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Deformation Behaviors of Engineered Cementitious Composites (ECC) modified with Nano-silica (NS)

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ABSTRACT

The effects of adding nano-silica (NS) and polyvinyl alcohol fibre (PVA) on drying shrinkage, Poisson's ratio, and elastic modulus of NS-modified self-consolidating engineered cementitious composite (NS-modified SC-ECC) are investigated in this work. The NS-modified self-consolidating ECC mixes were developed using the two variables, that is, NS particles (0%, 1%, 2%, 3% and 4%) and PVA fiber (0.5%, 1%, 1.5%, and 2%). However, to ensure each mix complies with the self-consolidating requirements, a high-range water reducer (HRWR) was utilized to guarantee the self-consolidating qualities of the mixtures. The self-consolidating mixes were used to prepare three samples for each mixture and tested for elastic modulus, shrinkage, and Poisson's ratio. The results of the experiments revealed that adding 2% of nano-silica particles raised the elasticity modulus for each constant PVA fibre volume. The Shrinkage behaviours improved at 2% NS and 2% PVA percentages. Nano-silica particles further improved the bond between the fibre and matrix by utilising the calcium hydroxide created during cement hydration to start a pozzolanic reaction that generates more calcium-silicate-hydrates (C-S-H) gel. The results of the Poisson's ratio range between 0.11 – 0.22 for the eight mixed combinations of PVA fibre (0.5%, 1.0%, 1.5%, and 2.0%) and NS (1% and 2%), m5 – m12. Mix m12 had the lowest value of Poisson's ratio, indicating having the best strength value as the fibre/matrix interface is improved by densification by NS particles and pozzolanic reaction products.

1. Introduction

Fiber-reinforced cementitious composites (FRCC) were created to improve on the drawbacks of concrete, such as its excessive brittleness and low stretchability, and to increase its durability and application life [1]. The larger cracks in FRCC served as the inspiration for High-performance Fiber-Reinforced Cementitious Composites (HPFRCC), which exhibit strain hardening behaviour after the emergence of early fractures once exposed to uniaxial tensile testing. Micromechanics principles served as the foundation for ECC's design. ECC is designed using micromechanics concepts [2]. When compared to regular concrete and conventional fiber-reinforced composites, the capacity of the tensile strain can typically be well over a hundred times greater depending on the composition of the combination. When exposed to uniaxial tensile testing, the ECC is a kind of HPFRCC constructed using micromechanics principles to exhibit strain-hardening capabilities [3]. The fiber volume in ECC has been designed not to exceed 2% [4]. The preferred fiber used in ECC has been the PVA fiber; this is attributed to its ability for suitable composite action and performance and economic concerns. Similarly, PVA fibre has been established to possess suitable properties for applications in PVA-ECC [5]. When put through uniaxial tensile testing, the PVA-ECC differs from other concrete materials in that it exhibits tight and numerous cracking qualities. A record of inherent crack width not exceeding 100 µm in ECC has been attributed to the enhanced durability and ductility [6]. The PVA-ECC has exhibited tensile strain capabilities above 5% using routinely available ingredients and equipment used in industry to produce concrete [5]. The use of ECC has grown dramatically over the years; it is especially useful in structural application [7], repairs and retrofitting [8]. Shown in Figure 1 below is a typical PVA-ECC curve tested in uniaxial tensile strain after 28 days of curing.

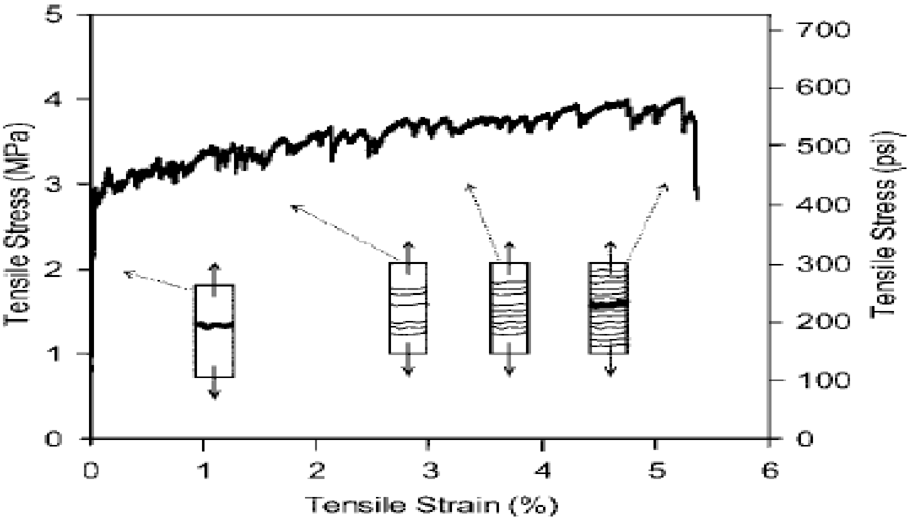

FIGURE 1. TYPICAL PVA-ECC MIXTURE UNIAXIAL TENSILE STRESS-STRAIN CURVE [9]

A typical ECC mixture (ECC M45) with a Fly Ash-Cementitious (FA-C) ratio of 1.2 is used in this paper to create NS-modified SC-ECC mixes. This paper highlights the impact of NS and PVA fibre-matrix on NS-modified SC-ECC's deformation behaviors. The use of NS reduces the loss of early strength associated with the use of High Volume Fly Ash (HVFA) in PVA-ECC. Scanning electron microscopy (SEM) images utilized to assess the interaction of the PVA fiber-matrix through cautiously monitoring the changes in the interfacial transition zone (ITZ) due to NS particles incorporation [10]. The primary variables of the NS-modified SC-ECC, such as the elastic modulus, shrinkage, and Poisson's ratio, have received little attention in the literature. Compression and tension are the two main types of forces that affect materials like ECC and concrete, as is well known. Tensile forces must be handled with extraordinary caution since failure under tension could have terrible consequences in terms of both financial losses and the loss of lives.

In light of this, the purpose of this research is to evaluate the deformation properties of Engineered Cementitious Composite (ECC), such as shrinkage, modulus of elasticity, and Poisson's ratio, which incorporates materials such as high-volume fly ash, NS particles, and PVA fiber.

2.0 Programme for Examination

2.1 Materials and characteristics of the constituents

The self-consolidating (SC) composites with only the force of gravity acting upon it, can seep into every nook and cranny of the formwork and completely embed the steel reinforcement [11]. Among other things, SCC's major advantages include speeding up and improving the quality of concrete casting, It yields concrete with remarkable durability and a flawless finishing surface [12]. The SC-ECC combinations were created using FA, washed river sand with an average size of 450 µm, tap water, high range water reducer (HRWR) polycarboxylate-base, NS particles, and PVA fibre in accordance with ASTM C150's specifications. Tables 1 and 2 provide the characteristics of Fly Ash (FA) and Ordinary Portland Cement (OPC), while oxides and charcteristics of nano-silica particles are provided our previous work [13]. With SiO_2+Al2O$_3$+Fe2O$_3$ of approximately 82.12% and less than 6% losses on ignition, the FA falls under ASTM C618 Class F according to the oxide composition presented in Table 1. The characteristics of the PVA fiber are provided in Table 2, with 1.2% by weight of oil applied to the surface of the PVA fiber.

Table 1: Oxides and FA and OPC’s attributes [13]

Oxide compositions (%)	FA	OPC
SiO_2	57.01	20.76
Al_2O_3	20.96	5.54
Fe_2O_3	4.15	3.35
MnO	0.033	-
CaO	9.79	61.4
MgO	1.75	2.48
Na_2O	2.23	0.19
K_2O	1.53	0.78
TiO_2	0.68	-
LOI	1.25	2.2
SG	2.38	3.15
Blaine fineness (M^2/Kg)	290	325

Table 2: Polyvinyl alcohol fibre characteristics [13]

Type	Fiber Grade	Fiber length (mm)	Specific gravity	Fiber Diameter (µm)	Tensile strength (Mpa)	Aspect ratio (l/d)	Elastic Modulus of elasticity (GPa)
PVA	REC S-15	12	1.3	40	1600	462	41

2.2 SC-ECC proportions in mixtures

Twenty mixtures were created using PVA fiber, which was determined by volume fraction, and nano-silica particles, which was measured by the total weight of the cementitious materials, as shown in Table 4. The mixtures of the designed cementitious composites were subjected to the provision of European Federation of National Associations Representing for Concrete (EFNARC) 2002 for self-consolidating to ensure compliance with the requirements for self-consolidating. This has been achieved by adjusting the mixture's flowability by adding a superplasticizer (HRWR). Based on the weight of the cementitious material (C + NS + FA), the amount of HRWR applied. In some instances, a higher amount of HRWR has been used for some mixtures due to the higher volume of NS and PVA to meet self-consolidating requirements. Nevertheless, the adverse effects of HRWR overdose (segregation and bleeding) were considered throughout the fresh characteristics tests (Table 3). Based on the requirements for strain-hardening and self-consolidation behaviours, the amounts of NS particles and PVA fibre considered are 0%, 1.0%, 2.0%, 3.0%, 4.0%, and 0.5%, 1.0%, 1.5%, and 2.0%, respectively.

2.3 Procedures and specimen preparation

Mixing the constituent materials was carefully done to ensure proper and uniform dispersion of the mixtures. Mixing of the constituent's materials was done in the following order; firstly, the measured amount of cementitious materials and sand were mixed for about two minutes in the dry state in the rotating drum mixer. Secondly, while the mixing was going on in the rotating mixer drum, measured amounts of HRWR and water were mixed and slowly added to the content in the drum. The mixing lasted about 2 to 3 minutes to ensure the homogeneity of the mixtures. Upon attaining a uniform and homogenous mixture, the rotating mixer drum continued to rotate as PVA fiber was gently added. The stage lasted another 2 to 3 minutes until the PVA fiber dispersion was notably uniform. When the amount of nano-silica increased, HRWR was added to meet self-consolidating requirements, and the fresh mixtures were poured into the moulds. Presented in Table 3 and Table 4, respectively, are the fresh mixes and specimens' moulds for shrinkage, and Poisson's ratio and elastic modulus, on which the two parameters were measured simultaneously. The specimens were maintained in the curing tank after being de-moulded after casting for 24 hours, it was set up till the testing at the age of 28 days at room temperature of 23± 2^{o}C with a relative humidity of around 80%. Simultaneously, samples for shrinkage tests were stored in cellophane in a climate-controlled space at a temperature of 20 ± 2^{o}C with a relative humidity of roughly 80%.

Table: 3: Mixture proportions of SC-ECC [13]

Mix ID	Cement (kg/m³)	Sand (kg/m³)	Fly Ash (kg/m³)	Water (kg/m³)	Super-plasticizer (HRWR) (kg/m³) cementitious materials (cement + Fly ash+ nano-silica)%	PVA Fibre (%)	Nano-Silica (%)
m1	583	467	700	187	9.5	0.5	0
m5	583	467	700	187	13.0	0.5	1
m9	583	467	700	187	18.5	0.5	2
m13	583	467	700	187	22.5	0.5	3
m17	583	467	700	187	34.8	0.5	4
m2	583	467	700	187	10.5	1	0
m6	583	467	700	187	14.7	1	1
m10	583	467	700	187	19.5	1	2
m14	583	467	700	187	26.5	1	3
m18	583	467	700	187	36.5	1	4
m3	583	467	700	187	11.5	1.5	0
m7	583	467	700	187	16.2	1.5	1
m11	583	467	700	187	22.5	1.5	2
m15	583	467	700	187	32.2	1.5	3
m19	583	467	700	187	38.8	1.5	4
m4	583	467	700	187	12.7	2	0
m8	583	467	700	187	16.8	2	1
m12	583	467	700	187	25.5	2	2
m16	583	467	700	187	33.7	2	3
m20	583	467	700	187	42.5	2	4

Table 4: Tests detail and specification

Test	Amount of samples per mix	Mould sizes	Specifications
Shrinkage	3	25 x 25 x 285 mm	ASTM C157 & C596
Elastic modulus	3	300 mm height X 150 dia.	ASTM C469-02
Poisson’s ratio	3	300 mm height X 150 dia.	ASTM C469-02

3.0 Results and Discussion

3.1 Flow Characteristics of NS-modified ECC

The designed mixes for control (without nano-silica) and mixes with nano-silica for modified self-consolidating ECCs were prepared for fresh properties tests [10]. The mixes were tested to confirm that they met the conditions for self-consolidation outlined in EFNARC [14]. The slump spreads are measured within the range of 650 mm and 800 mm as provided for self-consolidating and were valid for all the mixes. The measured T50 values for all the mixes are in the range of 2-5 seconds, as prescribed for self-consolidating. The V-funnel flow time and ratios of (h2/h1) for L-box were 6 – 12 seconds and 0.8 - 1.0, respectively, for all the mixes. The visual stability index (VSI) was applied for all the mixes, and the VSI of zero was used based on the VSI ranking prescribed in ASTM C 1611.

3.2 Modulus of elasticity

Several factors have been reported to influence the modulus of elasticity of concrete, among which are the compatibility of the concrete, cement paste, nature of the aggregate, and the interfacial transition zone (ITZ). From Figure 6, it is noticed that the modulus of elasticity of ECC appreciates with increasing amount of PVA fiber. This is due to the PVA fiber's ability to bridge and constrain cracks at the microstructure internal level of the ECC matrix, resulting in increased toughness and, as a result, an increase in ECC modulus of elasticity. The modulus of elasticity also increases with increasing nano-silica particles up to 2%. Further increasing of nano-silica will cause dropping in modulus of elasticity values. As the modulus of elasticity is a function of compressive strength, this agrees with the results of compressive strength. This is consistent with the compressive strength data; the modulus of elasticity is a function of compressive resistance.

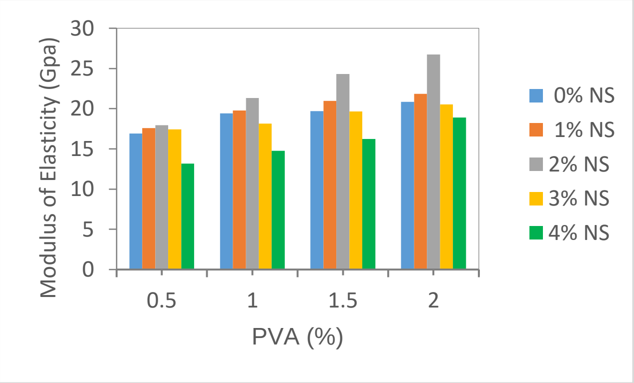

Figure 2. Modulus of elasticity with varied nano-silica amount

3.3 Shrinkage of NS-ECC

Fiber volume fraction contributes to resisting shrinkage in high-performance fiber-reinforced cement-based materials. Including nano-silica in cement-based materials improves shrinkage behaviour through the densification of fibre-matrix and aggregate-matrix interfacial zones, particularly noticed at the hydration stage. Nano-pores and micro-pores are refined and densified by nano-silica particles through physical and chemical behavior. The interaction at the fiber-matrix interface controls stresses due to tensile forces. Studied shrinkage behaviours of the mixes are shown in Figures 7-11. When the amount of nano-silica particles was set at (0%, 1%, 2%, 3% and 4%), the volume fraction of PVA fiber (0.5%, 1%, 1.5%, and 2%) controlled the effect of shrinkage. The sample of ECC with PVA fiber at 2% showed less shrinkage strain than other samples of ECC having a smaller fibre volume fraction. At 62 days and 0% nano-silica, shrinkage strain fell by 33% for 2% PVA, 15% for 1.5% PVA, and 4% for 1.0% PVA when compared to specimens with 0.5% PVA.

Similarly, increasing the nano-silica particle concentration to 2% reduced the shrinkage strain of ECC specimens with fixed PVA fibre volume fraction. Afterwards, the shrinkage strain increased at 3% and 4% nano-silica amount, indicating nano-silica amount exceeded the threshold rate. The excess nano-silica creates a loose matrix with more pores, making the fibre-aggregates contact loose. Additionally, the amount of HRWR added to maintaining SC-ECC requirement as a result of the increase in the amount of nano-silica would have aggravated the intensity of the matrix pores. Equally, a decrease in shrinkage strain could have been a result of the increase in the amount of PVA, improving in restraining shrinkage. Mainly, when the amount of nano-silica (matrix) was fixed and the amount of PVA fibre varied, the effectiveness of restraining shrinkage increased with an increase in fibre amount. The volume fraction of the fibre essentially controls the shrinkage resistance.

Additionally, the collective effort of PVA fibre and the amount of nano-silica in restraining shrinkage was higher when equated to the effect of PVA fibre alone. The improved fibre-matrix interaction caused by densified ITZ could be responsible for shrinkage resistance. Likewise, the reduced shrinkage strain could be attributed to the reduced quantity of water utilized by nano-silica particles in refining pores and the improved hydrophilicity of the paste.

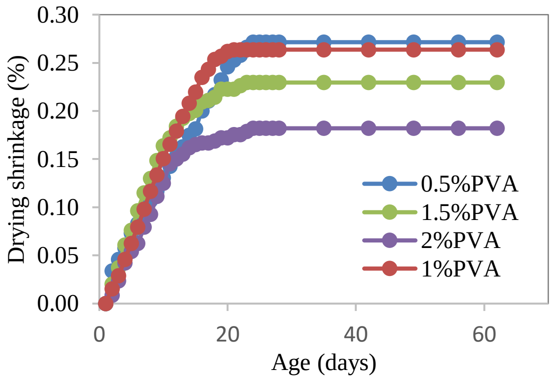

Figure 3. drying shrinkage at 0% NS amount

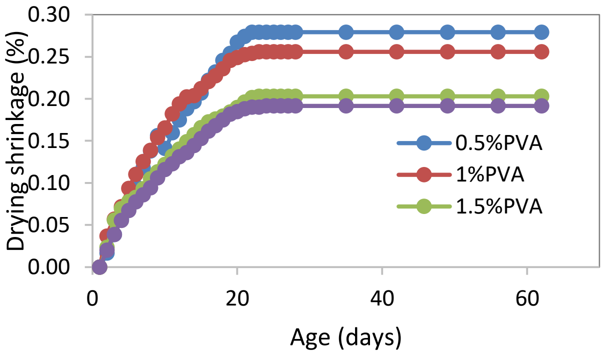

Figure 4. drying shrinkage at 1.0% NS amount

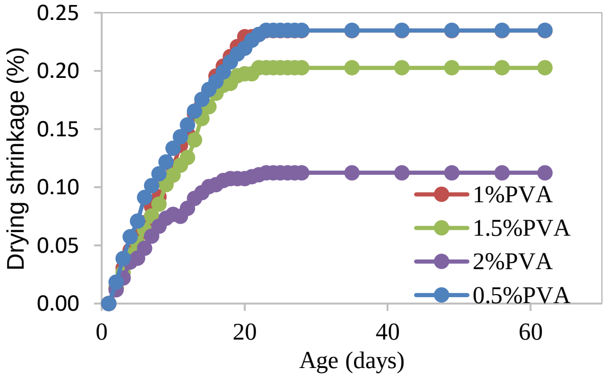

Figure 5. drying shrinkage at 2% NS amount

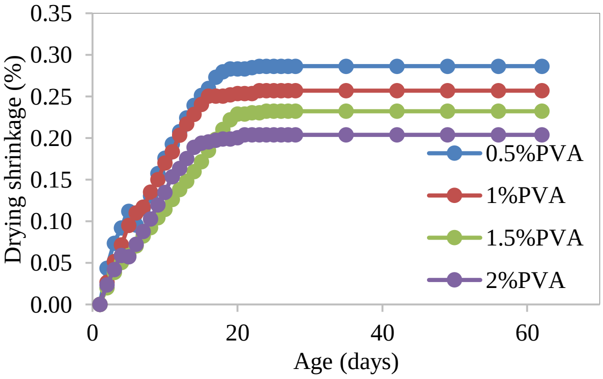

Figure 6. drying shrinkage at 3% NS amount

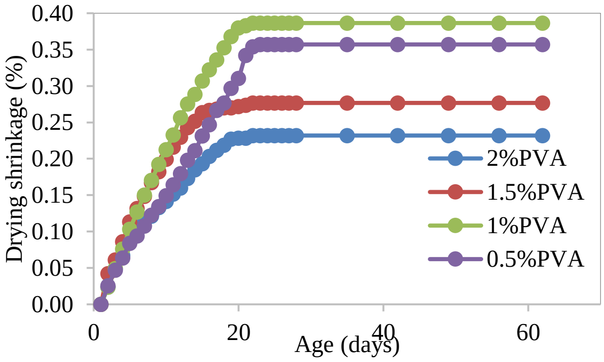

Figure 7. drying shrinkage at 4% NS amount

3.4 Poisson’s Ratio

When a concrete cylinder is loaded, the lateral and longitudinal strain observed is referred to as the Poisson's ratio. Usually, the Poisson’s ratio of concrete ranges between 0.1 to 0.2 and high strength concrete are assigned a Poisson’s ratio value of 0.1 while low strength concrete are assigned a value of 0.2 [15], while for design purposes, the value of 0.15 is usually used. Table 5 shows the values of Poisson’s ratio for various mixes of NS-modified SC-ECC. The results indicate that the value of the NS-modified SC-ECC is higher than that of conventional concrete as a result of higher Poisson’s ratio value of PVA fiber, which ranges between 0.247 and 0.278 [16]. Also, it could be observed that at a fixed NS particle s amount, the Poisson’s ratio values increased with increase in PVA fiber volume. However, when the NS particles amount increased from 1% to 2%, the values of the Poisson’s ratio decreased which is attributed to the densification of the fiber/matrix by the NS particles and the pozzolonic reaction products of the NS particles. For example, between M8 (2% PVA &1% NS) and M12 (2% PVA & 2% NS), the value of the Poisson’s ratio decreased by about 35% which indicate corresponding increase in strength. At a fixed NS particles amount, the value of the Poisson’s ratio increases as the volume of PVA fiber increases. This indicates the high deformation increases with increase in PVA fiber amount due to the ability of the PVA fiber in absorbing high energy during loading.

Table 5: Poisson’s Ratio Results

Mix ID	**NS (%)**	**PVA (%)**	**Poisson’s Ratio value**
M5	1	0.5	0.19
M6	1	1.0	0.20
M7	1	1.5	0.22
M8	1	2	0.26
M9	2	0.5	0.17
M10	2	1.0	0.19
M11	2	1.5	0.18
M12	2	2	0.17

4.0 CONCLUSION

Based on the investigations carried out on the fresh properties, mechanical properties, and deformation properties of SC-ECC mixes, some deductions were drawn as follows:

I. Compared to the normal SC-ECC, the shrinkage strain in NS-modified SC-ECC decreases. Hence, it can be recommended that NS-modified SC-ECC can be a suitable repair material in reinforced concrete structures.
II. The enhanced Poisson's ratio and modulus of elasticity in NS-modified SC-ECC materials without adversely affecting shrinkage properties can guarantee the use of NS in concrete materials.

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