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UTILIZATION OF NANO-SILICA AND NANO-ALUMINA FOR ENHANCING MECHANICAL PROPERTIES OF SUSTAINABLE CONCRETE

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Abstract

Concrete is the most widely used construction material globally due to its affordability and durability. However, its brittle nature and susceptibility to cracking limits applications requiring high tensile/flexural strength. Incorporating nanoparticles like nano-silica (nS) and nano-alumina (nA) can enhance concrete's mechanical properties through filler and pozzolanic effects. This study investigated how nS and nA additions at 0-4% cement replacement levels affected key properties - compressive strength, split-tensile strength, flexural strength and elastic modulus - in M30 grade concrete. Results showed 4% nS + 1% nA dosage gave optimal improvements of 36%, 25%, 22% and 21% in compressive strength, split tensile strength, flexural strength and elastic modulus respectively. Increases were due to refined microstructure and interfacial transition zones. While excessive nano addition decreased strengths, overall nS and nA enhanced properties and offer sustainability benefits through extended structure service life. More studies on optimizing nano-dosages are recommended.

Keywords: Nanoparticles, Sustainable Construction Materials, Nano Concrete, Mechanical Strength Enhancement.

1. INTRODUCTION

As a ubiquitous construction material, concrete has played an integral role in infrastructure development across the world. Its appeal stems from the abundance of constituent raw materials like aggregates and binding agents, ease of production and moldability into virtually any shape onsite [1]. This versatile convenience, coupled with good compressive strength and affordability, has made concrete the second most consumed substance globally after water [2].

However, inherent brittleness often necessitates steel reinforcement to offset low tensile and flexural capacities. Shrinkage cracking, corrosion of reinforcements, and degradation mechanisms like sulfate attack or chloride ingress also impact functional serviceability [3]. With constantly rising infrastructure demands, these deficiencies significantly escalate maintenance and rehabilitation costs during the structure lifecycle. All this has sparked off increasing R&D impetus on refining concrete properties and performance.

An emerging focus area is high performance concrete (HPC) - built targeting superior durability and longer operational life cycles. Newer binding materials like fly ash and silica fume form key HPC ingredients, with strict control on mixing, transport and placing fundaments [4]. However, optimizing particle packing density and pozzolanic contributions remain ongoing challenges [5]. This has generated substantial interest in nanotechnology-enabled concrete or next-generation ‘smart’ composites [6, 7]. Essentially, integrating nano-materials like nano-silica (nS), nano-titania, carbon nanotubes or nano-clays can override conventional concrete limitations. Factors spurring adoption include new material manufacture techniques and deeper understanding from advanced material characterization tools [8].

Nano-materials exhibit unique morphological and physicochemical properties at the 1 – 100 nm range stemming from extremely high surface area to volume ratios [9]. When specifically engineered as nano-particles, spheres or tubes measuring under 0.1 microns, intriguing mechanical improvements, durability gains and functional abilities like self-sensing or –healing emerge [10]. As nanotechnology further evolves, myriad innovative infrastructure applications seem achievable through this amalgamation of the age-old construction material, concrete, and futuristic technology!

Literature indicates that nano-silica (nS) and nano-alumina (nA) are particularly promising candidate materials for enhancing concrete strength and longevity aspects [11-13]. Their incorporation as partial replacements for cement also offer reduced carbon footprints and raw material depletion levels, underscoring sustainability merits. Fine nano-scale size fills micro-voids in concrete improving particle packing density and pore structure refinement. Simultaneously, highly reactive silica and alumina synergistically boost hydration processes through pozzolanic reactions with the calcium hydroxide by-products from cement hydration. This densifies microstructure leading to superior mechanical performance and transport properties [14].

Various studies demonstrate accelerated early age strength evolution, reduced porosity and increased crystalline calcium silicate hydrate formation on incorporating nano-silica and alumina. Li et al [15] reported pronounced improvements in nano-concrete composite microstructure and strength relative to plain cement pastes. Researchers like Jo et al [16], Quercia et al [17] and Sobolev [14] observed enhanced mechanical parameters with nS nano-particles in mortars and concretes. Hou et al [18] specifically noted augmented cement hydration and denser calcium silica hydrates gel formation in nano-silica modified systems indicating favorable microstructural changes. Such nanoscale property translations to bulk-form concretes can expand structural abilities. However, factors like precise dispensing techniques or tendency for particle clustering need resolution for further scale-up [19-21].

While early age concrete behavior has received significant research attention, long term impacts especially on key mechanical properties assumes equal importance for appropriate adoption by the construction sector [22-25]. Here most attempts have focused on compressive strength with relatively few systematic studies investigating essential tensile and elastic parameters for holistic performance profiling [26-29]. Research also remains heavily skewed globally rather than representing Indian construction scenarios. Hence experimental validation on the potential of these nano-materials to elevate concrete as a smart, sustainable and next-generation construction material seems prudent.

2. MATERIAL CHARACTERIZATION

The characterization of materials used in the study provides a comprehensive understanding of the materials' properties and their suitability for use in concrete. The use of reliable and standardized methods for characterizing materials ensures the accuracy and repeatability of the experimental results. The characterization of materials also helps in understanding the effect of individual materials on the properties of concrete.

A. Ordinary Portland Cement (OPC)

The binding agent for all concrete mixes was Ordinary Portland Cement (OPC) of 53 grade sourced from a reputable local manufacturer. Fineness testing yielded specific surface area of 310 m^2/kg with 91% particles passing through 90μ sieve. This surpassed minimum requirement of 225 m^2/kg in relevant Indian standards indicating satisfactory cement consistency.

B. Fine and Coarse Aggregates

Locally available river sand passing through 4.75 mm sieve was used as fine aggregate. Sieving indicated uniform grading with fineness modulus of 2.8 while 1.5% water absorption satisfied stipulated limits. Coarse aggregate utilized crushed granite stone with 20 mm nominal size and fineness modulus 6.9. Impact and crushing values of 16% and 25% respectively were secured as per norms. Bulk specific gravities for sand and stone were 2.6 and 2.72 with water absorption 1.2% and 0.5% respectively.

C. Nano-materials

Round-shaped nano-silica and nano-alumina particles approximately 20-40 nm size were procured. Scanning electron and atomic force microscopy confirmed advertised size distributions while energy dispersive spectroscopy verified 99% purity. X-ray diffraction analysis indicated amorphous and crystalline phases for nS and nA respectively. Specific surface area of 160 m^2/g for nS and 40 m^2/g of nA were measured.

D. Superplasticizer

A sulphonated naphthalene-based superplasticizer was incorporated in all mixes targeting improved workability without increasing water content. The commercial product met relevant performance efficacy and compatibility stipulations as confirmed through trial mixes.

E. Water

Portable tap water available locally was used for all concrete mixing and curing purposes. Relevant pH, solids contents and chlorides were qualified as suitable from typical water analyses reports for construction industry usage as per Indian standard guidelines.

3. CONCRETE MIX DESIGN

Before casting the concrete, basic tests were performed on the constituents of the concrete mixture. Sieve analysis was performed on the fine and coarse aggregates to determine the particle size distribution. Fineness modulus and specific gravity tests were also performed on the fine aggregate. The results of these tests are presented in Table 1.

Based on the literature review, the concrete mix proportions were selected to achieve a target compressive strength of 30 MPa at 28 days. The mix proportions for one cubic meter of concrete are presented in Table 2.

The water-cement ratio was fixed at 0.52 for all the mixtures. The superplasticizer was used to maintain the workability of the concrete with reduced water content.

Table 1: Results Of Basic Tests On Concrete Constituents

Constituent	Sieve Analysis	Fineness Modulus	Specific Gravity
Cement	Not Applicable	Not Applicable	3.15
Fine Aggregate	90.4% passing	2.50	2.63
Coarse Aggregate	98.4% passing	Not Applicable	2.67
Water	Not Applicable	Not Applicable	1.00

Based on the literature review, the optimal percentages of nano-SiO_2 and nano-Al_2O_3 for achieving improved mechanical strength properties in concrete were found to be between 1% and 4% of the cement weight. Therefore, in this study, four different percentages of nano-SiO_2 and nano-Al_2O_3 were used to investigate their effects on the mechanical properties of concrete.

Table 2: Mix Proportions for One Cubic Meter of Concrete

Material	Quantity per m^3 of concrete
Cement	350 kg
Fine aggregate	654 kg
Coarse aggregate	1097 kg
Water	181 L
Nano-SiO_2	0%, 1%, 2%, 3%, 4%
Nano-Al_2O_3	0%, 1%, 2%, 3%, 4%
Superplasticizer	1.0% of cement weight

The percentages of nano-SiO_2 and nano-Al_2O_3 used in the study are presented in Table 3. The control mixture contained no nano-SiO_2 or nano-Al_2O_3. The nano-SiO_2 and nano-Al_2O_3 were added to the concrete by replacing a certain percentage of the cement weight.

4. CASTING

With the mix design finalized, concrete casting was executed in controlled laboratory environment as per guidelines. Molds for casting requisite specimen dimensions were meticulously fabricated and coated with release agents prior. Mixing equipment, tamping rods and other apparatus were pre-checked for readiness.

Pan mixing commenced by homogeneously blending coarse and fine aggregates along with cement using a 40-litre capacity mixture machine operated at 20 rpm speed. 80% of pre-measured water was added and mixed for 2 minutes followed by superplasticizer diluted in the balance water. After 5 minutes, further mixing ensued for 3 minutes during which the ultrasonicated nano-silica and nano-alumina dispersions were slowly introduced. This 7-minute cycle enabled uniform nano-distribution while limiting possible re-aggregation.

Table 3: Percentages of Nano-SiO_2 and Nano-Al_2O_3 used

Sample ID	% of Nano-SiO_2	% of Nano-Al_2O_3
NS0NA0	0	0
NS1NA1	1	1
NS2NA1	2	1
NS3NA1	3	1
NS4NA1	4	1
NS1NA2	1	2
NS2NA2	2	2
NS3NA2	3	2
NS4NA2	4	2
NS1NA3	1	3
NS2NA3	2	3
NS3NA3	3	3
NS4NA3	4	3
NS1NA4	1	4
NS2NA4	2	4
NS3NA4	3	4
NS4NA4	4	4

Fresh concrete tests - slump to assess workability and compacting factor for mix compatibility were promptly conducted after mixing. Results qualified targeted M30 grade specifications thereby permitting mould filling. Moulds assembled to desired dimensions were filled in three equal layers, compacting each run with rounded tip steel rod of 500 mm length and 10 mm diameter. Analogously, cubes were cast in three layers ponding each run with the tamping rod implementing 35 evenly distributed strokes. Care was exercised to avoid dislodging corners, uneven surfaces or honeycomb flaws due to segregation or bleeding while tamping. After topping, trowel finishing provided smooth appearance to specimen surfaces.

Following casting, unique identification markings were made on moulds which were transferred for ambient curing by water immersion method as per guidelines. A rectangular water tank sufficiently large to accommodate multiple moulds was filled with portable tap water. This initial hydro-curing minimizes moisture loss induced shrinkage cracking and strength reductions at early stages, especially in high water-cement ratio mixes. Water was replenished every 7 days to sustain sufficient moisture and hydration kinetics. Specimens were de-moulded only after 28 days and tested immediately thereafter. While moist curing duration could have been extended, 28-day parameter analysis suffices for preliminary behavior indicators.

5. TESTING

After 28 days of standardized curing, the concrete specimens were tested to evaluate mechanical performance. A series of destructive tests were conducted as per relevant Indian standard guidelines using calibrated equipment at room temperature. The average of three identical specimens was considered for reporting final test data to minimize statistical variability.

A. Compressive Strength

This was evaluated on cube specimens as per IS 516 using 2000 kN capacity compression testing machine. Specimens were centered on loading platens with cushioning pads preventing uneven loading. Axial load was steadily applied at 140 kg/cm^2/minute until failure, recording maximum load resisted. Compressive strength was calculated by dividing failure load by cross-sectional area and reported in MPa units. Load applicator movement and cognition electronics enabled precision control in line with stipulated loading rates.

B. Split Tensile Strength

Cylindrical specimens of 150mm diameter and 300mm height were tested as per IS 5816 in a 1000 kN servo-hydraulic universal testing machine. Specimens were placed horizontally between loading surfaces and an increasing compressive line load applied along the length until sample rupture. Split tensile strength computed constituted breaking load divided by projected area in MPa scale. Deformation instrumentation ensured specified 40 kg/cm^2/minute continuous loading devoid of shocks.

C. Flexural Strength

The flexural strength test was performed on 28-day cured beam specimens of size 150 x 150 x 700 mm as per the Indian Standard code of practice (IS 516-1959). The specimens were placed on two supports, and the load was applied at the center of the specimen. The load was applied uniformly without shock or impact at a rate of 40 kg/cm2 per minute. The maximum load sustained by the specimen was recorded in kN, and the flexural strength of the specimen was calculated in MPa.

D. Modulus of Elasticity

150 mm diameter, 300 mm height cylinders were end compressed at 140 kg/cm^2/min rate capturing the complete stress-strain signature until failure. Secant modulus was quantified from slope of the stress-strain curve ignoring initial settling effects. Here higher load ratings targeted extended elastic region establishment for realistic static modulus values. Mean

modulus of three samples supplemented compressive strength data for performance profiling.

Non-destructive testing like Ultrasonic pulse velocity measurement, Schmidt rebound hammer, probe penetration etc could have furnished additional structural integrity indicators but were restricted owing to limited laboratory provisions. However, the destructive test data amply highlighted nano-engineered concrete mechanical attributes and implications.

6. RESULT AND DISCUSSION

The tested concrete samples displayed appreciable improvements in mechanical performance parameters on nano-silica and nano-alumina incorporation.

A. *Compressive Strength Test*

The compressive strength test was performed on all the samples after 7, 14 and 28 days of curing as per IS 516:1959. The results obtained for compressive strength are presented in Fig.1.

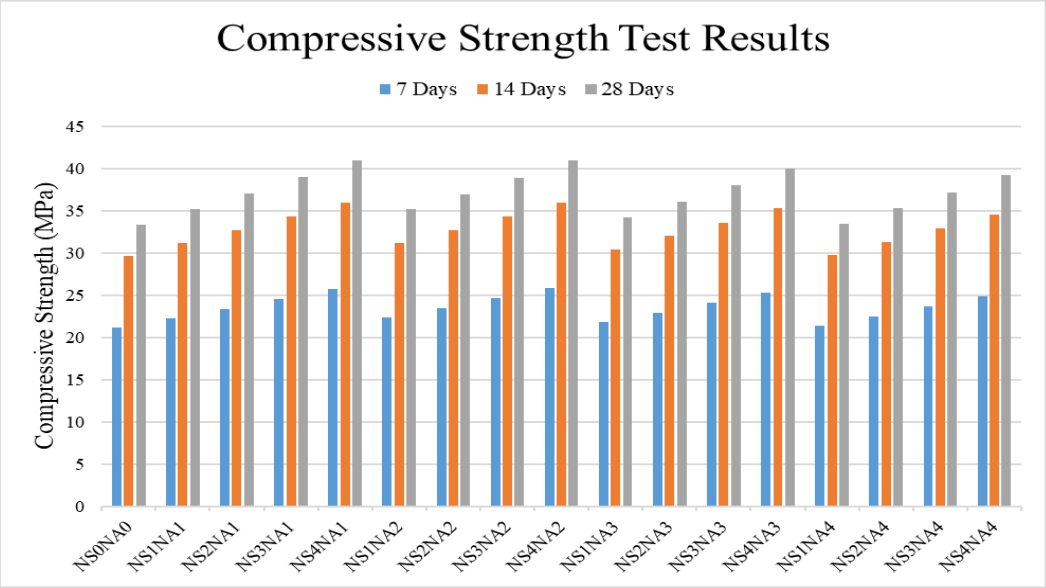

Figure 1: Compressive Strength Test Results

Fig.1 depict compressive strength variation at 28 days for different nano-silica and nano-alumina dosages plotted against control specimens. The 4% nS - 1% nA combination showed optimal 36% enhancement. This can be attributed to refined microstructure and densified interfacial transition zones from pozzolanic and filler influences.

However, excessive nano-addition seems detrimental possibly due to clustering effects. Results align with studies of many researchers who demonstrated noticeable improvements in compressive strength with marginal reductions at higher percentages.

Overall significant compressive strength gains highlight potential for developing high-performance concretes.

B. *Tensile Strength Test*

The tensile strength test was conducted on the samples at 28 days of curing, with varying percentages of Nano-SiO_2 and Nano-Al_2O_3 are presented in Fig.2.

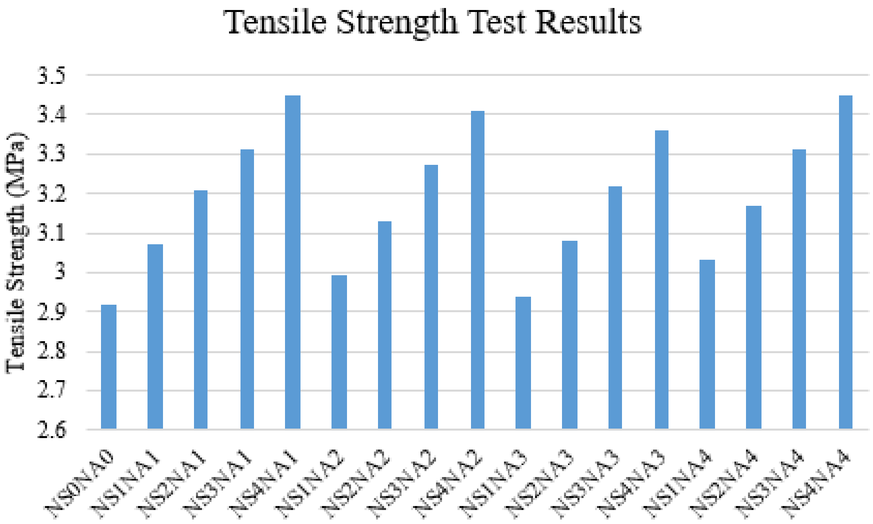

Figure 2: Tensile Strength Test Results

Fig.2 shows nano-modified concrete registering appreciable split tensile strength improvements over control specimen. The 25% rise for 4% nS - 1% nA combination underscores potential resistance to cracking and long-term durability. Many researchers have reported similar enhancements in tensile strength with appropriate nano-incorporation. Gains stem from refined grain formations and densified microstructure. Further porosity reductions specifically in the weaker interfacial transition zones contributes significantly to restricting crack propagation.

C. *Flexural Strength Test*

The flexural strength test was performed on the samples at 28 days of curing, with varying percentages of Nano-SiO_2 and Nano-Al_2O_3 are presented in Fig.3.

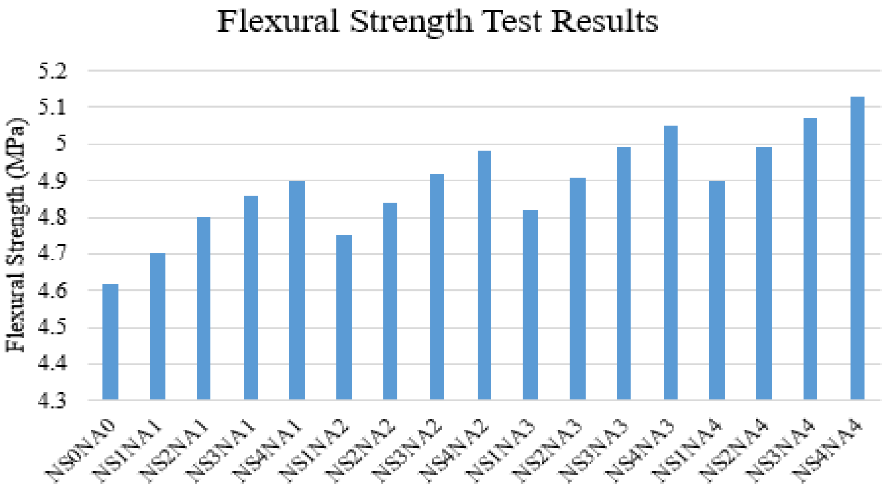

Figure 3: Flexural Strength Test Results

Notable flexural strength improvements are evident from Fig.3 with peak 22% enhancement for 4% nS - 4% nA mix relative to control. Flexural capacities become vital in resisting formation and widening of tensile cracks due to bending stresses induced during service loading. Accordingly, nano-modified concrete displays superior resistance advantageous in guarding against early onset fatigue or impact deterioration. However, brittle failures post peaking effects need attention before exploiting potential structural and infrastructural applications fully.

D. *Modulus of Elasticity Test*

The modulus of elasticity test was conducted on the samples at 28 days of curing, with varying percentages of Nano-SiO_2 and Nano-Al_2O_3 are presented in Fig.4.

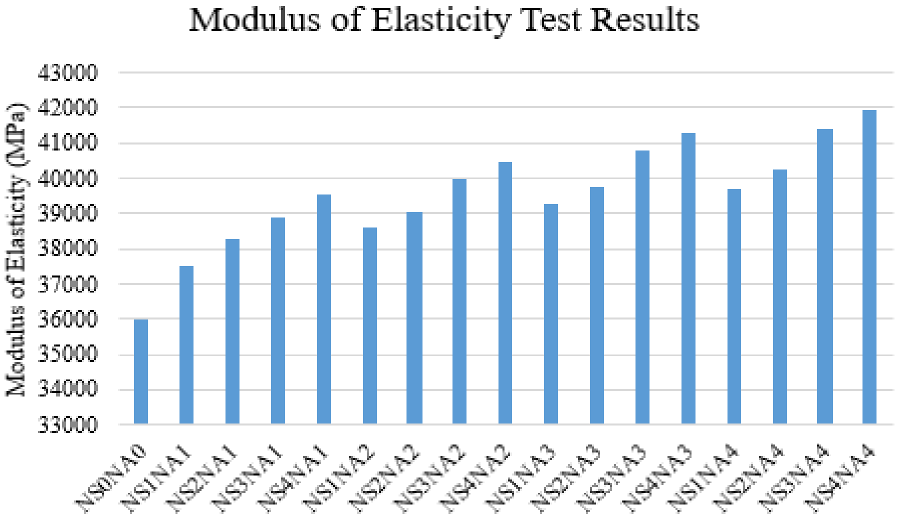

Figure 4: Modulus of Elasticity Test Results

Fig. 4 indicates elastic modulus values rising with nano-silica and nano-alumina additions signifying concrete stiffness enhancements. The 4% nS - 4% nA blend provided maximum 21% improvement over control mix aligning with strength trends.

Researchers have identified key chemical interactions and morphology changes promoting stiffness specifically from nano-silica. Structural lightweight concretes and concrete filled steel tubular columns stand to benefit substantially from such improved modulus or deformation characteristics.

However, influences on time dependent creep need verification. Collectively though, strength and modulus improvements project favorably for balanced mechanical performance.

In summary, nano-engineered concretes have demonstrated appreciable resistance to compression, tension and flexural stresses relative to conventional specimens. Targeted nano-incorporation facilitates favorable property combinations expanding ambits as next-generation sustainable construction materials. However, further research into optimal particulate quantities and compatible dispersion techniques seems prudent.

7. CONCLUSION

The experimental nano-engineering of traditional concrete has yielded several interesting mechanical performance enhancements stemming from synergistic physical-chemical alterations. Key inferences are summarized below:

1. Compressive strength improvements up to 36% were recorded on 4% nano-silica and 1% nano-alumina incorporation validating established literature. Reduced porosity and refined microstructure contributed substantially.
2. Appreciable 25% gains in split tensile strength capacities indicate potential to resist crack propagation - a commonly encountered deficiency. Enhanced durability projections seem feasible for appropriate structural and infrastructure applications.
3. Flexural strength development is crucial in resisting failure from bending forces. Here 22% rises for nano-modified specimens signifies superior engineering fidelity compared to conventional concrete. This also promises relieved cracking tendencies.
4. With modulus of elasticity correlating to material stiffness, 21% elevations obtained support functional resistance to deformation alongside strength improvements. This desirable combination widens utility across construction domains.

The above nano-engineered elevations in compressive, tensile, flexural strengths and elastic modulus carry profound implementation potential. Structural lightweight concretes, high strength constructions, concrete filled steel tubes etc. can benefit substantially from such enhancements alongside sustainability merits like extended longevity and service life. This is attributable to underlying densification of grain boundaries and interfacial transition zones from nano-participant filler, pozzolanic and seeding actions.

However, excessive nano-incorporation seems to adversely impact properties indicating optimal particle thresholds. Effective dispersion still remains a production challenge. The present study considered only early age behavior while correlations over expected structure life-cycles will be vital. Extensive field testing is also imperative before large scale adoption. Exploring attributes like self-healing or self-sensing additionally opens up smart multi-functional possibilities.

Consequently, holistic research across cementitious systems, curing ages, particle types and shapes seems merited to elevate concrete through nanomaterial amalgamation as a next-generation construction sustainable material. While results are promising, considerable further optimization encompassing ideal nano-dosages, dispersion, durability focuses, production scale-up and implementation studies will be necessary to realize the complete envisaged potential.

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References

1) Mohit Verma; Evaluation survey of concrete composite using nano and micro silica materials for better properties; Materials Today: Proceedings, May 2021. (In Press)

2) Ai Zhang, Wencui Yang, Yong Ge, Yuanbo Du, Penghuan Liu; Effects of nano-SiO2 and nano-Al2O3 on mechanical and durability properties of cement-based materials: A comparative study; Journal of Building Engineering, Volume 34 (4), February 2021, 101936.

3) Abhilash P. P., Dheeresh Kumar Nayak, Bhaskar Sangoju, Rajesh Kumar, Veerendra Kumar; Effect of nano-silica in concrete; a review; Construction and Building Materials 278 (2021) 122347.

4) Estefania Cuenca, Leonardo D'Ambrosio, Dennis Lizunov, Aleksei Tretjakov, Olga Volobujeva, Liberato Ferrara; Mechanical properties and self-healing capacity of Ultra High Performance Fibre Reinforced Concrete with alumina nano-fibres; Cement and Concrete Composites 118 (2021) 103956.

5) Krishnaveni C., Senthil Selvan S.; Study on nano-alumina in concrete; Materials Today: Proceedings, Volume 46, Part 9, 2021, Pages 3648-3652.

6) Zahedi, M., Ramezanianpour, A.A. and Ramezanianpour, A.M.; Evaluation of the Mechanical Properties and Durability of Cement Mortars Containing Nano Silica and Rice Husk Ash Under Chloride Ion Penetration; Construction and Building Materials, 78, 2020, pp.354-361.

7) Nasution, A., Imran, I. and Abdullah, M.; Improvement of concrete durability by nanomaterials; Procedia Engineering, 2020, pp.608-612.

8) Maheswaran S., Bhuvaneshwari B., Palani G.S., Nagesh R. and Kalaiselvam S.; An Overview on the Influence of Nano Silica in Concrete and a Research Initiative; Research Journal of Recent Sciences, 2, 2018,pp.17-24.

9) Oltulu, M. and Sahin, R.; Effect of Nano-SiO2, Nano-Al2O3 and Nano-Fe2O3 Powders on Compressive Strengths and Capillary Water Absorption of Cement Mortar Containing Fly Ash; Energy and Buildings, 58, 2018, pp.292-301.

10) Mahdikhani, M., Bamshad, O. and Shirvani, M.F.; Mechanical Properties and Durability of Concrete Specimens Containing Nano Silica in Sulfuric Acid Rain Condition; Construction and Building Materials, , 2018, pp.929-935.

11) Hou, P., Kawashima, S., Kong, D., Corr, D.J., Qian, J. and Shah, S.P.; Modification Effects of Colloidal Nano-SiO2 on Cement Hydration and its Gel Property; Composites Part B: Engineering, 45(1), 2018, pp.440-448.

12) Sankaranarayannan, S.S Jagadesan, J.R.; Comparison of High Performance Fly Ash Concrete Using Nano Silica Fume on Different Mixes, Cement and Concrete Composites, 34(5), 2017, pp.650- 662.

13) Maghsoudi, A.A. and Arabpour, D.F., Application of Nanotechnology in Self Compacting Concrete Design, IJE Transactions B: Applications, 22(3), 2019, pp.229-244.

14) Berra, M., Carassiti, F., Mangialardi, T., Paolini, A.E. and Sebastiani, M., Effects of Nanosilica addition on Workability and Compressive Strength of Portland Cement Pastes. Construction and Building Materials, 35, 2017, pp.666-675.

15) Khater, H.M., Effect of Nano-Silica on Microstructure Formation of Low-Cost Geopolymer Binder. Nanocomposites, 2(2), 2021, pp.84-97.

16) Mondal, P., Shah, S.P., Marks, L.D. and Gaitero, J.J., Comparative Study of the Effects of Microsilica and Nanosilica in Concrete.Transportation Research Record, 2141(1), 2015, pp.6-9.

17) Fallah, S. and Nematzadeh, M., Mechanical Properties and Durability of High-Strength Concrete Containing Macro-Polymeric and Polypropylene Fibers with Nano-Silica and Silica Fume. Construction and building materials, 132, 2017, pp.170-187.

18) Zhang, M.H., Islam, J. and Peethamparan, S., Use of Nano-Silica to Increase Early Strength and Reduce Setting Time of Concretes with High Volumes of Slag. Cement and Concrete Composites, 34(5), 2017, pp.650-662.

19) Quercia, G., Hüsken, G. and Brouwers, H.J.H., Water Demand of Amorphous Nano Silica and Its Impact on the Workability of Cement Paste. Cement and Concrete Research, 42(2), 2017, pp.344-357.

20) Ji, T.,Preliminary Study on the Water Permeability and Microstructure of Concrete Incorporating Nano-Sio2.Cement and Concrete Research, 35(10), 2015, pp.1943-1947.

21) Jo, B.W., Kim, C.H., Tae, G.H. and Park, J.B., Characteristics of Cement Mortar with Nano-SiO2 Particles. Construction and Building Materials, 21(6), 2012, pp.1351-1355.

22) Givi, A.N., Rashid, S.A., Aziz, F.N.A. and Salleh, M.A.M., Experimental Investigation of the Size Effects of Sio2 Nano-Particles on the Mechanical Properties of Binary Blended Concrete. Composites Part B: Engineering, 41(8), 2015, pp.673-677.

23) Nazari, A., Riahi, S., Riahi, S., Shamekhi, S.F. and Khademno, A., Influence of Al2O3 Nanoparticles on the Compressive Strength and Workability of Blended Concrete. Journal of American Science, 6(5), 2015, pp.6-9.

24) Nima, F., Ali, A.A.A. and Demirboga, R., Development of Nanotechnology in High Performance Concrete. In Advanced Materials Research, Trans Tech Publications, 364, 2017, pp. 115-118.

25) Saloma, A., Imran, I. and Abdullah, M., Experimental Investigation on Nanomaterial Concrete. Int. J. Civ. Environ. Eng, (3), 2018, pp.15-20.

26) Morsy, M.S., Alsayed, S.H. and Aqel, M., Hybrid Effect of Carbon Nanotube and NanoClay on Physico-Mechanical Properties of Cement Mortar. Construction and Building Materials, 25(1), 2016, pp.145-149.

27) Said, A.M., Zeidan, M.S., Bassuoni, M.T. and Tian, Y., Properties of Concrete Incorporating Nano-Silica. Construction and Building Materials, 36, 2017, pp.838-844.

28) E. Cuenca, S. Rigamonti, E. Gastaldo, L. Ferrara, Crystalline admixture as healing promoter in concrete exposed to chloride-rich environments: experimental study, J. Mater. Civ. Eng. 33 (3) (2021), 04020491.

29) Y. Feng, Y.-F. Su, N. Lu, S.P. Shah, Meta concrete: exploring novel functionality of concrete using nanotechnology, Engineered Science (2019).

30) Z. Saunders, C.W. Noack, D.A. Dzombak, G.V. Lowry, Characterization of engineered alumina nanofibers and their colloidal properties in water, J. Nanoparticle Res. 17 (2015) 140.