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Application of Nano Silica in Cement-Based Materials - A Review

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Abstract— *Nanotechnology aids a lot to bind materials in the construction industry. Nowadays due to the emergent uses of abundant nanoparticles in buildings, an enhanced understanding of nanotechnology in cement-based materials is needed to assess. Among them, nano silica shows a dynamic role in cement-based materials. The content of this paper summarized the evidence from past published research related to this study area. In this paper, we briefly introduce the impact of nano-silica on cement-based materials and the challenges related to it. Nano silica can act as both filler and pozzolanic material. It is reported that the addition of nano-silica leads to a reduction in setting time; this is due to the hydration reaction which is achieved through the high action of nano-silica. The size of nano silica is influenced by its specific surface area. Due to its tiny particle dimension, it has an excessive specific surface area. A denser microstructure of cement paste is observed by the addition of nano silica. This has an improved effect on the durability of concrete. In the case of the mechanical properties of concrete, it should be recognized that nano-SiO2 displays a restricted improvement*.

Keywords— *Nano-silica, nanomaterial, mechanical properties, durability*.

I. Introduction

In the present world, commonly used building materials are cement and concrete, because of their exceptional individualities. Such as being defiant to water, simply design into various forms and sizes, inexpensive, and able to obtain readily. While the expansion of cement and concrete stuff is facing massive complications and tasks, they will continue to personate a substantial role in construction materials. Manipulation of cement and concrete has improved extensively owed to developing populations and organizations. Even though, the chief adhesive used in concrete is Portland cement; its production of it requires more energy and raw materials. The making of Portland cement influenced the release of CO_2 gas. It is observed that, during the formation of 1 ton of Portland cement, it emanates 0.8 tons of CO_2 gas. This represents 5%-7% of the whole CO_2 gas release. Hence, there is a necessity to build up several novels and substitute cement-based materials to minimize the release of CO_2 gas, energy intake, and raw materials throughout the production of cement. The discharge of CO_2 is controlled by numerous approaches. Such as geopolymer cement, the introduction of nano cement in concretes, usage of mixed cement, and also the properties of concrete are enhanced by the addition of nanomaterials into the concrete mix.

Nanotechnology helps a lot in binding materials in buildings [1]. It can change the properties of building materials mainly cement and concrete. After the growths in the region of nanoscience and nanotechnology, it is easy to realize the facts happening in cement and concrete. The values of utilizing nanotechnology in construction industries are low-priced, can be built quicker, harmless, and extra strong. Once the nano cement might be synthetic and managed, it will lead to the modernization of the building industry. So far functions and innovations of nanotechnology have brought new strength to cement-based materials [2].

The introduction of silica slag into cement and concrete dates back to 2001 [3]. The nature of nano silica is in the form of white powder with a soft texture. It is comprised of amorphous silica powder with high purity. The tiny particle size of nano silica gives rise to enhancement in its properties like huge specific surface area, tough surface adsorption, great surface energy, expert diffusion, and elevated chemical purity. In common micro silica is the precursor for the nano-silica (Fig. 1).

Nano silica has an altered hydrophilicity. Because of this nature, this can be in two various forms. They are hydrophilic nano silica and hydrophobic nano silica respectively. Hydrophilic nano-silica can undergo effective diffusion in water. This unique feature makes it easier to use in concrete. Nano silica has some better characteristics than silica fume. Such as greater thinness, certain surface area, and pozzolanic activity [4]. The improvement effect of nano silica was observed on mechanical [5] and durability properties [6] of ordinary and high-performance concrete.

Ma et al. [7] discovered that the formation of hydrated silicate gels (C-S-H) and ettringite crystal (Aft) increased gradually during the addition of nano silica. But the dose of nano silica should be inside a certain range. In recycled aggregates concrete, insertion of nano silica has the ability to improve the pore structure and also restrict the dispersion ability of chloride ions [8]. The early hydration of concrete is quickening through nano silica to the cement matrix. This is responsible for the initial strength of concrete [9].

The positive effects in nano silica modified concrete were discovered by Prashanth et al. [10]. They observed a reduction in concrete permeability. The interface is the weakest area in concrete which is located among the cement matrix and the aggregate. The enhancement in the interface strength and improvement in pores were observed due to the addition of nano silica, which effectively decrease the water permeability of concrete [11]. Development of interface strength in waste concrete and cement slurry were observed in prior studies which is results due to the formation of more dense gel materials, which is stimulated through the hydration reaction after the addition of silica [12,13].

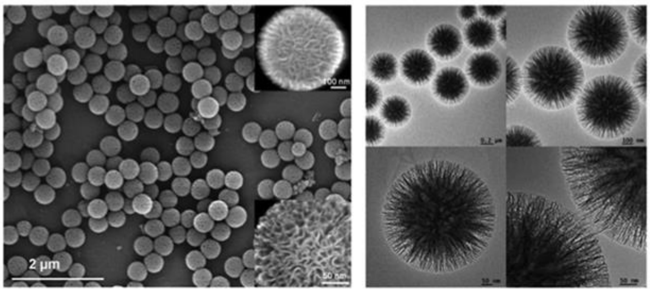

Fig. 1. FSSEM nano-silica image [13]

II. IMPACT OF NANO SILICA ON THE PROPERTIES OF CEMENT-BASED MATERIALS.

The impact of nano silica on the mechanical properties of concrete is studied by Singh et al. [14]. In his studies he used nano silica in two states, which includes colloidal and powdered forms. From his results he observed that in the presence of powdered nano silica there is some enhancement in the mechanical properties of concrete. The reason besides the improvement is, powdered nano silica will facilitate the formation of more C-S-H in cement paste. In previous studies it is observed that partial substitution of cement by nano silica influenced the pore volume of cement paste. And observed 13.4% of reduction in pore volume which is not adversely affects the porosity and penetrability of the paste [15].

The axial compressive properties of nano silica on reinforced concrete was studied by Chen et al. [16]. The concrete has packed round stainless-steel short columns. The extreme axial bearing capacity was observed when the amount of nano silica content was 1%. Another researcher Lin et al. [17], checked the correlation between the amount of freeze thaw cycles and the bearing capacity. Here they have used the circular nano-silica concrete which is packed with stainless steel tube stub columns. From the results they observed a small variation in the bearing capacity due to the number of freeze thaw cycles.

The influence of nano silica and high-volume slag mortar on cement's properties were studied by Zhang et.al [18]. They were replaced the weight of cement by 0.5 to 2% of nano silica. From the results they obtained they concluded that, the rate of hydration is proportional the quantity of nano silica. And also, they checked the impact of nano silica in the compressive strength of slag fillings. And they have found an increased compressive strength of slag mortars for the increased amount of nano silica. Along with this they also checked the effect of 2% of nano silica. And they obtained a deduction in both the initial and final setting time and rise in compressive strength.

Another researcher, Haruehansapong et al. [19], were changed both the weight percentage and particle size of nano silica in their experiments. Here they used 3, 6, 9 and 12 wt% of nano silica and 12, 20, 40 nm of particle size respectively. And they detected that the nano silica with 40nm size is more active rather than 12 and 20 nm sized nano silica.

The compressive strength of plain cement mortars were checked with the cement mortar with 9% of nano silica, and they obtained an increased compressive strength for 9% of nano silica which is 1.5 times greater than the plain cement mortars at 28 days. The ultra-high performance concrete using nano silica was made by Ghafari et al. [4] for their studies. And they have found an enriched early compressive strength.

From the experiments conducted in self-compacting concrete (SCC) using colloidal and powdered forms of nano silica, they were found that the freeze thaw resistance is elevated with colloidal nano silica rather than powdered nano silica. Quercia et al. [20] also got the rise in freeze – thaw resistance due to the addition of nano silica. The colloidal nano silica also has an improvement effect on the early age mechanical properties of fly ash concrete, ground ceramic powder concrete, recycled aggregate concrete, and other green concrete [21].

Li [22] was made a concrete with the combination of nano silica and fly ash with the percentage of 4 wt% and 50 wt% respectively. He compared the results obtained from the concrete made with nano silica and flyash and with controlld one which is without nano silica. 81% of increment in compressive strengths were obtained for 4% nano silica into concrete with 50 wt% of fly ash at 3 days.

Nano silica also promotes the compressive strength of sludge/fly ash cement paste which is evident from the study of Lin et.al [23]. Heidari et al. [24] made a fabricated concrete. The content of the formed concrete is with 0.5- 1% of nano silica and 10-25% of ground ceramic powder. The concrete results an improved compressive strength and reduction in water absorption capacity.

The studies conducted by Shaikh et.al [25], they were checked the initial and final setting time for various concrete types. And they obtained 4-7 hours of the time range for initial setting time and 6-10 hours of time for final setting time respectively (fig. 2). From the evaluation, it was observed a reduction in setting time of concrete in the presence of nano silica.

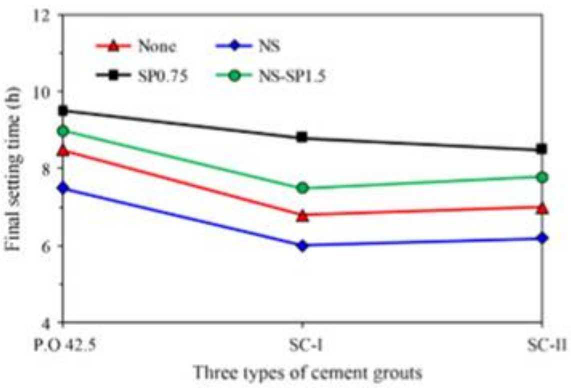

Fig. 2. Final setting time of different cement grouts [25]

The impact of nano silica hydrosols on electrical resistivity of concrete was examined by Madani et.al [26]. And silica fume was added with various specific surface areas. From their results, they concluded that when the nano silica was replaced

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in greater amount that led to the formation of tougher electrical resistance of concrete during the initial stage of hydration.

G. Quercia et.al. [27] Studied the effect of nano silica on cement mortars. The results were displayed through granular analysis. From the results they obtained they concluded that during the addition of nano silica there were a reduction in the necessity of water to cement mortar. They also determined the addition of 0.5- 4.0 wt% nano silica leads to the fall in water requirement.

The penetration depth of chloride ion was evaluated by the researchers Said et.al [28]. Here they used colorimetry technique for their analysis. And finally, they were compared the results between concrete which contains 6% of nano silica and concrete without nano silica. And they obtained lower penetration depth of chloride ions in concrete with 6% of nano silica over concrete without nano silica. Moreover, the charge and physical diffusion depth are disproportion to silicon oxide content.

Water loss directs to the formation of shrinkage in cement-based fillings. This has an adverse impact on bond strength between aggregates this is due to the expansion of cracks. Wang et al. [29] observed the development in shrinkage. Here they checked this property by using light weight concrete.

The effect of nano silica on compressive strength was investigated by many researchers. From the results they obtained they deduced some facts about the influence of nano silica. The compressive strength of concrete which contains nano silica is proportional to the quantity of nano silica. But, this is only up to the threshold value. Beyond that, the addition of nano silica will result in a reduction of compressive strength. The pozzolanic reaction carried out through the nano silica and calcium hydroxide is the key reason for this development of compressive strength. As a results formation of hydrated calcium silicate may happened. But, in the case of concrete without the content of nano silica, this depends upon mainly on cement hydration this results in a less quantity of calcium silicate hydrate. So, the hydrated calcium silicate is the main factor that delivers the strength in concrete. Hence, the concrete without nano silica has low compressive strength [30,31].

The early strength of nano silica was studied by Jalal and Abdellahi et al. [32,33]. They have been found that higher pozzolan activity of nano silica increased the early strength of modified concrete [34]. The drop in the later-stage compression growth of nano silica was observed due to the interruption in the curing time, this reduced the participation of nano silica in pozzolanic reaction [35].

The compressive strength of nano silica modified concrete was analyzed by Ibrahim et al. [36]. Here, they used the concrete after the treatment with extreme temperature. And they were found, at 400 °C had an extra noticeable improvement of compressive strength. The reason besides this is, when the temperature attained 400 °C this will result in increased amount of high-density calcium silicate hydrate within the concrete matrix. And also this will promote the action of nano silica which ultimately supports its hydration.

Distinct results on flexural strengths of concrete were observed because of various water-cement ratios and optimum content of nano silica [37,38].

Rongshen et al. [39] studied the impact of flexural strength over curing time. They were taken and checked the results at 3,7,28 and 90 days intervals. And they acquired the greatest flexural strength for the nano silica modified mortar, when the nano silica content was 3%.

The flexural strength on ultra-high performance concrete was examined by Li et al. [40]. They got 1% as an optimal content. And also they were checked the flexural strengths at 7 and 28 days. And gained 23.2 MPa and 25.8 MPa respectively for water-binder ratio was 0.16.

The effect of nano silica on flexural strength were experimented by Wu et al. [41]. They were used nano silica carbon fiber-reinforced concrete with various temperatures in order to conduct the experiment. They gained the maximum flexural strength at room temperature when nano silica content was 1 wt % and carbon fiber is 0.15 vol%.

The impacts of polypropylene fibers together with nano silica were tested by Sadrmotazi et.al. [42]. Substitution of nano silica equal to 7 % which enhanced the compressive strength of cement mix by 6.49 %. Polypropylene fibers amount beyond 0.3 % has a negative impact on compressive strength and reduce the strength. On the other hand, Polypropylene fibers amount beyond 0.3 % shows a development in flexural strength, indicating the efficiency of nano silica.

The impact of nano and micro silica on cement mortars were studied by Blyszko et.al. [43]. Here they use up various weight percentages of both nano and micro silica which is nearly 0-7 % and 0-20 % respectively. And they used a range of water to binder ratio which is 0.35 to 0.59. Quicker formation of calcium silicate hydrate gel is observed when the weight percentage of nano silica is 7 %.

The influence of nano silica on cement mortars were assessed by Adak et al. [44]. Different percentages of fly ash along with colloidal nano silica were added. Tests were conducted on 7 and 28 days. They were found an improvement in compressive strength as well as they gained increased flexural strength and split tensile strength over control value during the addition of 6 % nano silica in the fly ash.

The reduction of permeability was observed by the researchers Hou et al. [45] when the mixture was more durable. This was resulted due to the barrier to movement of aggressive agents. The nano silica has the ability to alter the pore structure of mortar which gives out minor passage property, in this manner reduce the pore volume.

The nanoparticles were subjected into cement pastes by Stefanidou and Papayianni [46], in order to produce materials with excellent qualities. They were taken high strength cement pastes and nano silica was added at different percentages. Then the samples were analyzed for mechanical and structural properties at different ages. They were observed the influence of nano silica on mechanical and structural properties even at small dosage.

Effect of nano silica and silica fume on the properties of concrete mortar was spotted by Senff et al. [47]. The used models contain 0-7 wt % of nano silica, 0-20 wt% of silica fume and water-binder ration is between 0.35-0.59. The nano silica content of 7 wt% was shown a significant effect on rheological properties.

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The fresh properties of mortar were tested by Senff et al. [47]. They joint the amorphous nano silica by cement in both cement pastes and mortars. In accordance to check the properties of mortars, they were taken binder/aggregate weight ratio of 1:2 and water/binder ratio of 0.35 respectively. The taken quantity of silica was 0 wt%, 1.0 wt%, 2.5 wt% and 2.5 wt%. They were observed reduction in apparent density by 2.4 % and improvement in the air content by 79 % after the addition of nano silica to the blend.

III. THE IMPACT OF NANO SILICA (NS) ON CEMENT HYDRATION

Nano particles play a vital role in construction industry. Among them nano silica is vastly used along with cementitious materials. Micro silica is the precursor for the production of nano silica [48]. Enhancement on the properties of cementitious materials is observed during the addition of nano silica. The accelerated hydration reaction is observed in the presence of nano silica [49].

Nano silica has an impact on the development of heat. This is studied by many researchers on their previous research work. They have observed that in the occurrence of nano silica there have been some developments on heat energy [50]. This leads to the reduction in the induction period.

There were three main prominent peaks were witnessed on the heat evolution curve of cementitious materials (Fig. 3). Hydration starts up on the surface of cement particles (mainly on C_3A). It will take nearly 0-2 hours for the completion of the reaction. This resultant peak is with high intensity.

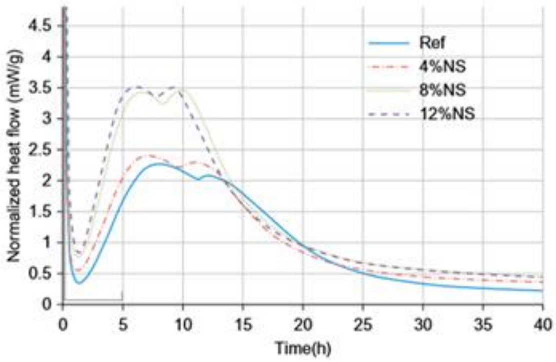

Fig. 3. Heat evolutions for the cementitious pastes in presence of NS [50]

The formation of second peak is due to the ingestion and hydration of tricalcium silicate. The products obtained from the above reaction are calcium silicate hydrate and calcium hydroxide. This will take nearly 5-8 hours for the completion.

The third peak is responsible for the formation of monosulphate and ettingite crystals. This will take 8-13 hours duration.

It is observed that nano silica offers a larger nucleation sites in order to carry out the hydration. It is widely used as a pozzolonic material. Pozzolanic effect, filler effect and shearing effect are the reasons for the accelerating effect of nano silica. Berodier and Scrivener [51], from their studies state that accelerating effect is influenced by shearing effect.

IV. CHALLENGES OF NANO SILICA IN CONCRETE

Generally, thickness on the surface of unhydrated cement particle is influenced by the hydration products which are formed during the hydration. Initial stage of hydration befalls only on particle surface. Later on due to the formation of hydration products this may develop thickness on the surface of anhydrate cement particles, which has the affinity to slows down the hydration. After the introduction of nano silica to the cement mixture, calcium silicate hydrate (CeSeH) is formed on the surface of silica due to pozzolanic reaction [52]. But choosing an appropriate amount of nano silica is a big task for the manufacturers. Once the nano silica is added in less quantity, this may reduce the formation of CeSeH. This will inversely affect the porosity of the matrix. On the other hand addition of excess amount of nano silica will increase the formation of CeSeH, which leads to the development of more dense structure. Therefore, the accumulation is the main problematic issue of nano silica.

Therefore, a suitable dispersion method should be used in order to get a good yield. Ultrasonic technology plays a vital role in the dispersion of nano silica in water [53]. In addition, colloidal silica sol along with concrete has been used to improve the hydration. Because, the colloidal silica contains mono scattered nanoparticles. After the joining with cement this make them to form floccules and coatings easily on the surface of cement particle. The formed floccules have the ability to hold more free water molecules. Thus, the combination of colloidal silica sol with concrete has great considerations [54,55]. The enhanced performance on dispersion in cement paste was achieved through amphoteric polycarboxylate superplasticizer (APC) and nano silica by Gao et.al [56]. The action mechanism of APC in cement paste which contains nano silica is shown in Fig. 4.

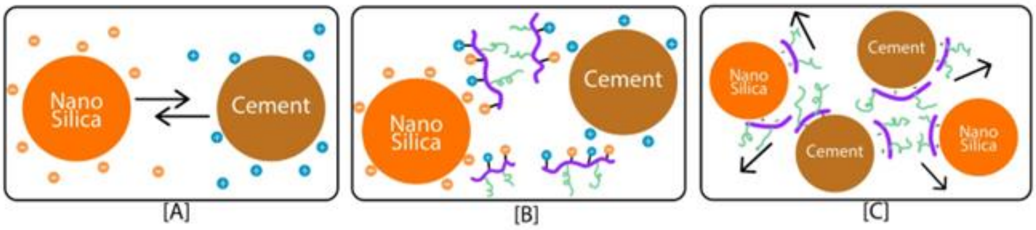

Fig. 4. The action mechanism of APC in cement paste with nano silica.

Cement and nano silica particles are gather together inexorably due to the electrostatic attraction (Fig. 4A). The APC molecule has positively charged ions on its surface. The nano silica itself has negative charges. These two are powerfully attached together via electrostatic interactions. The hydration of tricalcium silicate lead to the attachment of carboxyl groups on APC with positively charged cement particles. This will increase the absorption of APC on the surface of cement particles and nano silica (Fig. 4B). The dispersion retention is conserve through steric hindrance effect, due to the formation of hydrophilic solvation layer by the side chain of APC named polyethylene glycol. Lastly in the occurrence of APC, cement particles and nano silica successfully detached each other (Fig. 4C).

V. Conclusion

The most commonly used construction material for infrastructural expansion is concrete. The chief adhesive used in concrete is portland cement. The addition of nano silica leads to reduction in setting time; this is due to the hydration reaction which is achieved through the high action of nano silica. The size of nano silica, impact on its specific surface area. Due to its tiny particle dimension it has an excessive specific surface area. The reduction of concrete slump is observed during the formation of concrete mix, this is due to the absorption of more water molecules by nano silica, which is promoted by enormous unsaturated bonds. Degree of hydration of concrete is encouraged by nano silica, which forcing the concrete medium to yield more C-S-H gel, which has the ability to fill the pores in concrete. On the other hand, filling character is obtained by inactive nano silica. This may lead to reduction in pore volume and thus, generate more compact concrete. Developed pozzolanic activity is obtained in nano silica. The more adequate amount of pozzolanic reaction at the early stage of hydration is occurred in the presence of nano silica which enhanced the early strength of concrete. Curing time plays a role on particle size of nano silica. Once the curing time is increased, this will decrease the particle size of nano silica and leads to the weaker pozzolan reaction. Therefore, effect of nano silica on concrete strength is reduced in later part of hydration.

VI. Acknowledgement

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