HPC are also enhanced when using NS due to the improved quality of C-S-H gels and the interface transition zone between mortar and aggregate. The influence of NS on fracture characteristics of HPC is considered in the study as a basis for the effective application of HPC in the structure of buildings. The paper assesses the influence of NS on the strength and fracture characteristics of HPC. HPC mixes were produced by replacing Portland cement with NS at 0.5 % and 1.5 %. The fracture testing for HPC using NS was carried out based on the three-point bending test of beams with the notch. The result is the load-crack mouth opening displacement relationship curves (P-CMOD) and load-deflection (P-). Finally, fracture parameters and characteristics of HPC using NS are analyzed and calculated from the P-CMOD and P- relationship curves.

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1. Introduction

Many researchers have confirmed that the incorporation of nanoparticles into high-performance concrete (HPC) brings many benefits. Nanomaterials can considerably improve concrete's mechanical properties and durability [1–4]. In comparison to the use of silica fume (micrometer size), Sanchez and Sobolev determined that using nano-silica (NS) components in HPC is a new development step [5]. The NS particles aid in the formation of pozzolanic reactions by removing Ca(OH)2 components to produce high-performance pozzolan gel products. A small amount of NS added into the mixture helps increase the performance of C-S-H gels and interface transition zone (ITZ) [6, 7], resulting in positive impacts on the mechanic properties and fracture characteristics of HPC. According to recent investigations [8–10], mechanical parameters such as compressive, tensile strength, modulus of elasticity, and stress-deformation relationship are greatly improved for HPC with nano-silica added.

For decades, the study of the fracture characteristics of high-performance concrete and high-strength concrete has received attention. Some authors claimed that the fracture of structures designed with high-strength concrete are of high brittleness nature [11, 12]. The cause of brittle fracture in HPC is related to concrete's high strength characteristics, leading to cracks often passing through coarse aggregate instead of following the boundary of aggregate as with normal concrete. HPC has high compressive strength, high modulus of elasticity compared to normal concrete. For HPC the slope of the curve on the downside (after peak) becomes steeper. This proves that HPC is more likely to be damaged suddenly than normal concrete.

According to Van Mier [13], ultrafine material will significantly change the behavior of concrete in the fracture process. The increase of the ductility is shown by the stress-deformation (or crack mouth open displacement) curve, especially since the post-peak slope of the curves gradually decreases. The improvement of the toughness is explained by bridging cracked surfaces in the presence of ultrafine NS particles. According to the research of Ricardo et al. [11], concrete with silica fume has fracture characteristics better than concrete without it. The addition of silica fume improves the homogeneity, the structure of C-S-H gels, and the performance of the ITZ of mortar and aggregate. Fracture energy, toughness, and length characteristic are higher when using silica fume. The brittleness of HPC tends to decrease. According to Zhang et al. [14]. Increasing the density of the ITZ of mortar and aggregate with chemical and mineral admixtures in HPC causes it to affect the fracture properties of concrete.

Some studies using NS in HPC also claimed that ultrafine silica particles would provide mortar when hardened with higher performance and consistency. The fracture toughness of concrete is also significantly increased by increasing the cohesion between the cement particles and aggregates [1]. With ultrafine particles, the microstructure and the fracturing behavior of concrete is significantly enhanced. According to the researches of Quercia [15, 16], the presence of fine material substantially changes the fracture behavior of concrete. The load-deformation curve shows the increased ductility of the ultrafine concrete component. The post-peak slope of the curves is reduced compared to the concrete without fine particles. The increased toughness is explained by bridging higher cracked surfaces in the presence of ultrafine particles. Some empirical studies have also been conducted to understand the relationship between the cracking behavior of concrete and ultrafine particles. The results generally show an apparent influence of the ultrafine mineral composition on fracture parameters of concrete [7, 13].

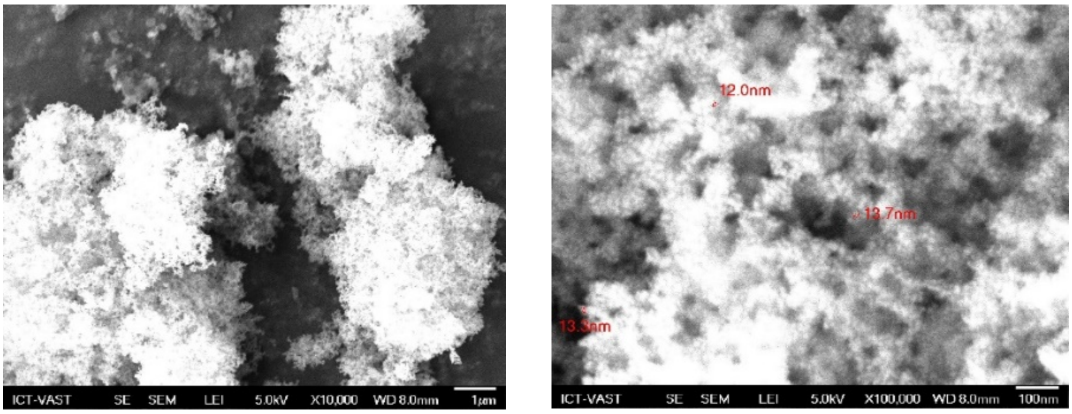
In addition, many studies have evaluated the influence of the constituent materials on the fracture characteristics of HPC, such as the study of Zang et al. assessing the effect of aggregates size on the fracture energy [17], the influence of fiber content on the fracture modes of concrete [12], the impact of silica fume on the fracture parameters of HPC [11], etc. However, there has not been any research analyzing the effects of NS composition on fracture characteristics of HPC, although they were mentioned in studies [7], [18-22].

The article's content focuses on determining parameters and fracture characteristics of HPC using NS in the form of mode I. A special testing method according to RILEM, conducted by controlling crack mouth open displacement, was applied to determine fracture parameters of HPC using NS. The three mixed proportions of HPC using NS, with the content of 0 %, 0.5 %, and 1.5 % were calculated for the component design according to ACI 211.4R-08 standards to serve for the experiments. The influence of the NS content on the fracture characteristics of the HPC was evaluated. The experimental results were analyzed according to the fracture mechanic method and used to calculate the crack extension resistance characteristics of HPC beams.

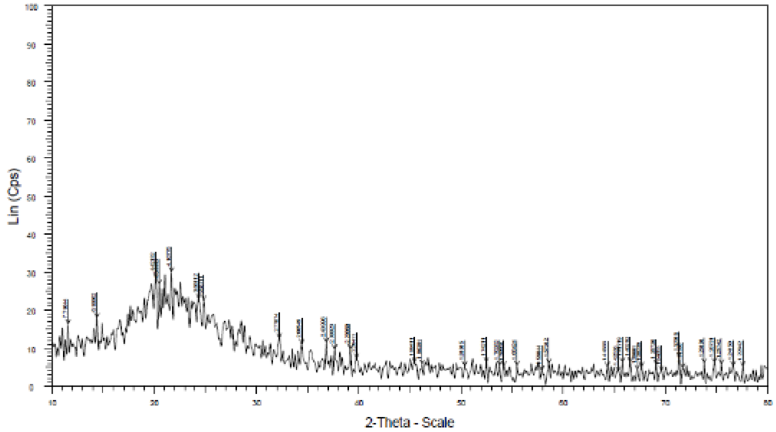
2. Materials and Methods

2.1. Materials

Materials included PC 40 cement; basalt with D_{max} 12.5 mm as coarse aggregates; fine aggregates with a module 2.7, superplasticizer, silica fume, and nano-silica. The research was conducted with Evonik chemical company NS product (Aerosil 200) of 5-50 nm dimensions with a typical 200 ± 25 m^2/g surface area. Fig. 1a shows the results of SEM tests for assessing the size and form of the NS. Fig. 1a shows that the nanoparticles are on average approximately 13 nm in size. The result of XRD testing in Fig.1b, between 16° and 30°, indicates that the compounds are 100 % amorphous.



a) SEM image of nano-silica



b) XRD image of nano-silica

Figure 1. SEM and XRD image of nano-silica.

2.2. Mix proportion

The compressive strength of HPC using NS is designed by the ACI method for 70 MPa [23]. For fracture test, mixes with 0 %, 0.5 %, and 1.5 % NS ratios were prepared. By the recommendations, the percentage is selected and adjusted to the mixtures. Table 1 presents a mix of the proportion of HPC with NS:

Table 1. Mixes proportion of HPC using nano-silica

Mix code	Materials							W/B
	C	FA	CA	F	NS	SP	W	
	(kg)	(kg)	(kg)	(kg)	(%)	(l)	(l)	
NS0.0	544.2	674.6	1049.7	8.64	0.00	5.44	54.6	0.27
NS0.5	541.3	673.6	1049.7	8.64	0.50	6.53	54.6	0.27
NS1.5	535.6	671.6	1049.7	8.64	0.50	7.62	154.6	0.27

Note: C – cement; CA – coarse aggregate; FA – fine aggregate; NS – nano-silica; SF – silica fume, SP – superplasticizer, W/B – water/binder.

2.2. Preparing for experiments

Material components such as fine aggregate, coarse aggregate, cement, silica fume, superplasticizer are ready for measurement before mixing. Particularly, NS is mixed with 50 % of the required water and stirred at high speed, ensuring that NS is evenly dispersed in the mixture.

After preparing the materials, the specimen mixing process is performed according to the procedure shown in Fig. 2.

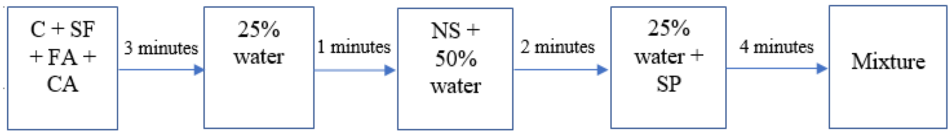


Figure 2. Mixing procedure of HPC using NS.

The beam specimens used in the fracture experiment are a 500×100×100 mm prism with a notch width of 2 mm and depth of 25 mm, as shown in Fig. 3.

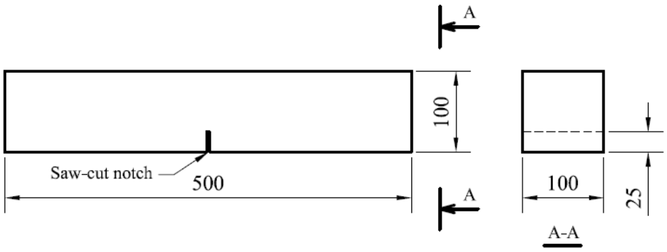
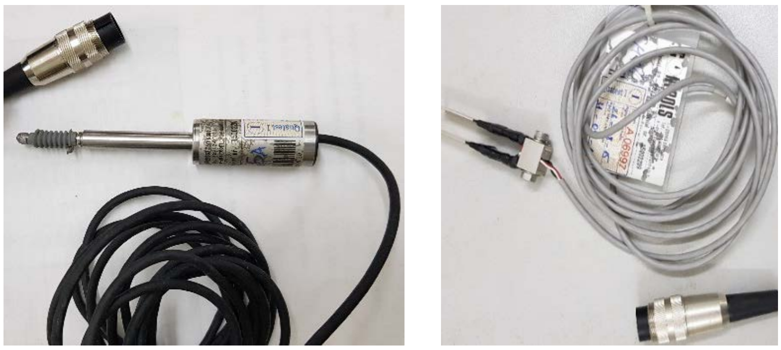


Figure 3. The specimen used in the fracture test.

According to Rilem's [15] tests on 28 day beams, the notch should be cut on the 21st day. Then, the specimens were cured up to the day of the experiment.

2.3. Experimental equipment

It is not easy to obtain a complete softening curve by the fracture test. Especially for high-strength concrete and high-performance concrete, the brittleness is very high. The equipment that controls the experiment only through the load cannot achieve the desired results. The test requires specialized equipment and very high sensitivity. A closed-loop experimental device can customize the load speed control according to the crack mouth open displacement (CMOD), and deflection will be used [24]. The linear variable differential transformer (LVTD) and the crack mouth extensometer (extensometer) are necessary to accomplish the experiment. LVTD and extensometer are shown in Fig. 4.



a) LVTD **b) Extensometer**

Figure 4. LVTD and extensometer for testing.

LVTD is used to measure deflection in the middle of the test beam to obtain the load-deflection (P-δ) relationship curve. LVTD has a 100 mm measuring stroke. Fig. 4b is an extensometer with high accuracy. Extensometer is specialized to measure crack mouth open displacement, with the sensitivity of 1000×10-6 strain/mm, the maximum measuring range is 5 mm. The load-crack mouth open displacement (P-CMOD) relationship curves are obtained using an extensometer.

2.4. Experimental method

For the experiment to be stable, the development of CMOD is controlled as a linear function of time. Their growth rate is minimal to ensure a stable experiment. The load is automatically adjusted to increase quickly or slowly or decrease depending on the structural behavior through the measuring head. In other words [25], the measuring head is an automatic device that uses a sensor core capable of two-way feedback to adjust the magnitude of the load according to the measured value. The arrangement of fracture tests of HPC specimens is shown in Fig. 5.

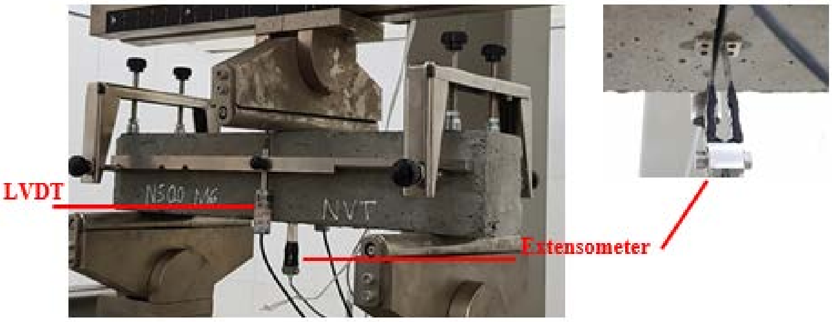


Figure 5. Three-point bending test of HPC using NS.

During the experiment, the test is kept at a certain speed by treating CMOD as a linear function of time. The experiment started at a rate of 0.04 μm/s. In this test, it takes very long time for each specimen to be subject to damage, unlike in ordinary mechanical experiments.

3. Results and Discussion

3.1. Effect of nano-silica in load-deflection and load–CMOD curves of HPC

The results showed the difference of the P-CMOD curves corresponding to the beam specimens cured up to 28 days using nano-silica with ratios of 0 %, 0.5 %, and 1.5 %, as shown in Fig. 15. After reaching the peak (Pmax), the P-CMOD curve of HPC without NS has a steep slope. When the CMOD is very small, the force value decreases quickly. When NS is added to concrete with the ratio of 0.5 % and 1.5 %, the P-CMOD curve has a significant change, especially with 1.5 % NS. The curves tend to grow the same in the early stages when the concrete is still in the elasticity limit, and the difference begins to appear when the curve is about to peak.

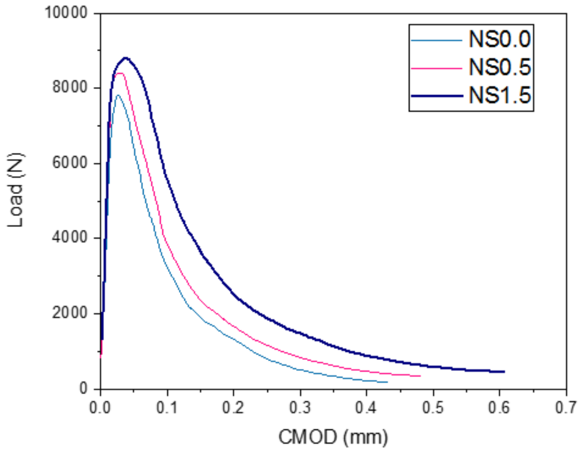


Figure 6. Effect of nano-silica in P-CMOD.

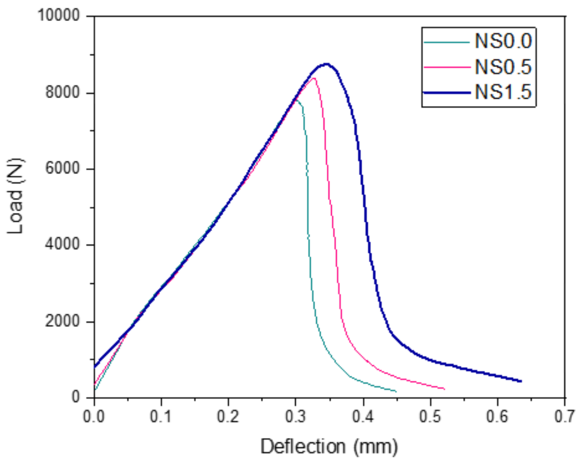


Figure 7. Effect of nano-silica on P-deflection.

In the post-peak period, the curve of HPC using NS has a slope of less than HPC without nanosilica. Fig. 6 shows that the force value decreases with the growth of the slower CMOD when comparing the same value of CMOD. The load valuation of specimens using NS remained higher than the non-NS specimens.

The load-deflection relationship curves (P-δ) of HPC using NS are shown in Fig. 7. For HPC using NS, P-δ curve will be thicker, the curve's nonlinear period is longer, and the load slowly decreases.

Observations of P-δ curves in Fig. 7 show that the area under the curve (work of fracture – W_F) of the graph varies depending on the NS ratio. To calculate the area under the P-δ curves, use the integral method. As shown in Table 2, W_F increased by 21.4 % when the NS ratio was 0.5 % and by 58.71 % when the NS ratio was 1.5 %.

Table 2. Work of fracture – W_F

Mix code	P_{max} (N)	δ_{max} (mm)	W_F (N.mm)
NS0.0	7813	0.449	1454.80
NS0.5	8416	0.520	1766.42
NS1.5	8810	0.634	2308.90

Compare the P-CMOD and P-δ curves obtained by the experiment to the results of other researchers [11, 12]. The characteristics before and after the P_{max} load in Fig. 7 and Fig. 8 are very similar in shape.

3.2. Effect of NS on fracture energy (G_F)

Table 3 shows the improvement in fracture energy when the NS ratio is changed from 0 % to 0.50 % to 1.50 %. Fracture energy G_F is calculated based on the load-deflection relationship curves and is obtained from a three-point bending test. The calculation results are averaged from the results of six specimens. In comparison to concrete specimens without NS, specimens with NS had fracture energy increased by 21 % and 58 %, while the NS ratio was 0.5 %, and 1.5 %, respectively, as shown in Table 3.

Table 3. Result of fracture energy

Mix code	W_F (Nmm)	δ_0 (mm)	a_0 (mm)	A_{lig} (mm^2)	m (kg)	G_F (Nmm/mm^2)
NS0.0	1454.80	0.449	25	7500	9.82	0.200
NS0.5	1766.42	0.520	25	7500	9.84	0.242
NS1.5	2308.90	0.634	25	7500	9.84	0.316

The Effect of NS on the fracture energy of HPC is shown in Fig. 8.

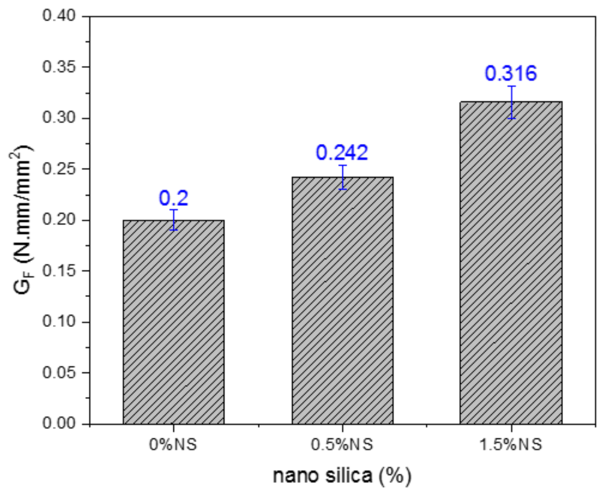


Figure 8. Effect of NS on the fracture energy.

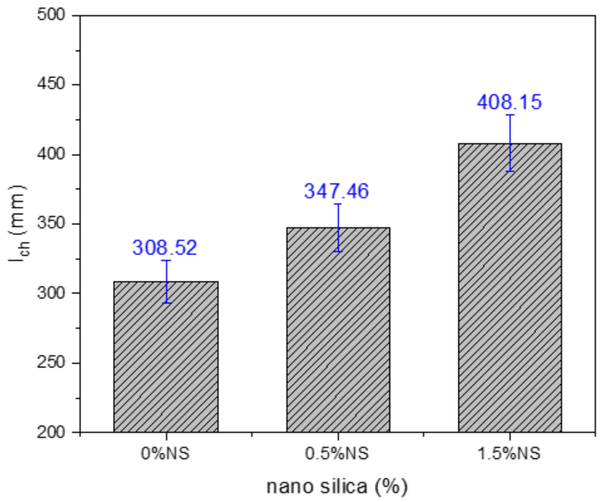


Figure 9. Effect of NS on the characteristic length.

3.3. Effect of NS on characteristic length of HPC

The characteristic length was determined based on the energy parameters of tensile strength, modulus of elasticity, and fracture energy. Tensile strength is determined indirectly through flexural strength according to the formula of CEB-FIP MC 90 [23], as shown in Table 4.

Table 4. The result of characteristic length

Mix code	E (MPa)	G_F (Nmm/mm^2)	f_t (MPa)	l_{ch} (mm)
NS0	45533	0.200	5.430	308.52
NS0.5	47620	0.242	5.760	347.46
NS1.5	50131	0.316	6.230	408.15

The effect of NS on this characteristic is presented in Fig. 9.

Based on the calculation results in Table 4 and Fig. 9, HPC with NS has a longer characteristic length than HPC without NS. This characteristic increases by 12.62 % and 32.29 % for 0.5 % NS and 1.5 % NS, respectively. It can be seen that the HPC without NS is more brittle than the one with NS.

3.4. Discussion

Through the experimental results and analysis, it can be seen that the fracture characteristics of HPC have been improved when using NS. When working in concrete, the effect of NS particles modifies the microstructure of the mortar and improves weak zones. That improves the performance of the C-S-H gels and the ITZ between the mortar and the aggregate, which enhances concrete failure characteristics. Some authors have also presented this point of view in their recent researches [7, 11, 13].

4. Conclusions

The following conclusions were obtained based on the results of the study:

1. This research determined fracture parameters and characteristics of HPC using NS in the form of mode I. The fracture parameters and characteristics of HPC using NS were determined through experiment and analysis, such as relationships between P-CMOD, load-deflection, fracture energy, and length characteristic.

2. The results show that the influence of NS content on fracture parameters and characteristics of HPC is significant. The NS ratio of 1.5 % is the most optimal in terms of use. The ductility of the HPC using NS is improved, which is shown by the fracture energy and characteristic length parameters.

3. The experimental and analysis results are similar to other researches on the fracture characteristics of high-performance concrete. Those results can be used to calculate crack extension resistance and the remaining life of HPC structures in subsequent investigations.

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