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Review

Effect of Alumina Additives on Mechanical and Fresh Properties of Self-Compacting Concrete: A Review

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Abstract: Self-compacting concrete (SCC) has been increasingly used in the construction sector due to its favorable characteristics in improving various durability and rheology aspects of concrete such as deformability and segregation resistance. Recently, the studies on the application of nano-alumina (NA) produced from factory wastes have been significantly considered to enhancing the performance, and mechanical strength, of SCC. Many experimental works show that NA can be used in SCC with appropriate proportion to enjoy the benefits of improved microstructure, fresh and hardened properties, durability, and resistance to elevated temperature. However, a limited detailed review is available to particularly study using NA to improve the performance of SCC, so far. Hence, the present study is conducted to fill the existing gap of knowledge. In this study, the effect of using NA in improving rheological, mechanical parameters, and elevated temperature resistance of SCC is reviewed. This research summarized the studies in this area, which have been different from the previous researches, and provided a discussion on limitations, practical implications, and suggestions for future studies.

Keywords: self-compacting concrete; self-consolidating concrete; waste alumina; nano alumina; nanoparticles

1. Introduction

Concrete is a construction material that is widely used in buildings [1,2], bridges [3–5], and other civil structures [6,7]. The application of nanoparticles in concrete has received great attention recently because of the ultrafine size of their particles [8]. A limited number of nanoparticles have demonstrated utility for improving the durability and mechanical properties of concrete. Nazari and Riahi [9] reported that the addition of nano-alumina (NA) particles into concrete mixtures can enhance strength gaining, water permeability, and the pore structure characteristics of concrete. Khoshakhlagh et al. [10] indicated that the inclusion of Fe_2O_3 nanoparticles in cementitious materials improves the compressive strength. Moreover, Fe_2O_3 nanoparticles act as nanofillers to recover the pore structure enhancing the water permeability of concrete.

Self-compacting concrete (SCC) is concrete with enhanced fresh properties that allow pouring without external compaction [11,12]. SCC was first reported in Japan in 1988 [13]. SCC contains the same components as conventional concrete but with different proportions and fresh characteristics [14]. The main fresh characteristic of SCC is high workability that enables the concrete to fill formwork to achieve full compaction without vibration [15]. The compressive strength of SCC compared to the ordinary concrete with the same water to cement ratio is considerably higher [16]. The higher compressive strength of SCC is attributed to its dense microstructure as compared to conventional concrete [17]. Apart from high workability, SCC must possess a high filling ability, passing ability, and resistance to static and dynamic segregation [18]. Nazari and Riahi [19] indicated that the inclusion of SiO_2 nanoparticles enhances the flexural strength of SCC and accelerates cement hydration. The inclusion of TiO_2 nanoparticles also can improve the formation of C-S-H gel in SCC resulting in faster hydration and improved growth of the mechanical and durability properties of concrete [20–22].

NA is a chemical compound containing aluminum and oxygen [23,24]. The addition of NA to concrete can significantly affect the fresh properties of concrete due to their high ratio of surface area to volume [25]. NA has high chemical reactivity and behaves as pozzolanic reaction promoters owing to its high ratio of the surface area [26]. NA can improve the mechanical parameters of cementitious composites exposed to elevated temperatures [27]. It was reported that the inclusion of NA in SCC can accelerate the formation of hydrated products, and pore structure while reducing the workability of fresh concrete, water absorption of hardened specimens [28]. Table 1 shows the advantages and disadvantages of SCC which has been exploited from literature. As can be seen from the presented pros and cons analysis, the advantages are significantly higher than the inconveniences provoked. In Figure 1 (a and b) the application of roller alumina in tile manufacturing factories and the factory wastes of the alumina rollers are shown, respectively.

(**a**) (**b**)

Figure 1. The application of roller alumina in tile manufacturing factories; (**a**) ceramic roller kiln, (**b**) factory wastes.

Since the introduction of SCC, a large number of studies are conducted on enhancing the engineering properties of the SCC as well as the prediction of the loading capacity of SCC based on the associated mixture design. Despite the large volume of literature on the production of SCC and the relevant admixtures such as nano-particles, little attention has been given to predicting the complex interaction between incorporated admixtures and mechanical characteristics of the SCC. To the authors' knowledge, there is no review paper on the prediction model for the compressive strength of SCC. Some papers have discussed the prediction of the mechanical and rhetorical behavior of SCC but their main focus is only on mixed design. This study attempts to fill part of this void in the literature by offering a discussion on the application of NA in SCC.

Table 1. The advantages and disadvantages of self-compacting concrete (SCC).

Advantages	Ref.	Disadvantages	Ref.
Speeded up construction	[29]	Prolonged demolding time	[30]
Improved the construction quality	[31]	Increased risk and associated uncertainty	[32]
Safer work conditions	[33]	Lowered elevated temperature resistance	[34]
The increased service life of formworks due to the elimination of vibration	[31]	Higher formwork pressure means higher formwork costs.	[35]
Improved quality of the final product	[33]	Not fully known fire behavior	[36]
Reduced manpower	[33]	Maintaining ready-mixed is not easy under the construction site	[37]
Improved ecological footprint	[38]	Not appropriate for every application	[39]
Improved economic	[38]	Unsuitable choice for horizontal castings	[40]
Enhanced filling spaces in dense reinforcement or inaccessible voids	[38]	Higher associated costs for ready-mixed	[41]
Improved freeze-thaw resistance	[42]	Using conventional drum mixers are not suitable for the distribution	[43]
Noise-free working atmosphere	[31]	Not standardized mix design	[44]

2. Nanoparticles

Nanotechnology has become a popular and necessary part of science and technology in recent years by addressing nanoparticles in atomic or molecular size [45]. Nanoparticles are defined as materials where at least one dimension of a particle is less than 100 nm. Partial replacement of nano-materials with cement in the mix design can enhance the physical and chemical characteristics of fresh and hardened concrete [46]. The addition of nanoparticles can improve the microstructural properties, filler effect, compactness, and durability, as well as accelerating cement hydration [47]. Nanoparticles can also act as pozzolanic materials and produce the additional formation of calcium–silicate–hydrates (C–S–H) gel and, by taking place of pozzolanic reactions. The C–S–H gel Formation can improve stiffness, flexural, tensile, and shear strength of cement-concrete [48]. Uniform dispersion of nanoparticles in concrete is the key issue in obtaining the expected mechanical and chemical characteristics [49,50]. The applied nanoparticles in the concrete mix to partially replace cement are spherical shapes cementitious materials.

The addition of nanoparticles can improve the microstructural properties, compactness, and durability of hardened concrete [19,48]. The effect of nanoparticles as partial cement replacement in the concrete mix has been studied by many researchers in recent years. Nano-SiO_2 is the most widely investigated nanoparticle [19,51–53] while the effect of adding other partials such as nano-TiO_2 [22,54,55], nano-Al_2O_3 [9,56,57], nano-ZnO_2 [58,59], nano-Fe_2O_3 [10,60], nano-CuO [61], nano-SnO_2, nano-ZrO_2 [62], nano-TiO_2 [63], carbon nanotubes [64], carbon nano-fibers [45], polycarboxylates [65], nano-Cr_2O_3 [48,66], nano-clay [45] and nano-$CaCO_3$ [62,67] in properties of fresh and hardened concrete has been investigated so far. For example, Tawfik et al. [68] evaluated the effect of nano-waste ceramic and nano-silica on the mechanical properties of hardened concrete. The obtained results showed improvement in the performance of concrete but also resolved the footprint caused by this waste. Jalal et al. [69] studied the effect of TiO_2 nanoparticle inclusion in tensile strength, thermal, rheological, transport, and microstructural properties of SCC. The chemical effect of TiO_2 as partial replacement of cement accelerates the formation of C–S–H gel and hydration resulting in increased split tensile strength of concrete specimens. Moreover adding TiO_2 nanoparticles can enhance the pore structure of concrete by shifting the distributed pores into a less harmful configuration. Joshaghani et al. [20] evaluated the fresh, mechanical, and durability properties of nano-TiO_2, nano-Al_2O_3 and nano-Fe_2O_3, on SCC two different contents of 3% and 5%. It was observed that addition of 3% nanoparticles can slightly improve workability properties of the mixes by increasing the water demand. Calcium ferric hydrate (C-F-H) gel formation enhanced the compressive strength and durability properties in nano-Fe_2O_3, nano-Al_2O_3 and nano-TiO_2. It was reported that nanoparticles addition controlled the formation of C-S-H gel, lowering permeability to penetration of malicious ions of chloride.

Fresh properties of concrete containing nanoparticles are one of the most investigated subjects. Workability, flowability, and consistency of concrete are greatly affected by the addition of nanoparticles [70]. Generally, the flowability of SCC mixes is reduced by the addition of nanomaterials [71]. This reduction is mainly attributed to the ability of nanoparticles to absorb more water molecules due to their large area surface [20]. Mechanical properties of hardened concrete including flexural, tensile, shear, and compressive strength and their change due to incorporation of the microparticle in concrete are another most important study in recent years [72]. It is stated that nanoparticles act as nuclei to form hydration products filling micropores [73]. The formation of a dense C-S-H gel is facilitated by altering cement hydration that leads to an increase in compressive strength [74]. Adding excessive amounts of nanoparticles may adversely affect the compressive strength due to restricting the $Ca(OH)_2$ crystals growth. Several research studies have investigated the influence of nanoparticles on the durability of hardened concrete. It was stated that the water absorption of SCC mixes with nanoparticles is different from the control specimens due to the formation of hydrated products [75]. On the other hand, the addition of nanoparticles may affect the capillary permeability of concrete and the specimens containing nanoparticles can better resist chloride penetration [76,77].

3. Production Processes of Nano Alumina

There are different methods for the extraction and production of alumina nanoparticles. Alumina is mainly extracted from two main resources of clays and coal fly ash (CFA) [78]. The row materials undergo several chemical processes for extracting their alumina contents. The production phase of nano alumina is performed by arc plasma, precipitation, hydrothermal, and sol-gel methods. Functionalization is the last step in NA production aiming at improving surface characteristics [79]. The functionalization process prevents agglomeration between alumina nano-particles that is mainly caused by the high surface energy and activity of nanoparticles [80,81].

3.1. Extraction of Alumina Nanoparticles

Clay is a natural mineral that is widely used to produce nano alumina due to its quite abundant availability and low cost. Kaoline is clay made from kaolinite $Al_2O_3.2SiO_22H_2O$ that contains high alumina content ranged between 25 to 40%. Kaolin is a product of weathering of all granitic rocks which is characterized by its fire resistance, good plasticity, and other unique chemical and physical properties [82]. Kaolin is a chemically inert material within a wide pH range and it is not listed as a hazardous material [83]. The alumina extraction process from clays is performed using acids such as nitric acid, hydrochloric, or sulfuric acid to dissolve the alumina followed by clay roasting. Heavy metal ores of clay are extracted using acid leachants [78]. The chemical reaction for removing heavy metals from clays can be shown below.

$$Al_2O_3H_2O + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 + 4H_2O \quad (1)$$

CFA is another major source of alumina nanoparticles. CFA is rich in alumina and alumina contents in CFA is found around 50%. The process of alumina extraction from CFA includes three important steps namely sintering [84], hydro-chemical [85], and acid processes [86]. The process of extracting alumina particles from CFA is shown in Figure 2.

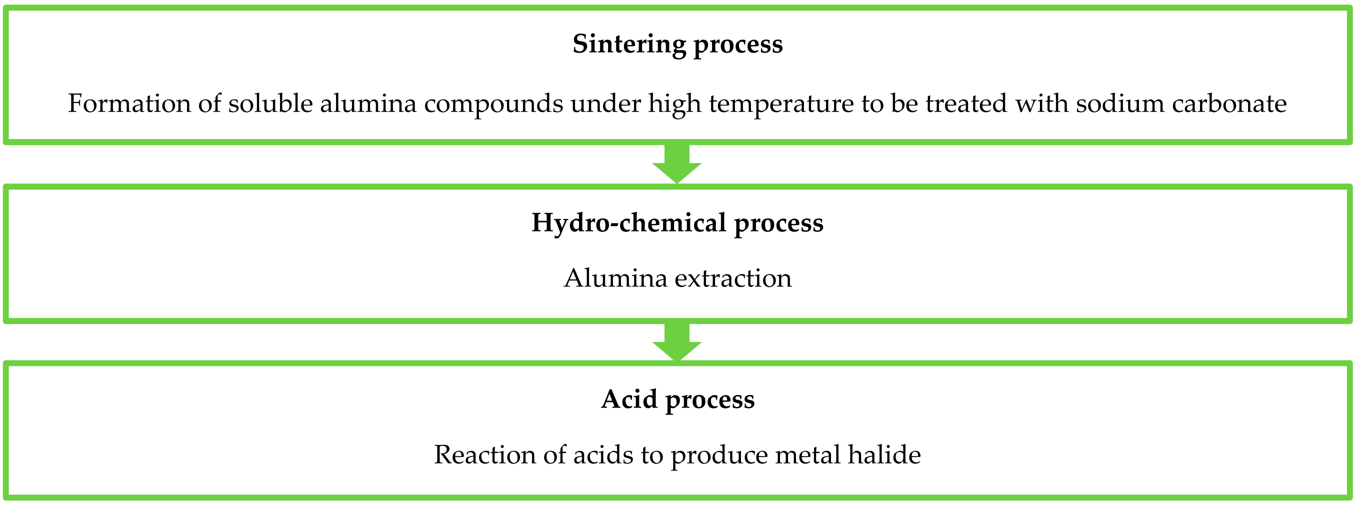

Figure 2. The process of alumina extraction from coal fly ash (CFA).

3.2. Production of Alumina Nanoparticles

Different methods are developed to produce alumina nano-particles that include arc plasma, hydrothermal, sol-gel, and precipitation. The arc plasma process is defined as a thermal treatment of solid feedstock utilizing an arc between anode and cathode generally made of graphitic carbon for generating plasma. Using plasma for the production of alumina has lower residue as well as lower production and maintenance costs compared to traditional gas and oil burners [87]. Saravanakumar et al. [88] converted aluminum dross into ultrafine alumina powder using a plasma arc melting process. It was reported that the amount of the conversion of Al dross to alumina powder substantially correlates with plasma power. Madhu Kumar et al. [89] and Kumar et al. [90] used a D.C. arc plasma reactor for the preparation of alumina nano-particles. Fu et al. [91] adopted microwave oxygen plasma to prepare alumina nanoparticles sized 21–24 nm. Stanislaus et al. [92] investigated the hydrothermal process for the production of alumina nanoparticles in the presence and absence of various additives. Noguchi et al. [6] used hydrothermal reaction in supercritical water using a continuous flow reactor to prepare alumina -crystalline nano particles.

Sol-gel and coprecipitation, two common methods to extract nano alumina with different sizes and morphologies. spherical particles of alumina can be prepared by using the sol-gel method while spherical and hexagonal alumina particles can be formed by the co-precipitation method [93,94]. Mirjalili et al. [95] synthesized alumina nanoparticles by a sol-gel method. It was shown that the addition of surfactant and incorporated stirring time are parameters that affect the shape and size of the formed particle. Belekar et al. [96] obtained alumina granules with an average size of 30 nm by a modified sol-gel method. The process included hydrolysis of Al $(NO_3)_3$ in aqueous media. Esmaeilirad et al. [97] prepared alumina by heterogeneous deposition-precipitation, sol-gel, and the co-precipitation methods. The alumina prepared by the sol-gel method using La-Cu/AlSE showed the best performance. Feng et al. [98] used aluminum powders as the aluminum source and acetic acid as precipitants to prepare alumina powders in a precipitation process.

4. Sustainability of Nano Alumina

The use of nanoparticles is not yet a cost-effective option for the construction industry and particularly as a concrete additive. Hence, meaningful approaches are needed to be carried out to overcome that limitation. The valorization of industrial waste is a sustainable way to wisely utilize renewable resources. Aluminum dross is a toxic industrial waste generated from aluminum refining industries that contain aluminum oxynitride (AlON), aluminum oxide (Al_2O_3), aluminum metal (Al), and impurities such as potassium chloride and sodium chloride [88]. Based on reports nearly 95% of aluminum dross is landfilled without treatment that is hazardous to the environment in China [99]. Using conventional disposal or landfilling practices of aluminum wastes without proper treatment and recycling strategy can adversely contribute to human health due to the toxic nature of materials [100]. Hence aluminum dross should be converted into inert or less toxic products [88].

EI-Katatny et al. [101] used caustic soda for leaching an aluminum factory waste under atmospheric and high-pressure aluminum to form alumina. David and Kopac [102] proposed an alumina extraction method from aluminum dross using a chemical route. Dash et al. [103] recycled aluminum dross using acid dissolution and salt treatment for recovering residual aluminum. Das et al. [104] adopted acid treatment for the recycling of aluminum dross to obtain alumina generated by Indian aluminum industries. Sarker et al. [105] used an acid dissolution process to extract alumina from Bangladesh foundry industries. Singh et al. [106] optimized a chemical process for the production of alumina through recycling aluminum dross. How et al. [107] recovered alumina from the wastes of an aluminum production factory in Malaysia. The recovering process of alumina consisted of acid leaching, alkaline precipitation, and calcinations steps. Most of the aforementioned processes incorporated alkaline salts for the treatment of aluminum dross that are hazardous to groundwater and agricultural soil and it is important to remove these chemicals before discharging them to the environment.

Plasma processing of materials is a fast and environmentally-friendly method to treat and high volume reduction of various types of wastes. Szente et al. [87] conducted a comparative study on using plasma systems and traditional oil and gas burners for recovering aluminum from dross. It was reported that the plasma process provides cheaper operation costs (at least 23%) with lower residues than oil/gas burners. Yang et al. [108] treated aluminum dross using a radio frequency-based plasma to recover high-purity fine aluminum oxide (with the size of 8 μm). Saravanakumar et al. [88] reported using arc plasma to convert dross of aluminum into alumina powder in an eco-friendly manner. The obtained results indicated that the application of arc plasma can be efficiently used to treat aluminum dross to recover alumina powder.

5. Self-Compacting Concrete (SCC)

SCC mixes always contain a large number of powder materials, viscosity-modifying admixtures, and superplasticizer [109–111]. Higher cement content in concrete has some negative effects such as a rise in material cost, increased thermal stress, and shrinkage [112]. The requirement for cement replacements in SCC is usually met by the use of filler materials such as fly ash (FA), pulverized fuel ash (PFA), marble powder (MP), basalt powder (BP), granulated ground blast-furnace slag (GGBS), limestone powder, etc. [112]. Uysal and Sumer [113] investigated the effect of different mineral admixtures on the properties of SCC such as durability, workability, and reducing cement content. The replacement of Portland cement with FA, GGBS, BP, and MP increases the fluidity and can improve mechanical properties, and durability of the SCC against sulfate attack. Fathi et al. [114] also testified that fibers reduce the slump and compressive strength of SCC but increase its flexural tensile strength. Talking about mechanical properties, Ahmad et al. [115] compared the mechanical properties of normal concrete (NC), SCC, and glass fiber reinforced SCC. It was observed that addition of fiber glass to SCC decreased the workability of the concrete but it significantly enhanced flexural of ruptures in test specimens. The change in compressive strength by addition of glass fibers was small enough to be ignorable.

SCC is extensively used in various types of structures such as commercial buildings and industrial structures that are subjected to high temperatures or accidental fires. Hence, gaining proper information on the effects of high temperatures on the performance of SCC is necessary. The effect of high-temperature on the behavior of SCC was studied by many researchers. Anand et al. [116] reviewed the effect of the elevated temperature on the chemical and mechanical properties of concrete. Distinct behavior was found in mechanical properties of normal, high strength, and SCC when they are exposed to high temperatures. It was revealed that parameters such as the compressive, tensile, and flexural strength of concrete, water-cement ratio, cement type, the density of concrete, aggregate type, reinforcement percentage, and reinforcement cover are some of the important factors that affect the concrete performance at elevated temperature.

Annerel et al. [117] revealed that the thermal influence of raised temperature on the mechanical behavior of SCC is much significant compared to normal concrete. Pineaud et al. [118] studied the mechanical properties of high-performance SCC under raised temperatures ranged from 20 to 600 ° C. The results of experiments on 11 different mix designs showed that increasing the temperature reduces their E-value and compressive strength significantly. Andiç-Çakır and Hızal [119] explored the properties of SCC under raised temperature ranged from 300 to 900 °C. It was shown that the aggregate type and w/c ratio are the most influential parameters in the modulus of elasticity and compressive strength of the SCC while the aggregate type is the main influential parameter in tensile strength. Table 2 shows some of these changes within a various temperature range of exposure. Further studies on the influence of raised temperature on the mechanical properties of concrete can be found somewhere else [120–122]. There are limited studies on the behavior of SCC with nanoparticles and subjected to high-temperature [123,124].

Table 2. The changes in physical and chemical parameters of concrete due to exposure to elevated temperature (data are exploited from [120]).

Investigated Parameter	Temperature Range	Effect of Temperature Rise
Compressive strength	100–800 °C.	• Decreases in a linear rate
Porosity and pore size	100–800 °C. Above 1000 °C,	• Increase of porosity and pore sizes • Porosities are smaller and better structured
Elastic modulus.	100–800 °C.	• Decreases in a linear rate
Splitting tensile strength	100–800 °C.	• Decreases in a linear rate
Stress-strain relationship	100–800 °C	• Flatter stress-strain curves, downwards and rightwards shift of the peak stress
Residual flexural strength	100–800 °C	• Decreases in a linear rate
Water evaporation	At 105 °C At 400 °C	• Free water and physically absorbed water are completely lost. Chemically bonded water start to lose • Capillary water is lost completely

Table 2. *Cont.*

Investigated Parameter	Temperature Range	Effect of Temperature Rise
Hydration	Up to 300 °C	• Hydration of un-hydrated cement is improved
Microstructure	Up to 200 °C 200 °C–400 °C	• No micro-cracks • The intensity of micro-cracks increases

6. Nano Alumina (NA) Applications in SCC

Nanotechnology is a research area that has revolutionized the mechanical and chemical properties of materials [125,126]. Nanotechnology is a promising research field with applications to improve the quality of the product and the performance of concretes [127]. The nanoparticle is applied in SCC aiming to reduce segregation and to modify fresh properties and mechanical strength., and. NA is a kind of ultra-fine chemical compound of aluminum and oxygen with a large surface area, high density, high melting point, high hardness, and good chemical stability with particle sizes in the range of 1~100 nm [128]. The advantages of using NA in concrete are presented in Table 3.

Table 3. Advantages of using nano-alumina (NA) in concrete.

Advantages	Reference
Reduced porosity of the microstructure as the voids were filled by NS.	[129]
Decreased in water absorption	[130]
Improved frost resistance of concrete	[131]
Controlled the setting time of the cement through a faster hydration process will be.	[132]
Reduced amount of un-hydrated cement in the mix	[129]
Increased modulus of elasticity of cement mortar.	[133]
Reduced segregation and flocculation.	[124]
Refined voids in the hydration gel as a nanofiller.	[124]
Reduced coefficients of permeability by 1–3 orders of magnitude.	[133]

Sua-iam et al. [134] studied the effect of using recycled NA and fly ash in SCC. It was shown that using recycled NA and fly ash could considerably enhance the compressive strength and workability of SCC. Mohseni et al. studied the effects of NA and rice husk ash (RHA) in polypropylene fiber (PPF) reinforced concrete. The combined inclusion of, NA, PPF, and RHA reduced the water absorption and drying shrinkage of mortars and increased flexural strength. Farzadnia et al. [135] investigated the chemical composition, microstructure and mechanical properties of NA-based high strength mortars subjected to elevated temperatures ranged from 100 °C to 1000 °C. It was indicated that the addition of NA improved 16% of the compressive strength of samples. Behfarnia and Salemi [136] studied the influence of NS and NA on frost resistance and mechanical properties of concrete. Higher frost-resistance was achieved for concrete with NA while concrete containing NS had higher compressive strength. Zhan et al. [137] analyzed the effect of NA in the hydration of cement. Accelerated cement hydration and enhanced compressive strength at all ages were recorded. Owing to accelerated cement hydration, the strongest growth at 28 days was less obvious. Mohammadyan-Yasouj et al. [27] investigated the compressive strength and modulus of elasticity of each SCC mix design under temperatures of 27 °C, 100 °C, 200 °C, 300 °C, 450 °C, and 600 °C for specimens cured in 7 and 28-days. It was observed that addition of NA into the mix enhances the compressive strength of SCC for samples cured at 28-day in temperature under 100 °C. E-value of the samples cured on 28-day exhibited increasing trend. Figure 3 shows the comparison compressive strength of self-compacting concrete (SCC) at target temperatures for specimens cured at 28-days.

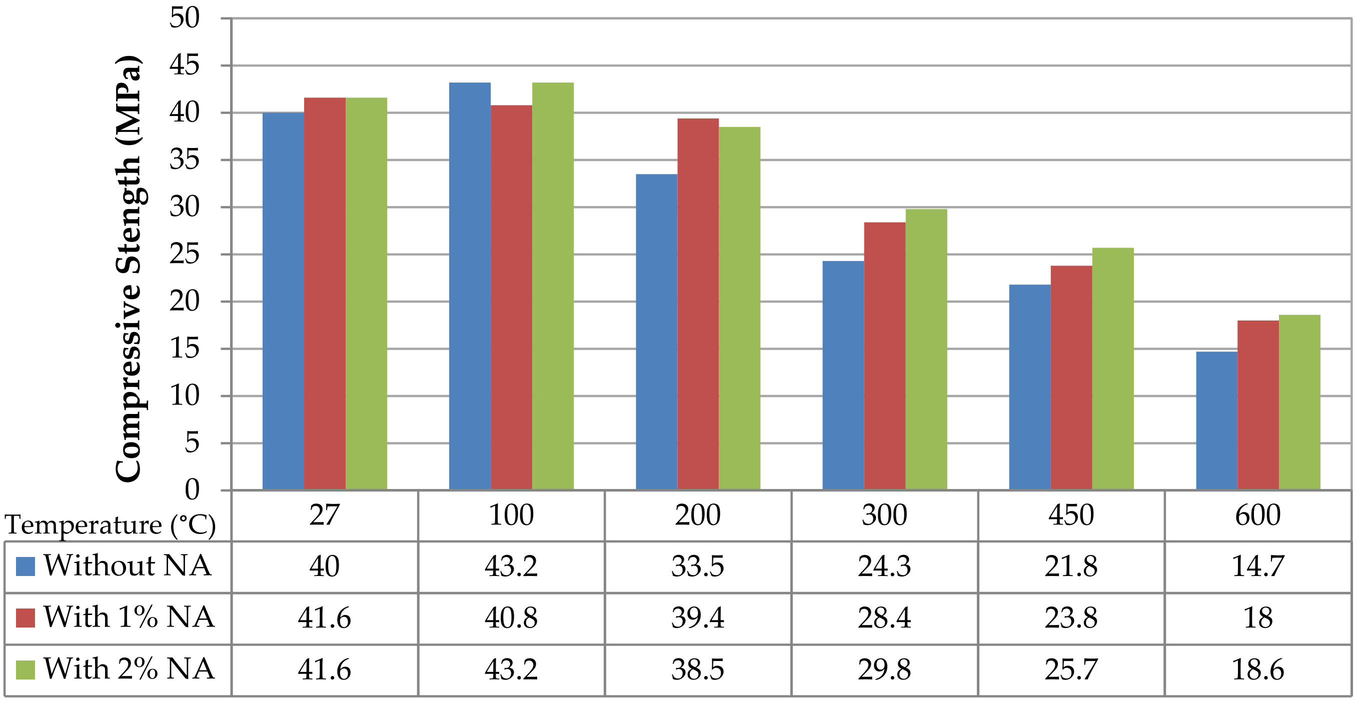

Figure 3. Comparison of 28-day compressive strength of self-compacting concrete (SCC) at target temperatures [27].

Szymanowski and Sadowski [138] explored the applicability of NA mortars for overlaying concrete floors. It was shown that the mortar with Al_2O_3 nano-powder used to make the overlay was less porous than the reference mortar. Li et al. [139] investigated the effect of NA on the elastic modulus of cement composite. Based on the experiment, the elastic modulus of mortars was increased by incorporating NA into the matrix. Nazari and Riahi [9] investigated the effect of curing medium on the physical, mechanical, and thermal properties of NA concrete. It was observed that curing of the specimens in saturated limewater resulted in accelerated setting time. Barbhuiya et al. [140] reported the effects of NA inclusion on the early-age microstructural properties of cement paste. It was revealed a denser microstructure with larger crystals of portlandite in the cement matrix. Mohseni et al. [77] conducted a comparative study on the single and the combined effects of adding NS), nano alumina (NA), and NT on the durability and mechanical properties of SCC. The ternary combination of NA, NS, and NT had the best permeability to chloride ingress and electrical resistivity at 3%. Heikal et al. [141] studied the resistance of cement pastes with NA against fire. By enhancing the hydration reaction of cement phases higher compressive strength, bulk density, gel/space ratio was reported for the prepared cement paste. Khaliq and Khan [121] investigated the material properties of calcium aluminate cement concrete (CACC) under elevated temperatures. It was revealed that the presence of alumina as a binding agent significantly enhances the mechanical performance and axial strain in CACC. Niewiadomski et al. [42] presented a comparative study to assess the effect of NA, NS, and NT nanoparticle additives. It was indicated that the addition of up to 4 wt.% of NA and NT showed no improvement in concrete strength. Table 4 summarizes the literature on the application of NA in SCC.

Table 4. Summary of the literature on the application of nano-alumina (NA) in SCC.

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Suaiam and Makul [134,142]	Rheological and mechanical properties SCC with high volumes of alumina	28 and 90 days	Φ150 mm × 300 mm	0.38	Alumina	Below ≈5 mm	0, 25, 50, 75, and 100% of the total fine aggregate	• Velocity measurements • Compressive strength, • V-funnel, • Blocking flow assessment • J-ring flow • Ultrasonic pulse • Slump flow,	• SCC mixtures containing waste alumina had 75% higher compressive strength.
Mohseni et al. [143]	Cement mortars containing rice husk ash, Polypropylene fiber (PPF), and nano-alumina (NA)	28 and 90 days	50 × 50 × 50 mm^3 and 50 × 50 × 200 mm^3	0.49	NA	20 nm	0, 1, 2 and 3%,	• Compressive strength, • Flexural strength, • Water absorption and • Drying shrinkage	• NA improved the compressive strength of mortar. • The addition of RHA, NA, and PPF reduced both drying shrinkage and water absorption and increased flexural strength.
Gowda et al. [129]	Durability and microstructural properties of mortars with NA	28 days	70.5× 70.5× 70.5 mm^3	0.79	NA	-	1, 3 and 5%	• Water absorption • Electrical resistivity • Scanning electron microscope (SEM)	• Increasing of the NA increased water absorption • Electrical resistivity was almost the same for 3% and 5% NA. • The addition of NA gave a denser microstructure in the mortar.

Table 4. *Cont.*

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Farzadnia et al. [135]	Elevated temperature's effect on NA -based mortars	1, 7, and 28 days	50 × 50 × 50 mm^3 and Φ20 mm × 50 mm	0.35	NA	the average size of 13 nm	0, 1, 2 and 3%	• Differential scanning calorimetry (DSC) • X-ray powder diffractometry (XRD) • SEM tests • Residual compressive strength, • Elastic modulus, and • Measurement of gas permeability coefficient	• NA enhanced the compressive strength of mortars by 16%. • NA improved residual properties of mortars at temperatures from 0 °C to 400 °C. • The addition of 1% NA reduced gas permeability of mortars at temperatures from 0 °C to 600 °C. • The inclusion of NA reduced the intensity of CH formation at room temperature and 400 °C. • The NA inclusion transformed the CH crystallization from well to ill.
Behfarnia and Salemi [136]	Frost resistance of NA concrete	7, 28 and 120 days	70 × 70 × 70 mm^3.	0.48	NA	15 nm	1% and more than 2%	• Compressive strength • Loss of mass measurement • Change in length • Water absorption test	• NA increased the compressive strength of concrete. • Frost resistance of concrete mixes improved by the addition of NA.

Table 4. *Cont.*

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Zhan et al. [137]	Effect of NA on early hydration and mechanical properties of cement pastes	1, 3, 7, and 28 days	cubes of size 20 mm × 20 mm × 20 mm cubes of size 6 mm × 6 mm × 13 mm	0.456	NA	30 nm	0%, 1%, 2% and 4%	• Compressive strength • Isothermal conduction calorimetry • Thermogravimetric analysis • Backscattered electron imaging and energy dispersive spectroscopy • Mercury intrusion porosimetry (MIP)	• NA speeded the aluminate and silicate phases reactions in ordinary cement. • NA improved compressive strength at all ages. • NA modified pastes at 12 h.
Szymanowski and Sadowski [138]	NA-based cement mortars for concrete floors	28 days	71 × 71 × 71 mm^3, 11 × 11 × 11 mm^3, and 40 × 40 × 80 mm^3	0.3	NA	Below 50 nm	0.5, 1 and 1.5%	• Compressive and flexural strength. • Subsurface tensile strength • Abrasion resistance • Hardness.	• The addition of 0.5% of NA increased subsurface tensile strength and reduced abrasion resistance • The addition of 0.5% of NA resulted in a less porous mortar than the reference.

Table 4. *Cont.*

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Li et al. [139]	Preparation and mechanical properties of the NA based cement composite	3 days, 7 days, 28 days	Φ20 × 40 mm	0.4	NA	Below 150 nm	5% and 7%	• Elastic modulus • Compressive strength	• In 5% of NA, the E-value of composites improved by 143%. • The compressive strength of 5% NA composites increased by 30% at 7 days.
Nazari and Riahi [9]	Different curing media for NA in concrete	7, 28 and 90 days	Cubes of 100 mm edge for compressive strength tests, cubes with 200 mm × 50 mm × 50 mm	0.40	NA	15 nm	0.5%, 1.5% and 2%	• Compressive strength water absorption • XRD analysis Split tensile strength Flexural strength • Thermogravimetric analyzer (TGA)	• Al_2O_3 nanoparticles have significantly higher strength. • The optimum level of NA content was achieved by 1.0%. • The pore structure of SCC containing NA is improved and the content of all mesopores and macropores is increased.

Table 4. *Cont.*

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Barbhuiya et al. [140]	Early-age microstructural properties of adding NA to cement paste	1, 3, 7, and 28 days	50 × 50 × 50 mm^3	0.40	NA	27–43 nm	2% and 4%	• Compressive strength water absorption • XRD analysis • FTIR analysis • Electron microscopy Scanning	• No noticeable change was observed in the early-age compressive strength by NA addition. • The addition of NA induced no phase change.
Mohseni et al. [77]	Effects of NA on mechanical, rheological, and durability properties of SCC	3, 7, 28 and 90 days	50 × 50 × 50 mm^3 and Φ100 × 50 mm	0.4	NA	15 nm	1%, 3%, and 5%	• Water absorption • Electrical resistivity • Rapid chloride permeability tests	• NA improved the flexural and compressive strengths of specimens with 10% and 20% RHA. • The most effective amount of NA was 3% by weight of the binder. • Water absorption decreased with the increase of NA dosage up to 3%. • The formation of denser microstructure with NA addition.

Table 4. *Cont.*

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Heikal et al. [141]	Physico-mechanical, microstructure characteristics and fire resistance of cement pastes with NA -	3, 7, 28, and 90 days.	-		NA	15 ± 3 nm	1, 2, 4 and 6 %	• Setting times, • Bulk density • Gel/space ratio • Compressive strength • XRD • TEM • Differential thermal analysis (DTA)/TGA • Free lime contents (FL, %)	• NA addition shortens the setting times. • 1% NA enhanced the compressive strength of the pastes up to 27.22%. • NA speeded up the hydration. • 1% NA enhanced the fire resistance.
Khaliq and Khan [121]	High-temperature material properties of calcium aluminate cement concrete	3, 14, and 28 days	Φ100 mm × 200 mm	0.5	calcium aluminate cement concrete	-	-	• SEM • Compressive and tensile strength • Elastic modulus • Compressive toughness • Visual investigations	• Better tensile and compressive strength was achieved in temperature up to 800 °C. • stress-strain response and E value were improved. • Compressive toughness was improved in temperature up to 800 °C.

Table 4. *Cont.*

Ref.	Research Topic	Test Age (day)	Sample Size	W/C (%)	Alumina				Remarks
					Type	Size (mm)	Amount of Alumina	Investigated Parameters	
Niewiadomski et al. [42]	Self-compacting concrete modified with NA	28 and 90 days	100 × 100 × 100 mm^3, 40 × 40 × 160 mm^3, and Φ25 mm × 20 mm	0.42	NA	Below 50 nm	Cement replacement 0.5 wt.%, 1.0 wt.%, 2.0 wt.% and 3.0 wt.% of the.	• Compressive strength • Flexural strength • hardness • Elastic modulus	• The fluidity of concrete deteriorated with an increased amount of NA. • The samples with the addition of NA had a larger size of air pores than the reference sample. • Concretes with NA showed no improvement in compressive and flexural strengths.

7. Conclusions

This review is aimed to investigate the effect of NA on rheology and mechanical parameters of SCC subjected to elevated temperature. Then the potential of predicting the mechanical parameters of SCC is further studied. It was concluded from the literature review that the rheology parameters of the fresh SCC are significantly affected by the addition of NA due to their high surface-area-to-volume ratio. The addition of NA reduces slump flow diameter while the variation of the workability is contributed with the replacement ratio. NA has lower water and chloride ions permeability that is due to the accelerated hydration process. Moreover, enhanced durability and compressive strength are achieved by adding a small amount of NA to SCC. Therefore, the use of NA enhances the performance of SCC. The addition of NA to SCC results in a denser microstructure as compared to normal SCC. The authors believe that future research in the field of NA should further concentrate on enhancing the elevated temperature resistance and thermal behavior of SCC to enable more sustainable and durable construction and to extend the SCC use to more application fields.

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