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Strength Performance Evaluation of Wood Ash Concrete Infused with Nanosilica

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Abstract. Concrete is among the most extensively employed construction materials globally, with an annual production estimated at 27.3 billion tonnes. Approximately 80% of all CO_2 emissions from concrete technology are attributable to the production of Portland cement, the essential binder in concrete, which accounts for 5 - 7% of global CO_2 emissions. Consequently, reducing cement utilization is vital for decreasing carbon dioxide levels. Nonetheless, the strength properties of cement are essential for achieving the desired strength of structures. Therefore, the development of cost-effective additives and alternatives to cement to produce environmentally friendly binding supplements for concrete becomes imperative. In pursuit of this, a 0.5 water/binder (w/b) ratio mix was formulated to evaluate the impact of nanosilica on the compressive strength of wood ash concrete and ascertain the optimal percentage for a partial replacement. The mix design was modified by incorporating wood ash into the cement fraction in proportions of 0, 5, 10, 15, 20, and 25% with nanosilica additions of 0, 0.5, 1.1, and 1.7% based on mixing water percentage. The wood ash was produced by thoroughly burning firewood from wattle trees (Acacia pycnantha). Concrete samples were cast in cube moulds with a w/b ratio of 0.5, and compressive strength testing was conducted on the samples at 3, 7, 14, 28, 56, 90, and 120 days, respectively. Results indicated that, in comparison to the control sample, the wood ash containing nanosilica decreased proportionally, regardless of the percentage of Nanosilica (NS) inclusion. However, the compressive strength of the wood ash (WA5%) group samples, including those without NS, gained 3% of the target strength of 50 MPa within just 14 days. At 28 days, this strength exceeded the target by 6%. This strength increase continued to rise by 6–13% from 28 to 120 days. Samples containing 10% WA with 1.1 and 1.7% NS surpassed the target strength of 50 MPa by 0.6% and 1.3%, respectively, at 28 days. This enhancement was also observed in other samples from 56 to 120 days.

1. Introduction

Concrete is one of the most widely utilized building materials worldwide, with an estimated yearly production of 27.3 billion tonnes [1]. About 80% of all concrete CO_2 emissions are caused by Portland cement production, the necessary binder for concrete, contributing between 5 - 7% of all CO_2 emissions worldwide [2–7]. By 2050, the demand for Portland cement is expected to reach 6,000 million tonnes annually, an increase of almost 200% compared to previous years [8]. These greenhouse gas emissions have caused global climate change, and many nations have responded to this challenge differently [9]. Consequently, reducing cement use is crucial to lowering carbon dioxide levels. However, the importance of cement in the production of composites cannot be overemphasized, as it plays a fundamental role in the development of strength. Therefore, it has

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become essential to develop cost-effective additives and cement alternatives to produce environmentally friendly binding supplements for concrete [10]. Previous studies have focused on resource efficiency by replacing conventional cement with industrial wastes as supplementary cementitious materials in the development of composites [11,12].

In a study by Farinha et al.[13], a volumetric ratio of 1:4 (binder: aggregates) was selected, and 5, 10, and 15% of wood ash were substituted for cement by volume. The mechanical behaviour tests focusing on compressive strength were conducted on prismatic specimens (40x40x160 mm^3), measuring the strength at 7, 28, 90, 180, 365, and 730 days. The compressive strength of mortar containing 5% WA increased. However, this increase was only noticeable between 28 and 180 days. The reference mortar's compressive strength was higher than that of the other mortars. Furthermore, the compressive strength decreased more at 730 days, ranging from 29% to 45%. Compared to reference mortar, this strength was reduced by adding WA. Similarly, workability and bulk density were unaffected by this substitution, according to the findings of [14,15]. In contrast to the reference samples, the compressive performance was diminished by as much as 45%. Nonetheless, up to 15% of cement can be replaced with wood ash without compromising mortar performance [13,14,15]. In a review by [16], the suggested wood ash percentage should not exceed 15% for optimum concrete performance.

The properties of concrete in both its fresh and hardened stages have led to a recent increase in the use of nanomaterials, such as nanosilica (NS), in manufacturing concrete [17]. Prior studies have demonstrated that the strength and durability of high-strength concrete (HSC) are improved when NS is used as a partial replacement for 0–6% cement. Furthermore, there are very few calcium hydroxide crystals in the dense, compact microstructure of the concrete mixed with NS [18–22]. Additionally, other investigations looked into the possible application of NS in different kinds of concrete. Self-compacting concrete with 2% NS, 0.08 percent nano-carbon, and 40% fly ash (FA) outperformed NS-free admixture, according to Aydin et al. [23]. The fresh and hardened characteristics of concrete at different water-to-binder ratios were improved by substituting NS for 3% of the cement weight, according to Naniz and Mazloom [24].

The quick rise in NS concrete's compressive strength demonstrated that NS serves as both an activating agent for the hydration reaction and a filler to boost the density of the concrete [25]. Adding merely 0.1% NS to ordinary concrete improved its strength by 84%, 93%, and 35% at 3, 7, and 28 days, respectively, for water-cement ratios (w/c) ranging from 0.42 to 0.45, according to experimental results [26]. While the gain was only 6.5 and 0%, respectively, at 0.55 and 0.5 w/b ratios, the concrete with 0.65 w/b ratios significantly increased by 41% in 28 days of compressive strength at 1.5% NS [27]. According to Makarova et al. [26], the concrete's strength was significantly increased when the NS content was raised from 0.05% to 0.5%; however, the strength was unaffected when the NS level was increased to 1%. The pozzolanic reaction at a low dose of 0.3% NS in concrete boosted the early-age compressive strength by decreasing porosity and refined pore structure, according to Du et al. [28].

According to an assessment of the impact of nano-silica in concrete by [29], NS dosages of up to 2–3% could enhance the material's durability and mechanical qualities. Its pore structure refinement, filling effect, and pozzolanic action may be responsible for this. The NS acts as an activator to encourage hydration, and compressive strength rises with NS content. However, the strength can be diminished if the NS dosage exceeds 3%. Because of the agglomeration of NS particles, higher dosages (i.e., 3% or more) may eventually impact the engineering qualities, leading to microcracking, excessive porosity, and decreased compressive strength.

For this reason, the present study focuses on the strength performance evaluation of wood ash-concrete infused with nanosilica. The research aims to investigate the effect of different percentage weight fractions of wood ash mixed with NS on the mechanical property (compressive strength) of wood ash concrete, with the objectives of determining the effect of NS dispersion on the

compressive strength of the nanocomposite concrete at the early and long-term strength development.

2. Materials and Methods

2.1 Materials and Properties

Ordinary Portland Cement CEM I 52.5N conforming to SANS 50197-1:2013 [30] was used in this investigation. The mineral fillers used include coarse and fine aggregates with compacting bulk density of 1557 and 1846 kg/m^3, respectively. The coarse aggregates of maximum particle size of 22 mm and fine (crusher sand) of maximum size of 4.75 mm obtained from a local quarry in Johannesburg were used. The particle size analysis of aggregates was conducted in conformity with SANS 3001-AGI:2014 [31]. The wood ash used was sourced from caterers' services situated in Johannesburg. The physical and chemical composition of OPC and the wood ash are provided in Table 1 and 2 respectively. The nanosilica solution (NSS) was used, an aqueous liquid containing colloidal nanosilica in the dispersed state with a 0.3 moles/L concentration. Silicon and oxygen are the only atomic components of the NS used, maintaining a 1:2 atomic ratio consistent with the theoretic composition of SiO_2 (46.74 wt% Si, and 53.26 wt% O).Tap water was used in all mixtures.

The water-to-binder ratio was kept constant at 0.5 for all the mixtures. The fine and coarse aggregates were graded in accordance with SANS 3001-AG1:2014 [31]. The mix ratio of the concrete samples was designed according to C & CI specifications. The cement consumption in the test group concrete (Zawa 5–25) was calculated according to the reduction rate in the concrete preparation process under the same water-binder ratio condition.

Table 1: *Chemical and Physical Composition of the PC*

Property	Test Result (%)	SANS 50197-1 Requirements
1. Oxide composition:		
Alumina, Al_2O_3	4.99	
Silica, SiO_2	19.98	
Ferric Oxide, Fe_2O_3	2.77	
Lime, CaO	64.91	
Sulphuric Anhydride, SO_3	2.10	≤4.0
Magnesia, MgO	1.54	
Sodium, Na_2O	0.08	
Insoluble Residue	0.90	≤5.0
Chloride	0.04	≤0.10
Loss in ignition	2.72	≤5.0
2. Compound composition		
C_3A	6.80	
C_2S	28.21	
C_3S	52.70	
Physical properties of PC		
Property	Test Result (%)	SANS 50197-1 Requirements
Fineness % (Residue on sieve size 0.15 mm)	3	Max. 5
Specific Area (Blaine) m^2/kg	400	No requirement.
Initial setting time (min.)	170	45 minimum
Final setting time (min.)	250	No requirement.
Specific gravity	±3.14	-
Compressive strength (MPa)		
At 2 days	±28	≥20.0
At 28 days	±58	≥52.5
Bulk density, aerated (kg/m^3)	1100 – 1300	
Soundness :		
Le Chatelier Expansion (mm)	1	Max. 10
The manufacturer (PPC) provides Table 2 results.		

Table 2: *Physical and chemical properties of wood ash*

Properties		Value	Chemical Composition (%)
		SiO_2	53.57
		Al_2O_3	33.98
		Fe_2O_3	6.12
Conventional parameters		MgO	6.23
Organic material (mg/kg)	<10	CaO	3.24
pH	12.1	MnO	1.66
		SO_3	1.58
Physical properties		Cl	0.07
Density (kg/m^3)	834	Na_2O	0.00
Specific gravity	1.92	K_2O	0.20
Mean size (µm)	0.4	TiO_2	0.20
		P_2O_5	0.30
		SrO_2	0.08
		ZrO_2	0.96
		ZnO	2.66
		(LOI)	**14.2**

The cement and wood ash exhibit both crystalline and amorphous phases owing to the pattern of their spectra as shown in Fig. 1. It could be observed that some points have very sharp humps and others with broader ones. However, edges with sharp humps are more prominent in the case of the cement as compared to the wood ash. Hence, the crystallinity in the cement is more than that present in the wood ash. The lesser crystallinity in the case of wood ash as compared to that of cement is due to the high visibility of broader humps. The peak intensity was observed to occur at 2θ less than 30˚in the case of wood ash. This agrees with what was obtained elsewhere [32, 33], and for the cement, the peak intensity was observed to occur in the range of 26-35˚. The result agrees with that obtained elsewhere. [34].

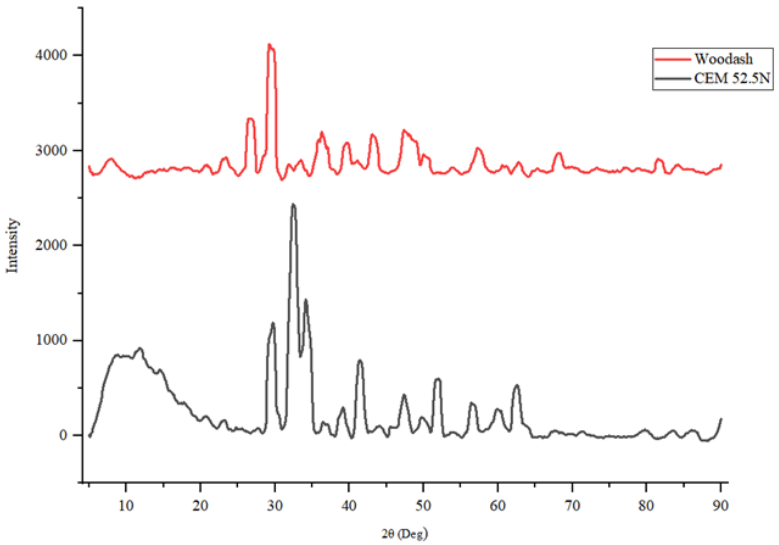


Fig. 1*. XRD of WA and Cement*

2.2 Research Method

Blended concrete containing cement, wood ash, and NS was prepared. Mixing procedures were carried out in a rotary mixer, according to SANS 5861-3:2006 [35]. Nanosilica (NS) was mixed with water at medium speed. The mixture was allowed to rest for 90 seconds and then mixed continuously for 1 minute at high speed. Details of the mix proportions of the cement concrete are given in Table 3. The mix proportion for the control sample with PC (without nanoparticles) is denoted by CC. At the same time, Zawa 5-25 represents South African wood ash consisting of cement concrete with varying percentages of wood ash between 5 and 25% by weight of cement, respectively. The percentage of nanoparticles varied between 0 and 1.7%, and other parameters, such as fine and coarse aggregates, remain constant as shown in Table 3. The concrete samples were cured in accordance with [35], as shown in Fig. 2.

Table 3: Mix Proportions of M50 Grade Wood Ash Concrete

Mixes	Cement (kg/m^3)	Water (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	NS (kg/m^3)	Wood ash (kg/m^3)	W/B Ratio
CC	385.256	200.333	1112.666	656.3	0	0	0.5
WA05NS0	365.993	200.333	1112.666	656.3	0	14.846	0.5
WA10NS0	346.730	200.333	1112.666	656.3	0	29.692	0.5
WA15NS0	327.468	200.333	1112.666	656.3	0	44.538	0.5
WA20NS0	308.205	200.333	1112.666	656.3	0	59.383	0.5
WA25NS0	288.942	200.333	1112.666	656.3	0	74.229	0.5
WA05NS0.6	365.993	199.131	1112.666	656.3	1.202	14.846	0.5
WA10NS0.6	346.730	199.131	1112.666	656.3	1.202	29.692	0.5
WA15NS0.6	327.468	199.131	1112.666	656.3	1.202	44.538	0.5
WA20NS0.6	308.205	199.131	1112.666	656.3	1.202	59.383	0.5
WA25NS0.6	288.942	199.131	1112.666	656.3	1.202	74.229	0.5
WA05NS1.1	365.993	198.129	1112.666	656.3	2.204	14.846	0.5
WA10NS1.1	346.730	198.129	1112.666	656.3	2.204	29.692	0.5
WA15NS1.1	327.468	198.129	1112.666	656.3	2.204	44.538	0.5
WA20NS1.1	308.205	198.129	1112.666	656.3	2.204	59.383	0.5
WA25NS1.1	288.942	198.129	1112.666	656.3	2.204	74.229	0.5
WA05NS1.7	365.993	196.927	1112.666	656.3	3.406	14.846	0.5
WA10NS1.7	346.730	196.927	1112.666	656.3	3.406	29.692	0.5
WA15NS1.7	327.468	196.927	1112.666	656.3	3.406	44.538	0.5
WA20NS1.7	308.205	196.927	1112.666	656.3	3.406	59.383	0.5
WA25NS1.7	288.942	196.927	1112.666	656.3	3.406	74.229	0.5

CC= Control Concrete with Portland Cement only, ZaWa05 = PC with 5% WA, Zawa10 = PC with 10% WA, Zawa15 = PC with 15% WA, Zawa20 = PC with 20% WA, Zawa25 = PC with 25% WA



Fig. 2: *Wood ash +NS concrete samples in a curing tank*

For each concrete mixture, 100 x 100 x 100 mm specimens were prepared and tested according to SANS 3001-AG1:2014 [31]. The test specimens were demoulded after 24 hours and then cured in water. A total of 105 concrete cube specimens were cast from each group, including 21 cubes for the control mix, making a total of 441 cubes, covering seven different ages of 3, 7, 14, 28, 56, 90, and 120 days. The compressive properties were tested at 3, 7, 14, 28, 56, 90, and 120 days, respectively, using a Toni Technic hydraulic test frame manufactured by Baustoffprüfsysteme GmbH, Gustav-Meyer-Allee 25, D-13355 Berlin, with a loading capacity of 3000 KN in accordance with [36] as shown in Figure 3. The concrete samples were prepared and tested in accordance with SANS 5836:2006 [39] Standards for test methods of concrete mechanical properties.



Fig.3: *Compressive strength testing: 1-testing machine, 2-spcimen, 3-support.*

3. Results and discussion

3.1 Compressive strength

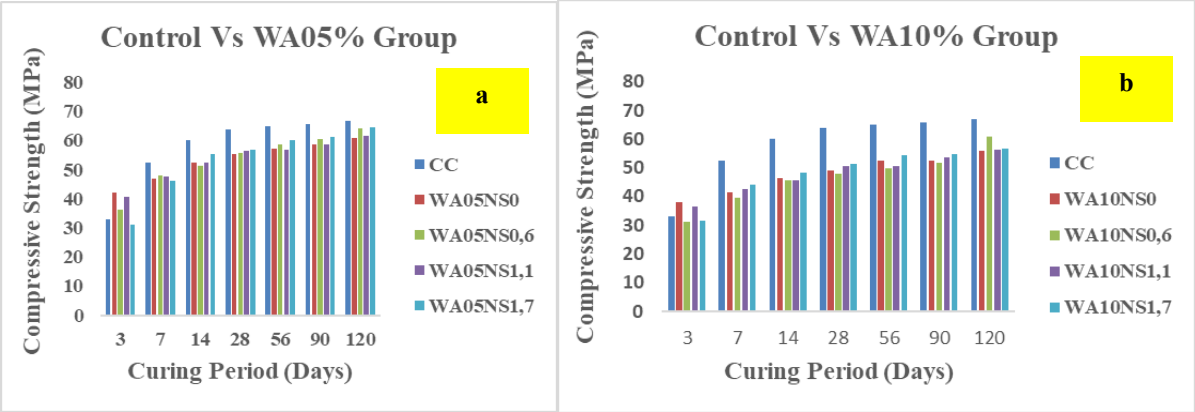
The compressive strength results of the 5% WA replacement group containing various proportions of nanosilica compared to the control sample as shown in Fig. 4a. revealed changes in the compressive strength of the WA concrete samples due to the changing percentage of nanosilica (NS) infused into the mix. The reference mix (CC) achieved compressive strengths of 63.8 and 66.9 MPa at 28 and 120 days, respectively. In addition, including WA as a partial substitute at 5% of PC increases the compressive strength to 42.2 MPa, representing an increase of 9.2% of the control sample at 3 days. Similarly, addition of NS of 0.6 and 1.1% increases the compressive strength to 36.2 and 40.6 MPa, representing an increase of 3.2 and 7.6 % at 3 days, respectively, of the control sample. An increase in the percentage of NS in WA05NS0.6, WA05NS1.1, and WA05NS1.7 mixtures enhanced the compressive strength at 56, 57, and 57 MPa representing a strength gain between 1 and 2% respectively, at 28 days compared to wood ash samples without nanosilica. Similarly, the same mixtures' compressive enhancement stands at 3, 1, and 4% at 120 days.

The results of 10% WA replacement as shown in Fig. 4b displayed an impressive outcome as the compressive strength increases over the testing periods for all the tested samples. Interestingly, samples WA10NS0 and WA10NS1.1 exceeded the control sample by 5% and 3.7% at 3 days, respectively. The results further revealed the effect of NS addition as it improves the compressive strength of tested samples containing NS between 0.6 and 1.7% compared to samples without NS between 14 and 120 days, respectively.

The compressive strength results of the 15% WA replacement group containing various proportions of NS compared to the control sample as shown in Fig. 4c showed that the sample WA15NS1.7 increased in compressive strength by 4.4, 3.5, 2.6, 1.6, and 3.7% compared to sample WA15NS0 (WA without nanosilica) for 7, 14, 28, 56, and 90 days respectively; though this consistent performance shows a linear decrease over the control sample by 12, 16.6, 16.2, 16.7 and 14.8% over the same testing ages.

The performance of 20% WA replacement group containing various proportions of NS compared to the control sample as shown in Fig. 4d indicates addition of NS between 1.1 and 1.7% increases the compressive strength to 40.2 and 40 MPa, compared to WA without NS at 28 days, representing an increase of 3.2 and 3%, respectively. However, samples WA20NS0.6 and WA20NS1.1 increase in compressive strength by 0.9 and 1.9%, respectively, compared to sample WA20NS0 at 120 days.

The increase of WA to 25% play a significant role in strength reduction irrespectively of the amount of Nanosilica inclusion in the 25% wood ash group, as none of the mixtures performance meets the target strength of 50 MPa.



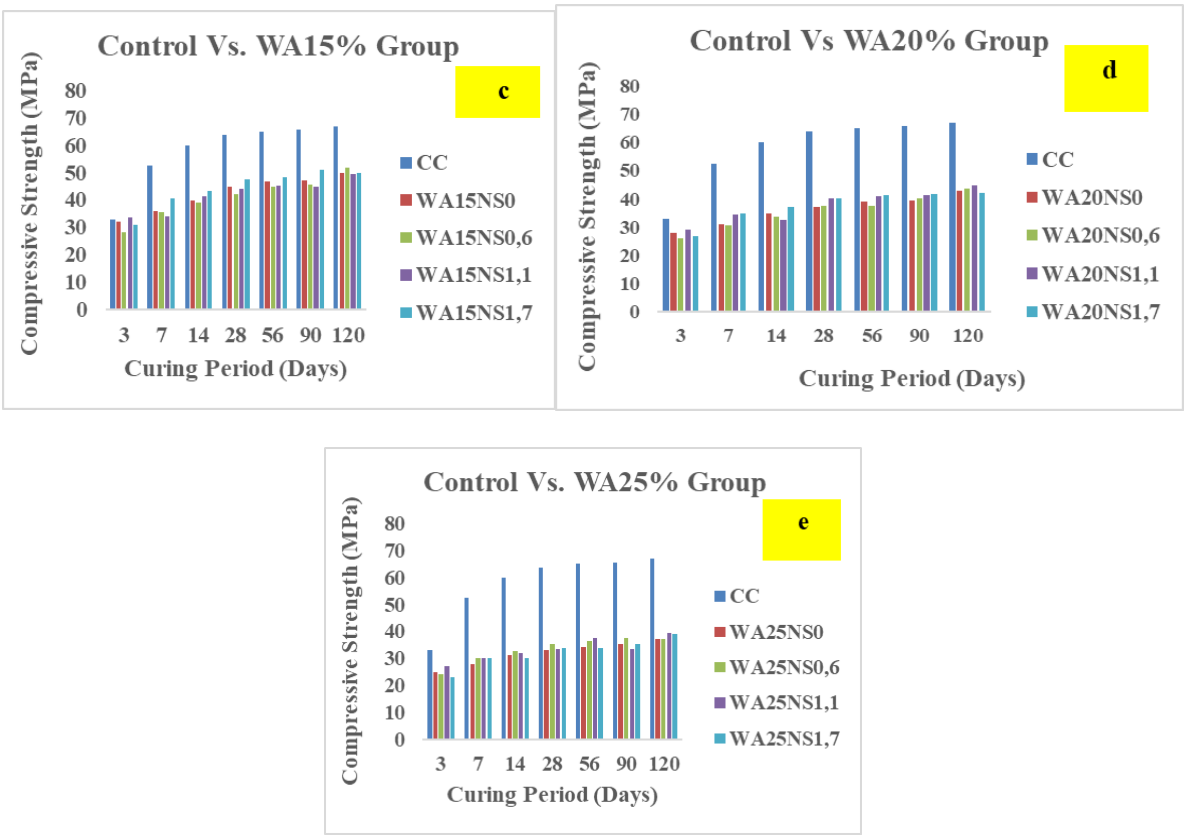


Fig. 4(a-e) Compressive strength of the wood ash containing NS vs. Control Sample

4. Conclusions

According to this study, which investigated the compressive strength of wood ash concrete infused with nanosilica, the following conclusions can be drawn. Compared with the target strength of 50 MPa within the WA5% group, the wood ash containing 1.7 % nanosilica produced the optimum compressive strength of 56.8 and 64.5 MPa, respectively for 28 and 120 days respectively. Similarly, within the WA10% group, wood ash containing 1.7% nanosilica produced the optimum results of 51.3 and 56.8 MPa for 28 and 120 days respectively. The results of these optimum samples are ideal for construction of high-rise buildings and bridges, which require high performance.

1. The replacement of WA at 5% without nanosilica increases the compressive strength to 42.2 MPa, representing an increase of 9.2% of the control sample at 3 days. However, the inclusion of NS of 0.6 and 1.1% increases the compressive strength to 36.2 and 40.6 MPa, representing an increase of 3.2 and 7.6% of the control sample at 3 days, respectively.

2. An increase in the percentage of NS in WA05NS0.6, WA05NS1.1, and WA05NS1.7 samples increased the compressive strength to 55.8, 56.8, and 56.8 MPa, representing a strength gain of 0.6, 1.3, and 1.6% at 28 days, respectively.

3. Samples WA10NS0 and WA10NS1.1 exceeded the control sample by 5, and 3.7% at 3 days, respectively. The results further revealed the effect of NS addition as the compressive strength of tested samples containing NS increases between 0.2 and 2.5% compared to samples without NS between 7 and 120 days, respectively.

4. The results further showed that sample WA15NS1.7 increased in compressive strength by 4.4, 3.5, 2.6, 1.6, and 3.7% compared to sample WA15NS0 (WA without nanosilica) for 7, 14, 28, 56, and 90 days respectively; though this consistent performance shows a linear decrease over the control sample by 12, 16.6, 16.2, 16,7, and 14.8% over the same testing ages.

5. An additional increase of NS between 1.1 and 1.7% increases the compressive strength to 40.2 and 40 MPa, respectively, compared to the WA sample without NS at 28 days, representing an increase of 3.2 and 3%, respectively. However, samples WA20NS0.6 and WA20NS1.1 increased compressive strength by 0.9 and 1.9%, respectively, compared to sample WA20NS0 at 120 days.

5. Recommendation

Future work should focus on how waste wood ash is processed to make it more reactive and effective in concrete strength development. Moreso, fine tuning nano-silica dosages and mixing methods to get better particle distribution is desirable. Long-term durability investigation like water absorption and chloride resistance are essential to understand how these mixes will actually perform over time. Finally, using techniques like scanning electron microscope (SEM), and X-ray diffraction (XRD) to study the concrete's internal structure would help connect the laboratory investigation and the real-world performance and application.

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