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Enhancing concrete durability: Sustainable ternary blends incorporating agricultural and industrial wastes

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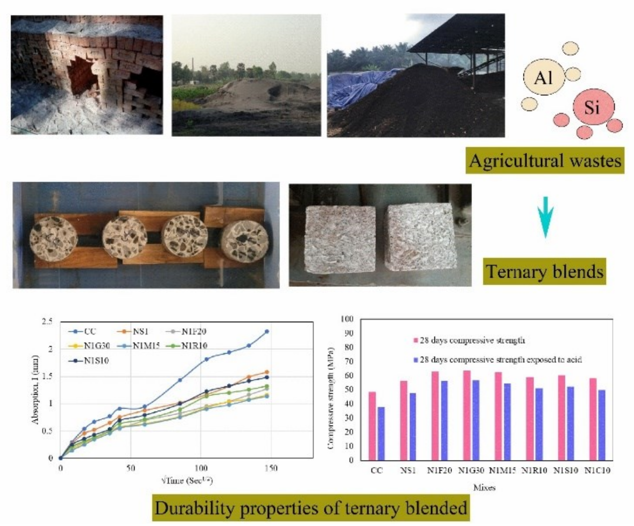
Graphical abstract



Abstract

The demand for sustainable concrete in civil infrastructure operations grows by the day, resulting in the use of agricultural and industrial byproducts and controlling high-cost nanomaterials. Ternary blended concrete is an excellent alternative to conventional concrete for long-term development by lowering carbon footprint. Ternary blended concrete is a green and sustainable concrete made from three separate source components to make a binder. The fundamental benefit of ternary mixed concrete is its densely packed particles of various shapes and sizes, resulting in superior characteristics. This study discusses experimental studies that were conducted to assess the durability properties of regular ordinary Portland cement (OPC) concrete and ternary blended concrete containing 1% nano-SiO_2 and industrial or agricultural byproducts. Six potential mixes were investigated in this work: three blends based on industrial byproducts (fly ash, ground granulated blast furnace slag, and metakaolin) and three mixes based on agricultural byproducts (rice husk ash, corncob ash, and sugarcane bagasse ash). This study investigated the durability characteristics such as water permeability, sorptivity, resistance to sulphate, acid attack, and alkaline attack. The experimental test findings were determined to be well within limitations when compared to the requirements specified in the standard/literature. The study also shows that ternary blended concrete with regulated nano-SiO_2 enhances durability metrics significantly. Furthermore, energy dispersive spectrophotometry (EDS) measurements show dense phases with high proportions of Si atoms in the substrate's penetration layer, and synergic effect between the ternary pozzolanic materials. As a result, ternary mixed concrete is strongly advised in structural repair works.

Keywords: Nano-SiO_2, durability, permeability, pozzolanic reaction.

1. Introduction

Cementitious materials continuing success as a building material for various infrastructure restoration and construction is due to its superior durability, strength, and adaptability when compared to steel and other composites (Amran *et al.* 2022, Chaitanya *et al.* 2023; Varma *et al.* 2023). Furthermore, the basic ingredients utilised to manufacture cementitious composites are generally inexpensive and widely available. However, the exposure of cementitious composite structures to various harsh environments has highlighted the need to improve the durability characteristics of these materials. The advancement of cement-based materials science has resulted in numerous improvements to the performance of cement composites (Ferrerira *et al.* 2017; Mohan *et al.* 2023; Raju *et al.* 2023). The usage of nanoparticles has lately attracted attention as an efficient strategy for improving the performance of cementitious composites. Nanomaterials are materials with dimensions ranging from 0.1 to 1.0 nm. The increased durability of cementitious composites including nanoparticles can be attributed to their tiny size, which alters the nano and morphology of the composite (De Souza *et al.* 2022; Salami *et al.* 2023). Furthermore, nanoparticles utilised in cementitious composites have pozzolanic capabilities, which result in increased product production and microstructure densification (Cerro-Prada *et al.* 2018; Dong *et al.* 2020). The reactivity of nanomaterials with calcium hydroxide in concrete pore fluids resulted in the creation of additional calcium silicate hydrate. In the presence of nanomaterials, the hydration reaction of cement was also accelerated, resulting in the creation of additional calcium hydroxide (Shaik and Supit 2015; Rao *et al.* 2023). The increase in hydration product creation can be attributed to nanoparticles acting as a nucleation region for hydration product formation due to their large surface area. Several other investigations have found that adding nanoparticles into cementitious composites promotes calcium hydroxide production, particularly at an initial age (Liu *et al.* 2015; Francioso *et al.* 2019). The creation of silica chains of various lengths in cementitious composites due to nanoparticles has also been reported to boost the composites' resilience to chemical attacks (Praveen *et al.* 2013). In addition to the increased durability of cementitious composites linked with the use of nanoparticles, the use of nanomaterials has been shown to reduce cement content. Using roughly 1 kg of nanomaterials, for example, will result in a reduction of about 4 kg of cement to attain improved characteristics (Nazari and Riahi 2011). Although there are many other types of nanomaterials for different uses, the most prevalent ones employed in cementitious composites are nano-SiO_2, and nano alumina. Tabish *et al.* (2022) found that introducing nano-SiO_2 and nano clay at a low dose improved the permeability qualities of concrete mixtures significantly. The introduction of nanoparticles improves the durability properties of cementitious composites due to the nanomaterials' pore filling and nuclei stimulating capabilities. Despite the benefits of employing nanoparticles in cementitious composites, it is critical to ensure that they are well disseminated in the mixtures when they are utilised. It has been discovered that incorrect dispersing of nanomaterials in cementitious composites results in the formation of weak regions and voids in the cementitious matrix (Alisha *et al.* 2023; Raju *et al.* 2023). The cementitious composites' durability performance was investigated in terms of permeability and resistance to physical and chemical attacks by many researchers (Al Fakih *et al.* 2021; Divya *et al.* 2022).

Nuaklong *et al.* (2018) looked into how nano-SiO_2 affected the characteristics of fly ash cement concrete. It was observed that the addition of nano-SiO_2 increased the chloride permeability and electrical resistivity of fly ash cement concrete. Oltulu and Sahin (2013) investigated the durability of concrete containing nano-SiO_2. The depth of water penetration was reported to be 56% lower in the 0.3% nano-SiO_2 mixtures compared to the control mix (without nano-SiO_2). The addition of nano-SiO_2 improved the properties of concrete by refining the pores through the filling action and by the pozzolanic reaction, which occurs between nano-SiO_2 and $Ca(OH)_2$ resulting in supplementary C-S-H gel, which enhanced the pore structure and resulted in a dense and homogeneous concrete. Hwang *et al.* (2022) investigated the influence of colloidal nano-SiO_2 on the immobilisation of chloride ions in fly ash blended cement concrete. The immobilisation of chloride caused by the use of nano-SiO_2 can be attributed to the improvement of pore structure caused by the creation of extra calcium-silicate-hydrate. Golewski (2022) investigated the influence of nano-SiO_2 on a ternary system composed of rice husk ash, silica fume, and Portland cement. It was discovered that quaternary combinations including nano-SiO_2 had the highest compressive strength and the smallest mean pore diameter. In the quaternary system, the synergistic impact of nano-SiO_2 has been reported to be advantageous. Khaloo *et al.* (2016) explored into the impact of nano-SiO_2 on the qualities of high-performance concrete. The properties of ultra-high-performance concrete with 0.5-2.0% colloidal nano-SiO_2 were studied. It was observed that adding colloidal nano-SiO_2 to concrete increased its mechanical qualities and durability. It was also discovered that colloidal nano-SiO_2 had a stronger influence in low water-cement ratio combinations than in high water-cement ratio mixtures. Zidi *et al.* (2021) investigated the characteristics of metakaolin and nano-SiO_2 concrete. Concrete with 10% metakaolin and 1% nano-SiO_2 was found to have the best mechanical qualities and durability.

This paper explores the extension of the previous work (Venkat *et al.* 2023), by performing the durability of the ternary blended concrete keeping nano-SiO_2 as 1%.

2. Methodology

2.1. Materials

In this investigation, conventional Portland cement (IS 53 grade) of Ultra Tech brand, industrial by-products (fly ash, metakaolin, powdered granulated blast furnace slag), and nano-SiO_2 were procured from the commercial market in Vijayawada, India. Agricultural ashes were sourced locally from industrial boilers. The chemical and physical features of the raw materials were emphasised in previous work (Venkat *et al.* 2023). In addition to cementitious ingredients, locally accessible coarse and fine aggregates were used as filler components in concrete. Based on the earlier study reported by Venkat *et al.* (2023), optimum mixtures were examined in this examination to compare the durability performance of ternary blended concrete.

2.2. Test procedure

Sorptivity is a measurement of the capillary force imparted by the innermost layer of concrete, allowing fluid to be absorbed into the material's core. It is determined as the rate of capillary rise absorption by a specimen of concrete submerged in water for 2 to 5 mm. Samples were tested according to ASTM C1585-2004 (Mehta and Siddique 2018). The specimens were preconditioned in an oven at 50°C for seven days. The samples were then removed and chilled to room temperature. Insulation tape was used to seal the sides of the samples completely. The original weight of the sample was recorded, and it was then placed in a tray with water to a depth of 5-10 mm. As illustrated in Figure 1a, the samples were positioned over supports to guarantee unidirectional water flow. The samples were taken out of the water regularly and weighed after the extra water was blotted out. The samples were then immersed in water once again. The gain in weight per surface area over the density of water was plotted against the square root of time.

The samples were tested for effectiveness in various settings, including sulphates, acidic, and alkaline conditions (see Figure 1b). After 28 days of water curing, the samples were submerged in a 5% H_2SO_4 solution for 30 days. After 30 days, the specimens were removed from the solution, and the % mass loss and compressive strength were calculated. Other series samples were similarly subjected to 5% 8M NaOH solution and 5% sulphates. Furthermore, with a scanning electron microscope, EDS analysis was performed on hardened fragments in cement paste slices for all concrete mixtures. The elements that make up the actual composition of the specimen under study are represented by peaks in the spectra produced by the EDS examination. It is also feasible to perform image analysis and mapping of the elements of a sample. The method can yield the spatial distribution of the components through mapping. Because the EDS approach is non-destructive, more sample preparation is needed to study important specimens in-situ.

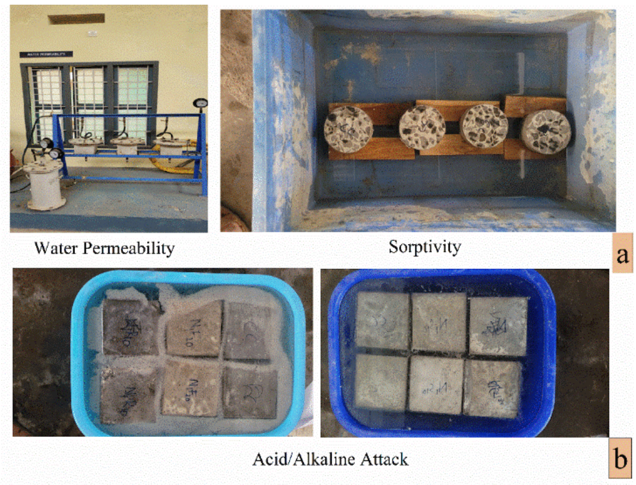


Figure 1. (a) Permeability and sorptivity test (b) acid/alkaline attack

3. Results and discussion

3.1. Water permeability

The findings of the water permeability test are shown in Figure 2. The figure demonstrates that the conventional OPC concrete (CC) and the 1% nano-SiO_2 blended concrete (NS1) had the highest water permeability. Furthermore, water permeability of ternary blended concrete specimens containing 1% nano-SiO_2 with 20% fly ash (N1F20), 1% nano-SiO_2 with 30% GGBS (N1G30), and 1% nano-SiO_2 with 15% metakaolin (N1M15) is less than 15%, which is well below the permissible value of 20% for good concrete. In addition, nano-SiO_2 reduces water permeability in ternary blended concrete samples. The addition of nano-SiO_2 and other micro-additives gradually lowered the water permeability of the concrete. The capacity of incredibly fine particles of fly ash, slag, and metakaolin to create an extraordinarily dense matrix. Because of the high fineness of the source substances, no bleed-water became lodged beneath the large aggregate particle, and porosity was decreased.

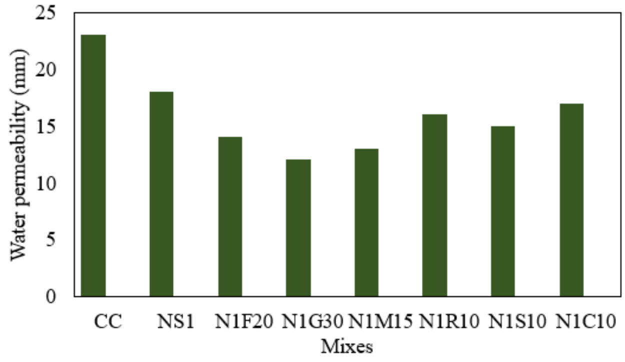


Figure 2. Variation of water permeability with different ternary blended mixes

3.2. Sorptivity

Figure 3 depicts the results of the sorptivity test. The figure shows that the values are well within the range of 0.09-0.17 mm/min for concrete. The results clearly demonstrate that adding agricultural or industrial by-products, combined with 1% nano-SiO_2, lowered the sorptivity value, indicating an improvement in the dense phases of the concrete. Ternary blended concrete has lower sorptivity coefficients than OPC concrete (CC) and 1% nano-SiO_2 concrete (NS1). The lowest sorptivity coefficient is found in ternary blended concrete containing 15% metakaolin. The improvement in sorptivity over TGPC samples is around 11%.

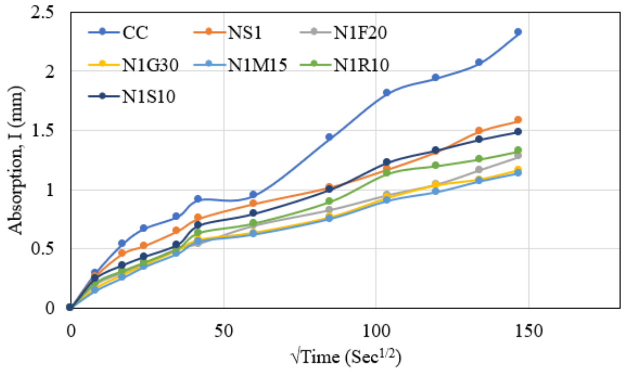


Figure 3. Sorptivity results of different ternary blended mixes

3.3. Mass loss and compressive strength

The first stage of measuring damage caused by an acid attack is done visually by analyzing colour changes, deposition of new components on the surface, surface fissures, and sample spalling. The samples were found to be structurally sound. The specimens' surfaces softened slightly but could not be easily scraped with fingernails.

Table 1 shows the samples' weight loss due to various environmental exposures. The ternary blended concrete samples lost less mass than OPC concrete (CC) and binary concrete with 1% nano-SiO_2. The rate of deterioration for agricultural-based ternary blended concrete is higher than for industrial by-products based on acid solution, but it is well within limits. This could be owing to the decreased concentration of reactive components in the concrete, which slows the deterioration process more than standard concrete.

Table 1. Mass loss of the specimens exposed with sulphate, acid, and alkaline environments

Mix	Percentage mass loss with various exposure conditions		
	Sulphate	5% H_2SO_4	5% NaOH
CC	2.01	3.36	1.39
NS1	1.01	2.97	0.99
N1F20	0.51	2.13	0.37
N1G30	0.37	1.84	0.25
N1M15	0.62	1.99	0.49
N1R10	0.88	2.46	0.74
N1S10	0.61	2.33	0.61
N1C10	0.89	2.52	0.89

The samples with the lowest weight decrease values had 1% nano-SiO_2 and industrial by-products, demonstrating that industrial by-products are possible under all environmental exposure circumstances. The compressive strength of conventional and binary concrete samples is lower (Figures 4–6). The immersion in the acid medium reduces the strength of all concrete samples. The reduction in strength loss could be attributed to the combined effect of nano-SiO_2 and agricultural or industrial source materials with varying particle sizes, which resulted in a denser concrete medium.

Sulphate solution was used to immerse the samples. It is apparent that the samples were physically intact and showed no signs of degradation. This could be due to the source material's low calcium level, which causes concrete breakdown.

The test results show that ternary blended concrete has excellent control over durability characteristics. This demonstrates that the presence of different sizes of binders and their packing has the greatest influence on the durability attributes of ternary blended concrete.

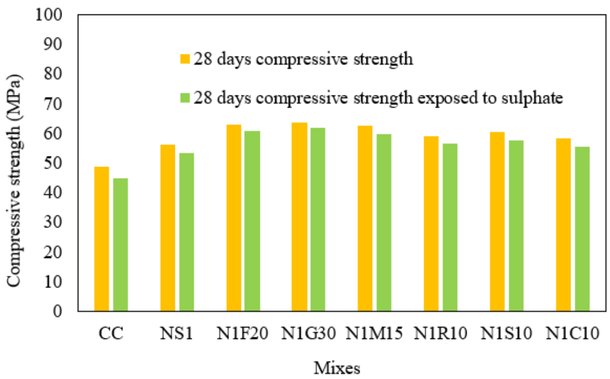


Figure 4. Compressive strength variations with sulphate attack

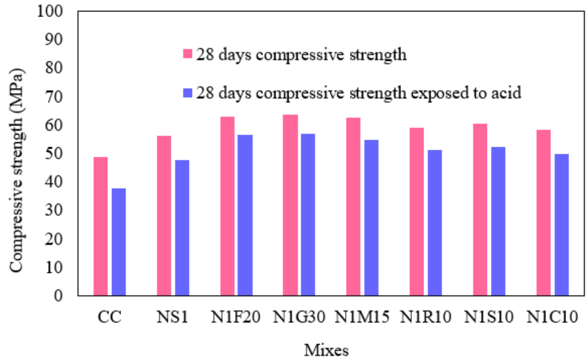


Figure 5. Compressive strength variations with acid attack

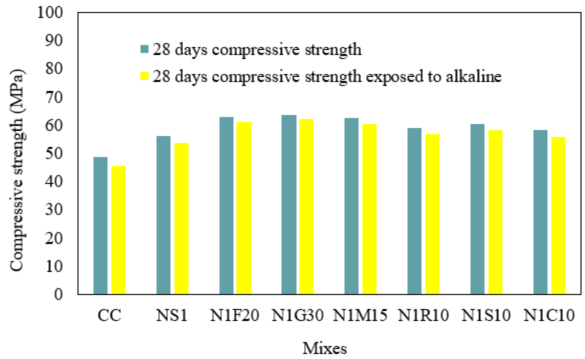


Figure 6. Compressive strength variations with alkaline attack

3.4. Microstructural behaviour

EDS analysis on paste samples was utilized to examine the microstructure of all the mixtures employed in this study, as shown in Figure 7. To understand the formation and enhancement of the microstructure of cementitious pastes, EDS analyses were done on SEM micrographs at various magnification levels for the optimum mixes of NS1, N1G30, and N1S10. The Ca/Si ratio from EDS analysis was computed for each mix to comprehend the phases further. Previous research on cementitious mixes discovered that the Ca/Si ratio for the C-S-H phase varies from 1 to 2 (Kapeluszna *et al.* 2017). In contrast, a Ca/Si ratio larger than 2 indicates the presence of C-S-H phases in the paste sample. According to the EDS results, the NS1 mix has a greater Ca/Si ratio than the other ternary blended concrete mixes. This is owing to the higher fineness and superior pozzolanic characteristics of both GGBS and sugarcane bagasse ash which induce densification of the paste matrix due to the development of high-density C-S-H and C-H phases. These findings demonstrate the formation of the microstructure as a result of the integration of GGBS and its blend with nano-SiO_2 in the cementitious matrix. The production of typical high-density C-S-H and C-H phases induces densification and refinement of the microstructure, resulting in improved performance in actual engineering applications.

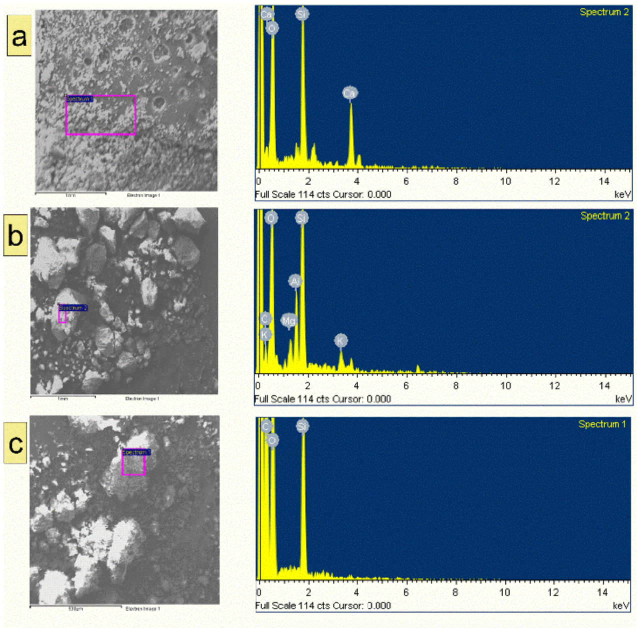


Figure 7. EDS of concrete samples (a) NS1, (b) N1G30, (c) N1R10

4. Conclusions

Based on the experimental findings, the following conclusions can be drawn from the durability characteristics of ternary blended concrete containing 1% nano-SiO_2 and the optimum dose of agricultural or industrial by-products.

1. The water permeability values of ternary blended concrete samples were less than 15%, significantly lower than the normal value. Adding extra admixture to 1% nano-SiO_2 content boosted water absorption by more than 35%.
2. The findings of ternary mixed concrete sorptivity tests show that the capillary pressure exerted by the pore structure is significantly lower. With the addition of 30% GGBS content to the ternary mix, the maximum improvement in sorptivity was around 15%.
3. Chemical attack results demonstrate that ternary blended concrete samples were more resistant than conventional and binary concrete samples. The effects of weight loss and compressive strength indicate that ternary mixed concrete, including agricultural or industrial by-products, performed better in all circumstances.
4. The production of high-density C-S-H and C-H phases was also seen in EDS analysis by adding agricultural or industrial by-products containing 1% nano-SiO_2, which induced microstructure densification.

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