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EFFECT OF NANOSILICA ON THE STRENGTH OF CONCRETE WITH VOLCANIC PUMICE AS COARSE AGGREGATES

*Marish Sabiniano Madlangbayan[1], Jeza Mae Monocay Avendaño[1], Kim Fuentes Prodigalidad[1], Milagros Momongan Peralta[2], Ronaniel Almero Almeda[3], Engelbert Kasilag Peralta[3], Marloe Baclayon Sundo[1] and Maricel Aquino Eneria[1]

[1]Department of Civil Engineering, University of the Philippines, Los Baños, Philippines
[2]Institute of Chemistry, University of the Philippines Los Baños, Philippines
[3]Institute of Agricultural Engineering, University of the Philippines Los Baños, Philippines

*Corresponding Author, Received: 21 June 2020, Revised: 25 June 2020, Accepted: 15 July 2020

ABSTRACT: The use of concrete with volcanic pumice as aggregate is limited to masonry. The main reason for its limited utilization is that when volcanic pumice is used as a coarse aggregate in concrete, the result leads to poor performance. Such poor performance is attributed to the weak mechanical properties of volcanic pumice. Past research works show that the use of a stronger mortar counteracts the poor mechanical properties of lightweight aggregate. In this study, the mortar phase of Volcanic Pumice Concrete (VPC) was improved through the incorporation of amorphous nanosilica synthesized from rice hull ash. Nanosilica was admixed in VPC at a concentration of 0.5% by weight of cement. Cylindrical test specimens were prepared, cured for 7, 14, and 28 days, and subjected to compressive and splitting tensile strength tests. Test results show that VPC specimens with 0.5% nanosilica have higher compressive and splitting tensile strength for all cases of 7, 14, and 28 days curing time compared to specimens without nanosilica. The highest percentage increase in compressive and splitting tensile strength was observed in specimens cured for seven days.

Keywords: Lightweight Concrete, Volcanic Pumice, Nanosilica, Rice Hull Ash

1. INTRODUCTION

Concrete is one of the most versatile materials used in the construction of almost all types of structures. Although proven to be versatile, it is still being improved so that specific properties for specific applications are met [1]. For example, conventional concrete structural members have to be made lighter so that the high-stress level due to their heavy self-weight is reduced. Lower stress level then allows for a more economical structural member section [2]. Also, the same property would be desirable in the case of weak soil, tall buildings, or long bridge spans [3,4]. Through time, this need for a construction material that is lighter than the conventional concrete leads to the development of lightweight concrete.

Contrary to conventional concrete that has a unit weight of 2240 to 2480 kg/m^3, lightweight concrete has a unit weight that typically ranges from 1860 to 1920 kg/m^3 [5]. Lightweight concrete can be made by introducing air into the mortar, by eliminating finer aggregates, or by using porous lightweight aggregate. All of which induce voids either in the aggregate itself or in between the mortar and the aggregate. The simplest and most common method to produce lightweight concrete is the use of porous lightweight aggregate [4,6].

Lightweight aggregates in the natural form include pumice, diatomite, scoria, volcanic cinders, sawdust, rice husk, and tuff. On the other hand, processed or artificial lightweight aggregates include expanded or bloated clay, foamed slag, artificial cinders, coke breeze, expanded shale and slate, sintered fly ash and exfoliated vermiculite. Lightweight aggregates absorb more water than natural aggregates due to their very porous cellular structure. They also absorb more water during the process of concrete mixing leading to longer internal curing [7].

Volcanic pumice is an igneous rock formed from the rapid cooling of lava. Its structure is rough and sponge-like with a color that is either white or grey. It also has a very low density that some pumice even floats in water. This aggregate has been used as an insulator and as an absorbent and abrasive material. As an infrastructure material, the use of this aggregate has been limited to masonry and block making [8]. This is because Volcanic Pumice Concrete (VPC) has a very low compressive strength [4]. The cube compressive strength of lightweight concrete with pumice as aggregate has been reported to be equal to 8.73 MPa while the cylinder compressive strength has been reported to be equal to 8.60 MPa. These compressive strength values are 20-40% lower than the values reported for normal concrete. On the other hand, lightweight concrete with volcanic pumice as coarse aggregate has been reported to have a splitting tensile strength equal to 1.25 MPa [9]. This value is lower than the

4MPa tensile strength reported for normal concrete [10]. The poor performance of Lightweight Aggregate Concrete (LWAC), such as VPC, is attributed to the poor mechanical properties of the lightweight aggregate itself [11].

According to literature, the performance of LWAC could be improved with stronger mortar [12]. One way to strengthen mortar is through modification using nanosilica [13]. Nano-silica has a size of 1-50 nm with a concentration of amorphous silica higher than silica fume. Due to this, its reactivity as an admixture in concrete is very high, and a relatively small amount is needed to boost the compressive strength and improve the micro-structure of concrete [14]. Nano-silica not only acts as a filler, but it can also activate more pozzolanic reaction. Moreover, its addition to concrete showed the early formation of calcium hydroxide, which can develop the mortar's early strength. It also forms more C_3S that may form into C-S-H gel, strengthening and making the concrete more packed [15].

There are studies on the performance of concrete and cement incorporated with nanosilica synthesized from rice hull ash [16]. With the incorporation of nanosilica in concrete, the hydration products are smaller, the void spaces are fewer, and the cement paste matrix is finer. Consequently, concrete with nanosilica achieved compressive strength values that are higher for plain concrete [17]. A study reported that at 4% nano-silica and 500kg/m^3 cement content, the compressive strength increased by 5.1% at 7 days curing period and 11.75% at 28 days curing period. Moreover, at 4% nano-silica and 800 kg/m^3 cement ratio, it increased by 2.1% and 11.4% respectively [18]. Introduction of nano-silica can accelerate the early cement hydration causing the compressive strength at a curing period of 7 days to increase, but at 28 days curing period, the compressive strength stopped to increase at a certain percentage of nano-silica [19].

Aside from improving the concrete microstructure, nanosilica also promotes cement hydration. Studies show that during the induction period of plain cement, the degree of hydration is constant. Whereas, when nanosilica is incorporated in the mix, the degree of hydration increased. This was attributed to the quick reaction of nanosilica with water and Ca^{2+}, which then lead to the early formation of CSH gel. On the other hand, during the acceleration period, this pozzolanic reaction also reduces Ca^{2+} concentration. Since the supersaturation of Ca^{2+} is prevented, the dissolution of silicates is accelerated. As a consequence of early CSH gel formation, concrete strength is gained earlier as well [20,21].

Besides, there are studies where nanosilica has a positive effect on lightweight concrete, which utilizes lightweight coarse aggregates like Lightweight Expanded Clay Aggregate (LECA) and expanded shale ceramsite [13,22].

This study incorporated nanosilica from rice hull ash into concrete with volcanic pumice as coarse aggregates in an attempt to contribute towards improving the strength performance of VPC. The study also investigated the effect of the synthesized nanosilica from RHA on the compressive and splitting tensile strength of VPC. This was done using a VPC containing 0% and 0.5% (by cement weight) nanosilica and subjected to 7, 14, and 28 days curing. The results of the study contribute to the literature on the use of VPC and to the limited but growing literature on the use of nanosilica synthesized from RHA in concrete.

2. MATERIALS AND METHODS

The American Concrete Institute Standard Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2 – 98) was the mix design method used in this study to determine the proportions of raw materials required for concrete mixes containing 0% and 0.5% (by cement weight) nanosilica. For both concrete mixes, volcanic pumice was utilized as coarse aggregates in full proportion. Table 1 shows the number of specimens for each sample type. A total of 60 specimens were prepared.

Table 1 Number of specimens prepared per sample type

Strength test	Percent Nanosilica	Curing period (days)		
		7	14	28
Compressive	0	5	5	5
	0.5	5	5	5
Splitting tensile	0	5	5	5
	0.5	5	5	5

2.1 Materials Used

2.1.1 Type 1 portland cement

The Type 1 Portland cement used in this study was taken from local hardware, which conformed to the American Society for Testing and Materials Standard Specification for Portland Cement (ASTM C150-09). The chemical composition of the cement used in this study is shown in Table 2.

2.1.2 Aggregates

River sand was used as fine aggregate, while volcanic pumice (Fig.1) was used as a coarse aggregate. The volcanic pumice was hauled from Mabalacat City, Pampanga, Philippines. The lightweight coarse aggregates were remnants of the Mt. Pinatubo eruption in 1991. The properties of the fine and coarse aggregates are summarized in Table 3.

Table 2 Chemical composition of Type 1 Portland cement.

Compound	Weight (%)
SiO	19 – 21
Al_2O_3	5.0 – 5.2
Fe_2O_3	3.2 – 3.4
CaO	63 – 64
MgO	1.3 – 1.5
LOI	3.4 – 3.5

Fig.1 Volcanic pumice hauled from Mabalacat, Pampanga

Table 3 Properties of aggregates.

Property	River Sand	Volcanic Pumice
Specific Gravity	2.73	1.33
Absorption Capacity (%)	2.18	32.90
Fineness Modulus	2.76	---
Dry-rodded Unit Weight (kg/m^3)	---	49.97

2.1.3. Nanosilica

The powdered nanosilica (Fig.2) utilized in this study was synthesized from rice hull ash. This was provided by the Nanotechnology Center of the University of the Philippines Los Baños. The physical properties of nanosilica are summarized in Table 4. Its crystallography was determined through X-ray Powder Diffraction (XRD). In contrast to the crystallographic analysis of crystalline silica, which has a peak at 22°, the crystallographic analysis of the powdered nanosilica used in this study (Fig.3) showed no peak at 22°. This means that the powdered nanosilica used in this study is highly amorphous. Also, the presence of other contaminants was not observed, which means that the powdered nanosilica used in this study was pure.

Fig.2 Powdered nanosilica synthesized from rice hull ash

Table 4 Physical properties of the nanosilica used in the study

Property	Value
Average Particle Size	24.39 ± 0.38 nm
Surface Area	~260 – 300 m^2/g
Pore Radius	~16 – 19 Angstrom
Pore Volume	~0.246 cc/g

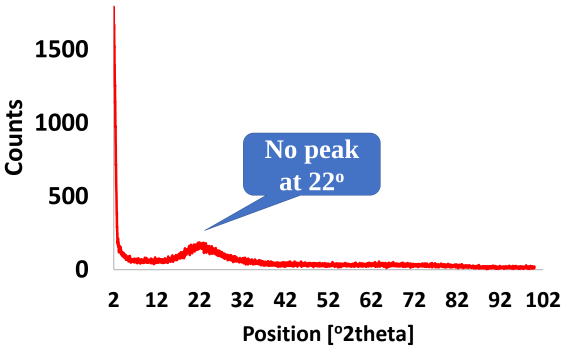

Fig.3 Crystallographic analysis of the powdered nanosilica

2.2 Mix Proportions

The concrete mix proportions were prepared following ACI 211.2-98. The parameters (and their corresponding values) listed in Table 5 are considered. The resulting mix proportions of both concrete mixes are summarized in Table 6.

Table 5 Parameters considered and used in the study to generate mix proportions.

Parameter	Value
Slump	25 - 50 mm
Maximum Size of Aggregates	19 mm
Air Content	2%
Water-to-cement ratio	0.5

Table 6 Mix proportions in kilogram per cubic meter of concrete

	Concrete Mixes	
	Without Nanosilica	With Nanosilica
Cement	486	486
Water	243	243
Fine Aggregate	974	974
Coarse Aggregate	769	769
Nanosilica	---	24

2.3 Compressive Strength Test

After 7, 14, and 28 days of curing, concrete samples were removed from the water bath and then wiped dry in preparation for compressive testing. The compressive strength test was performed following ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen. Each sample was placed in Universal Testing Machine (UTM), as shown in Fig. 4. The compressive load applied to the sample was increased at a constant rate until failure is reached. The compressive strength is then calculated as the maximum load sustained by the concrete specimen divided by the area perpendicular to the load.

Fig.4 Compressive strength test setup

2.4 Splitting Tensile Strength Test

ASTM C496: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens was followed in conducting the splitting tensile strength test in this study. Fig.5 shows the setup of the splitting tensile strength test.

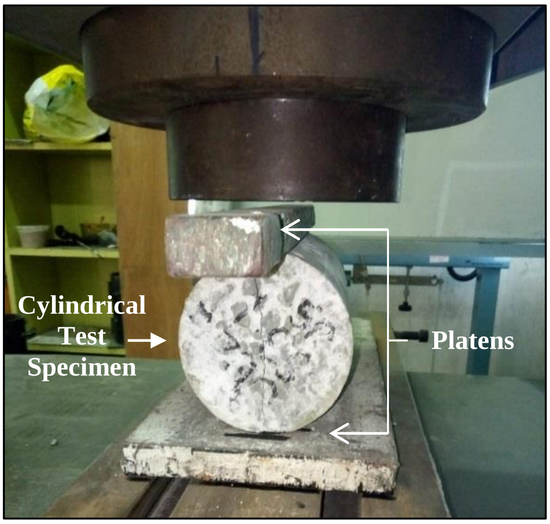

Fig.5 Splitting tensile strength test setup

The UTM was used to determine the maximum force applied, which can then be used to determine the splitting tensile strength of the concrete by using Eq. (1).

$$\boldsymbol{T = \frac{2P}{\pi l d}} \qquad (1)$$

where $\boldsymbol{T}$ is the splitting tensile strength, $\boldsymbol{P}$ is the maximum applied load indicated by the universal testing machine, $\boldsymbol{l}$ is the length of the cylindrical specimen, and $\boldsymbol{d}$ is the diameter of the cylindrical specimen.

3. RESULTS AND DISCUSSION

3.1 Slump Test

Immediately after mixing the raw materials, slump test procedure as per ASTM C143-15: Standard Test Method for Slump of Hydraulic Cement Concrete was performed. The results of the said test are summarized in Table 7.

Table 7 Slumps of freshly mixed concrete

Concrete Mix	Slump at 0.5 w/c (mm)
Without Nanosilica	28.6
With Nanosilica	28

Table 7 shows the averages of slump values from three (3) trials. Both mixes achieved the desired slump of 25 to 50 mm. Also, the slump recorded was almost the same. Thus, at 0.5% of cement weight, nanosilica does not affect the workability of freshly mixed VPC.

3.2 Fresh and Hardened Density

Measurement of density is very important when it comes to lightweight concrete. According to the ACI, structural lightweight concrete density ranges from 1860 to 1920 kg/m^3. Table 8 shows the fresh and hardened density of VPC with and without the 0.5% nanosilica.

Table 8 Average Fresh and hardened density of VPC with and without 0.5% nanosilica.

	DENSITY (kg/m^3)			
		Hardened		
	Fresh	7 days	14 days	28 days
Control VPC	1839	1850	1799	1865
VPC with 0.5% Nanosilica	1866	1889	1879	1875

It can be observed that the fresh and hardened density of VPC increased upon the incorporation of nanosilica. The fresh density increased by 1.43% while the hardened density increased by 2.87%, 4.45 and 1.67% when 0.5% nano-silica by weight of cement is incorporated in VPC cured for 7, 14 and 28 days respectively. This trend can be attributed to the formation of more C-S-H gel on concrete.

Moreover, nano-silica also acts as a filler and promotes hydration process making concrete denser [23]. The hydration process was improved which eventually led to the production of more C-S-H gel. This in turn minimized the formation of voids thus making the concrete specimens denser. Despite the increase in density of the concrete specimens, the density of VPC with 0.5% nanosilica is still within the range for it to be classified as lightweight concrete.

3.3 Compressive Strength Test

The results of the compressive strength test are shown in Fig.6. The average values for five (5) specimens were reported. For all curing period considered, the average compressive strength of VPC with nanosilica is greater than that of the control samples.

The percent increase in the compressive strength of VPC due to nanosilica at each curing period is summarized in Fig.7. From Fig.7, the percent increase in the compressive strength of VPC due to nanosilica decreases with increasing curing period. The effect of 0.5% (by cement weight) nanosilica is most significant on the early-age compressive strength of VPC.

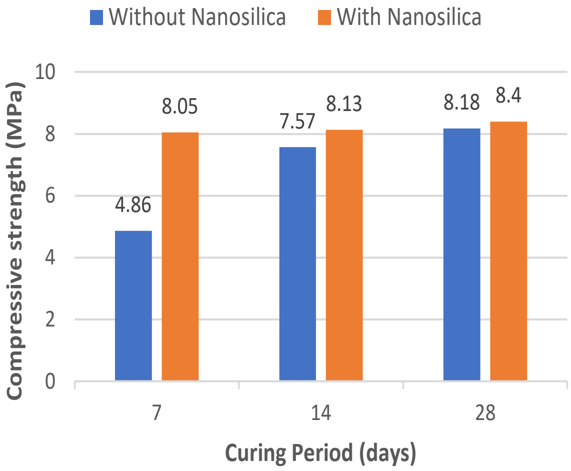

Fig.6 Compressive strength of VPC with and without nanosilica at 7, 14, and 28 days of curing

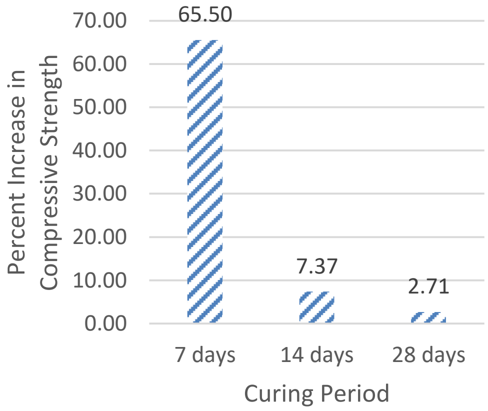

Fig.7 Percent increase in compressive strength due to incorporation of nanosilica at 7, 14, and 28 days of curing.

Concrete compressive strength is indicative of the degree of completeness of hydration [24]. Based on the results obtained, gradual hydration of VPC without nanosilica was observed, while hydration of VPC with nanosilica was immediate and was almost completed as early as 7 days. This can be attributed to the amorphous structure and high hydrophilic nature of the incorporated nanosilica, which tend to make it highly reactive during the early stages of hydration [25]. Other important factors that make nanosilica advisable for such applications are its high specific surface area and porous structure. These properties of nanosilica allow an effective and homogenous contact of each component as well as deep penetration of the components inside the solid structure. These factors contributed to the significant increase in the compressive strength of the VPC.

Also, the high surface area of nanosilica allows homogenous incorporation into a solid matrix, which allows an increased rate and faster product formation [26,27]. The rapid pozzolanic reaction observed can also be attributed to nanosilica's effective surface adsorption of Ca^{2+}, which can lead to the early formation of C-S-H gel during the induction period. The same reaction also prevents the supersaturation of Ca^{2+} during the acceleration period. As a result, the dissolution of silicates is accelerated. In this study, the rapid C-S-H gel formation contributed to the increase in the compressive strength of the VPC.

3.4 Splitting Tensile Strength Test

The results of the splitting tensile strength test are shown in Fig.8. The average values for five (5) specimens were reported. It was observed that the addition of nanosilica on VPC improved its splitting tensile strength at any curing period.

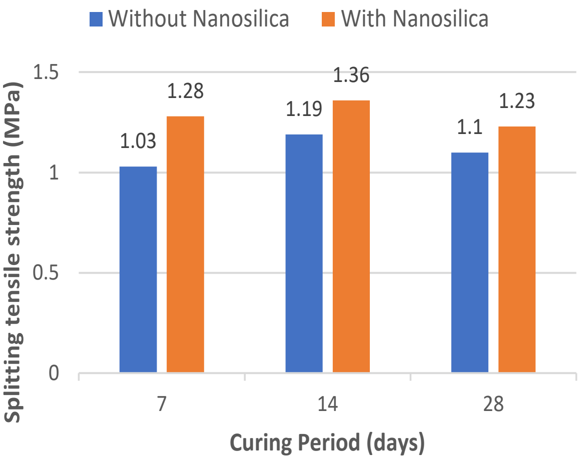

Fig.8 Splitting tensile strength of VPC with and without 0.5% nanosilica cured for 7, 14, and 28 days.

As seen in Fig.9, the splitting tensile strength of VPC increased by 23.93%, 14.48%, and 12.21% when cured for 7, 14, and 28 days respectively. Based on the percentage increases on the splitting tensile strength of VPC, the use of nanosilica as an accelerating admixture is effective. It can be observed how reactive nanosilica is at earlier stages, as evidenced by a high increase of splitting tensile strength at the early stages. A previous study investigated the effect of incorporation of nanosilica on the tensile strength of concrete [28]. It was found out that when 3% nanosilica was used, the tensile strength of the modified concrete improved by 16.10% compared to the tensile strength of ordinary concrete. It was theorized that the positive effect of nanosilica on the tensile strength of concrete could be attributed to the enhanced interfacial strength bridging between the concrete matrix and the aggregate [29].

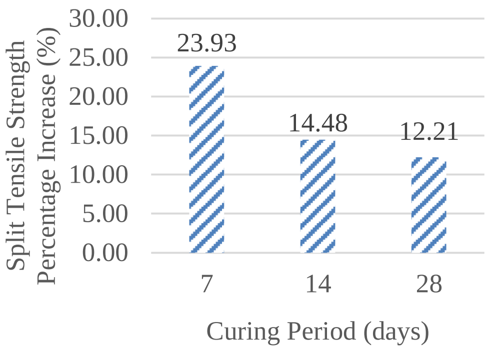

Fig.9 Percent increase in splitting tensile strength due to incorporation of nanosilica at 7, 14, and 28 days of curing.

Also, nanosilica significantly improved the early and over-all mechanical strength of VPC by accelerating and triggering more pozzolanic reaction on concrete, causing it to rapidly produce more C-S-H gel. Moreover, the sub-micron size of nanosilica also acted as fillers to detrimental voids on the solid microstructure of VPC concrete.

4. CONCLUSION

This study investigated the effect of nanosilica synthesized from rice hull ash on the compressive and splitting tensile strength of concrete with volcanic pumice as coarse aggregates. Mix proportions of VPC with and without nanosilica were designed and prepared. The slump of concrete was determined following ASTM C143. The slump recorded for fresh VPC without nanosilica is 28mm, while the slump recorded for the fresh VPC with nanosilica is 28.6 mm. Both groups achieved the desired slump of 25 to 50 mm. Based on these values, it can be concluded that at 0.5% admixture of nanosilica, by cement weight, does not affect the workability of fresh VPC. Moreover, it was determined that the density of VPC increased upon the incorporation of 0.5% nanosilica, but the values are still within the range for lightweight concrete.

Hardened concrete specimens were cured for 7, 14, and 28 days. Compressive strengths were then determined following ASTM C39. For all curing period considered, the average compressive strength of VPC with nanosilica is greater than the average compressive strength of VPC without nanosilica. The highest percentage increase in compressive strength was 65.50%, which occurred for specimens cured for 7 days. The percentage increase in compressive strength decreased to

7.37% and 2.71% as curing was increased to 14 days and 28 days, respectively. In terms of splitting tensile strength, this study confirms that the incorporation of 0.5% nanosilica increases the splitting tensile strength of VPC. This is true for all cases of 7, 14, and 28 days curing period. The highest percentage increase in splitting tensile strength was 23.93%, which occurred for specimens cured for 7 days. Afterwards, the percentage increase in splitting strength then decreased to 14.48% and 12.21% as curing was increased to 14 days and 28 days respectively.

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