Influence of nano particles on the properties of concrete: A state of art review

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Abstract

Use of nanomaterials such as nano-silica, nano-alumina, nano-iron oxide, nano titanium oxide, nano carbon tubes etc., in concrete has been extensively studied in recent years. By adding nanomaterials of size 0.1 nm to 100 nm having greater surface area improves the microstructure by reducing the voids and making the matrix denser. Nanomaterials improve the mechanical and durability properties of concrete. Nano materials expected to play an important role in future in the modern concrete infrastructure. This paper will give a brief review about the influence of nanoparticles on the properties of concrete.

Key words: *Nano-Silica, Nano-Alumina, Nano-Iron oxide, Nano-titanium oxide, Nano carbon tubes.*

1. Introduction

Concrete is one of the most used materials in the world after water. Due to urbanization infrastructure development is increasing therefore use of concrete is increasing. Cement which produces CO_2 and greenhouse gases is the main ingredient of concrete. Effect on climate change and global warming is increasing by use of cement. Therefore, it is important to find alternatives for sustainable production of ecofriendly concrete. There are materials like fly ash, GGBS, Silica fume used for the replacement of cement. The use of these materials reduces the impact on the environment (Aggarwal et al., 2015; Amran et al., 2021; Paul et al., 2018).
Without any doubt, in recent years the use of nano particles in many fields of application has received special attention in order to fabricate materials with new functionalities. When ultrafine particles were mixed into Portland cement paste, mortar, or concrete, they produced materials with distinct properties from conventional materials. Nano particles have great high surface area therefore they are highly reactive. When nano particles of size 1nm to 100nm used in cement-based materials they improve the properties of concrete significantly(Zhou et al., 2019)**.** A lot of research has been done and going on including various nano particles in concrete like nano silica, nano alumina, nano titanium oxide, nano $CaCO_3$ and many more (Sanchez & Sobolev, 2010). These are used in both powdered form and in colloidal particles form. Both have its own advantages. Overall including nano particles in any form has improved the mechanical and durability properties of concrete (H. Du & Pang, 2019; W. Li et al., 2015)**.**The benefits and drawbacks of using nano-materials can be summarized as follows (Al-Luhybi & Altalabani, 2021).

- Less maintenance.
- It reduces the rate of thermal transfer.
- It increases sound absorption.
- It increases glass reflection.
- It improves segregation resistance.
- It repairs small cracks.
- Its life cycle is cost-effective.
- It is costly.
- It is rust resistant

This paper provides a brief review of the studies focusing on the properties of concrete including nano particles. Various studies investigating the mechanical and durability properties are reviewed here.

Table 1: Physical and mechanical properties of concrete incorporating nano particles reported in previous studies

Reference	Physical Property	Mechanical Properties			
	Slump	Compressive Strength	Elastic Modulus	Tensile Strength	Flexural Strength
(Faez et al., 2020)	Y	Y	N	Y	N
(Nazari & Riahi, 2010)	N	Y	N	Y	Y
(Mukharjee & Barai, 2014)	Y	Y	N	Y	Y
(Vivek et al., 2020)	N	Y	Y	Y	N
(Mohseni et al., 2015)	Y	Y	N	N	N
(Shaikh et al., 2014)	Y	Y	N	N	N
(Ren et al., 2018)	N	Y	N	N	N
(Palla et al., 2017)	Y	Y	N	Y	Y

Note: Y - Studied; N – Not Studied

2. Review of existing studies of nano particles in concrete

The following sections review the concrete incorporating nano particles. Table 2 summarizes the literature reviewed in this paper.

2.1. Compressive strength studies

2.1.1. Influence of water to binder ratio

Water to binder ratio is the most significant parameter influencing the properties of concrete. The influence of water to binder ratio in concrete incorporating nano particles has been widely studied as shown in table 3. In some cases, they considered the effect of water to cement ratio. Fig. 1 shows the effect of water to binder ratio on compressive strength of concrete incorporating nano particles. As the water to binder ratio is increasing compressive strength of concrete and/or mortar decreases. By adding nano particles water requirement has been increased in order to maintain workability. The mechanical properties of concrete incorporation nano particles have higher strength for lower water cement ratios (Yazdani & Mohanam, 2016). From fig. 1 we can say that for same water cement ratio concrete containing nano particles can exhibit strength higher than conventional concrete which does not contain nano particles.

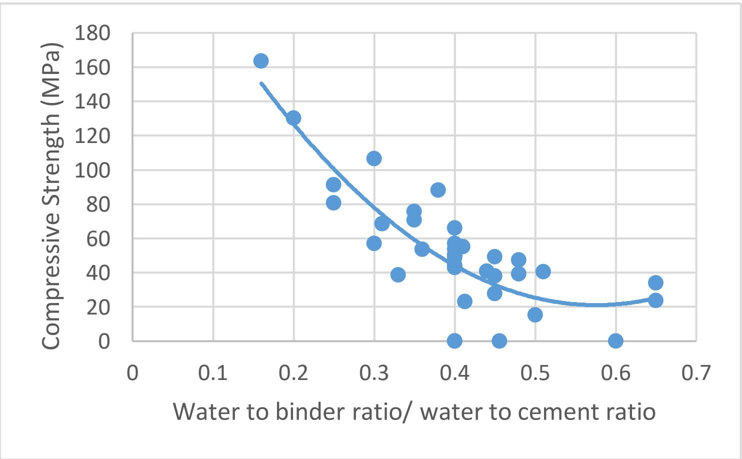

Fig. 1 Influence of water to binder ratio on compressive strength of nanoparticles

Table 2: Various parameters assessed in previous studies

Source	number of different mixes	Geometric shape of Compressive test specimens	Water to Cement ratio / water binder ratio	Nano particles replacement %	Compressive strength at 28 days (MPa)	Split Tensile strength at 28 days (MPa)	Flexural strength at 28 days (MPa)
(Bastami et al., 2014)	8	C_4	0.25	1.5 - 3	82.47 - 91.24	-	-
(Jalal et al., 2015)	14	S_1	0.38	2	51.8 - 87.9	3.6 - 4.8	3.9 - 7.3
(Atiq Orakzai, 2021)	12	C_3	0.51	0.5 - 2	18 - 40.47	2.5 - 4.58	3.1 - 5.84
(Palla et al., 2017)	18	C_3	0.23 - 0.3	0.5 - 3	35 - 57	2.2 - 5.9	7.6 - 9
(Liu et al., 2015)	18	-	0.25 - 0.5	1 - 5	15 - 80.6	-	-
(Ren et al., 2018)	8	S_2	0.4	1 - 5	10 - 55	-	-
(Shaikh et al., 2014)	13	C_3	0.4	1 - 6	14 - 37	-	-
(Mohseni et al., 2015)	22	S_3	0.4	1 - 5	37 - 43	-	-
(Vivek et al., 2020)	4	S_1	0.35	1 - 4	35.97 - 75.5	1.62 - 2.89	-
(Adak et al., 2014)	15	C_1	0.4	4 - 10	7 - 42.84	1.52 - 4.02	3.2 - 7.28
(Mukharjee & Barai, 2014)	8	S_1	0.4	0.75 - 3	40.67 - 49.89	2.12 - 2.63	4.33 - 4.97
(Kotop et al., 2021)	12	S_2	not used	2.5 - 7 and 0.01 - 0.02	29 - 65	-	9.4 - 12.6
(L. G. Li et al., 2018)	24	S_1	0.30 - 0.45	0 - 1	37.8 - 106.3	-	-
(Nazari & Riahi, 2010)	6	S_2	0.4	1 - 5	31.6 - 48.7	1.6 - 2.9	4.2 - 6.3
(Faez et al., 2020)	13	S_1	0.48	0 - 3	26.1 - 47.34	2.9 - 4.41	-
(Z. Li et al., 2006)	3	C_2	0.4	3 - 7	16 - 57	-	-
(Zhan et al., 2019)	4	-	0.456	0 - 4	12 - 59	-	-
(Sun et al., 2020)	10	S_2	0.4 - 0.6	1 - 3	30.35 - 53.3	-	3.68 - 6.32
(Thangapandi et al., 2020)	5	S_1	0.45	0.25 - 1	27.5 - 53.5	2.00 - 4.3	2.2 - 5.1
(Praveenkumar et al., 2019)	7	S_2	0.413	0 - 5	23 - 48	1.7 - 2.9	4.3 - 7.1
(Gamal et al., 2021)	4	S_2	0.45	0.01 - 0.04 and 5%	49 - 61.36	2.7 - 3.8	10.39 - 12
(Haruehansapong et al., 2014)	9	S_3	0.65	3 - 12	23.52 - 36.32	-	-

Table 2: continued…...

Source	number of different mixes	Geometric shape of Compressive test specimens	Water to Cement ratio / water binder ratio	Nano particles replacement %	Compressive strength at 28 days (MPa)	Split Tensile strength at 28 days (MPa)	Flexural strength at 28 days (MPa)
(Chithra et al., 2016)	7	S_2	0.31	0.5 - 3	56.5 - 68.3	-	7.8 - 10.6
(Ashok et al., 2021)	6	S_1	0.40 - 0.48	1	39 - 66	3.28 - 5.00	3.76 - 4.61
(P. Jaishankar et al., 2017)	4	S_2	0.33	0 - 1	25.9 - 38.4	2.98 - 3.89	-
(Isfahani et al., 2016)	12	S_2	0.5 - 0.65	0.5 - 1.5	33.8 - 53.5	-	-
(Said et al., 2012)	6	C_3	0.4	0 - 6	44.0 - 75.0	5.0 - 6.8	5.0 - 6.8
(Kumari et al., 2016)	19	S_1	0.44	0.5 - 3	40.53 - 58.14	-	-
(Tawfik et al., 2018)	23	S_2	0.35	1 - 6	70.7 - 81.7	4.132 - 6.500	14.63 - 17.73
(Amin & Abu, 2015)	34	C_1	0.2	1 - 5	74.4 - 130.2	4.1 -9.4	12.9 - 22
(Nejad et al., 2018)	8	S_1	0.36	0.5 - 1	34.67 - 53.57	3.25 - 4.45	4.67 - 6.78
(Javad et al., 2018)	12	S_2	0.41	2	30 - 55	2.1 - 3.6	-
(Ganesh & Reheman, 2016)	6	C_1	0.4	0 - 2	50.1 - 67	6.47 - 8.13	8.37 - 11.22

Note: S1 = 150 mm* 150 mm * 150 mm cubes; S2 = 100 mm* 100 mm* 100 mm; S3 = 50 mm* 50 mm* 50 mm
C1 = 70.6 mm* 70.6 mm* 70.6 mm; C2 = cylindrical specimen of dia. 20 and height = 40 mm; C3 = 100 mm* 200 mm cylinders
C4 = 150 mm* 300 mm cylinders.

2.1.2. Influence of nano particles in concrete

The influence of nano particles in concrete has been studied extensively as shown in table 3. chemical composition of nanoparticles effects the properties of concrete. Before using nano particles in concrete, one must should have an idea of what is the chemical composition of nano particles using in concrete. Below table shows the chemical composition of nano particles used by different researchers.

Chemical Composition	SiO_2 (%)	Al_2O3 (%)	Fe_2O_3 (%)	TiO_2 (%)	Size (nm)	Specific surface area m^2/g
(Nazari & Riahi, 2011)	-	>99.9	-	-	15 ± 5	163 ± 20
(Mukharjee & Barai, 2014)	99.1	-	-	-	8 - 20	-
(Vivek et al., 2020)	99.88	-	-	-	-	202
(Siang et al., 2020)	99.5	-	-	-	20 - 30	180 - 600
	-	-	99	-	20 - 40	40 - 60
	-	-	-	99.5	15	60
(Mohseni et al., 2015)	99	-	-	-	15 ± 3	200
(Sharaky & Badawy, 2019)	89 and 99	-	-	-	18 nm	-
(Ren et al., 2018)	99	-	-	-	20 ± 5	250 ± 40
	-	-	-	99	10 ± 5	150 ± 20
(Liu et al., 2015)	99.5	-	-	-	30 ± 5	220 ± 3
	-	-	-	99	25 ± 5	50–80
	-	99	-	-	15 ± 5	180–250
(Krishnaveni & Senthil Selvan, 2020)	0.01 –0.015	99	0.009 - 0.012	-	-	-
(Li et al., 2006)	-	≥99.99	-	-	<150	10±5
(Nagendra et al., 2016)	99.97	-	-	-	-	-
(Supit & Shaikh, 2015)	99	-	-	-	25	160
(Saloma et al., 2015)	99.99	-	-	-	-	170 – 230
(Bastami et al., 2014)	99.89	-	-	-	45nm	60
(Nazari & Riahi, 2010)	-	-	-	99.9	15 ± 3	155 ± 12

Table 3: Chemical composition of different nano particles used by different researchers

Fig. 2 shows the results obtained from the studies summarized. Nano particles can act as nano fillers, filling the voids this reduces the voids in the structure of hydration products. Adding nano particles improves the early pozzolanic reaction which leads to the formation of C-S-H gel. This will help in early strength development of mortar can be accelerated further (Siang et al., 2020). When you replace nano particles in concrete it enhances the durability properties. This may be because nano particles possess large surface area which will act as pore filler in the matrix (Vivek et al., 2020). For a given water cement ratio, the strength of concrete having nano particles mixes obtained from either cube specimens or cylindrical specimens decreased with increase in % of nano particles replacement. This again may be due to its larger surface area and higher inter locking particle leading to the agglomeration (Shaikh et al., 2014). Adding nano alumina in concrete increases the density of concrete specimens which indirectly results in strength of concrete (Gowda et al., 2017).

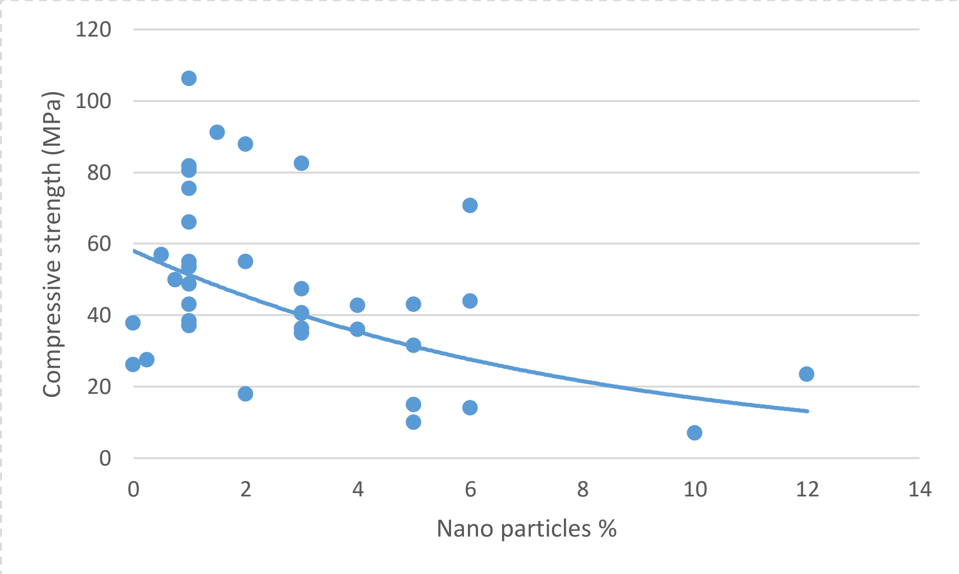

Fig. 2 influence of nano particles % on compressive strength

2.1.3. Influence of mineral admixture

Previous studies reported that adding mineral admixtures like silica fume, micro silica, ground granulated blast furnace slag etc., improves properties of concrete significantly (Mondal et al., 2010). Adding micro silica and nano silica in concrete improved the consistency which also reduces the bleeding and segregation(Jalal et al., 2015). Use of mineral admixture increased compressive strength of self-compacting concrete and compressive strength further increased when nano silica is added along with micro silica. This is due to its lower particle size that improves the concrete matrix thus increases the compressive strength of concrete (Massana et al., 2018).
Adding silica fume along with nano zinc oxide increased the consistency as these particles will have void filling effect due to its particle size there by improving the hydration process (Garg & Garg, 2020). Use of Silica fume 10% and nano alumina 2.5% combinedly resulted in reduced water absorption which will improve microstructure properties and durability properties of concrete (Faez et al., 2020). Adding silica fume at 5% and 10% by weight can improve the compressive strength as silica fume reacts with CH gel to produce more amount of C-S-H gel which will reduce the porosity during hydration there by increase in strength (Sharaky & Badawy, 2019).
Many studies have been done on utilization of fly ash as partial and/or full replacement of cement. Adding fly ash and nano particles together has shown a negative effect on workability but it also improves the compressive strength very significantly (Siang et al., 2020).

2.2. Split tensile strength and Flexural strength studies

Most of the studies reported higher split tensile and flexural strength than conventional concrete by adding nano particles. (Jalal et al., 2015) reported that split tensile strength enhanced by addition of nano titania up to 4%. (Prathebha et al., 2016) observed that by using nano silica 3% replacement there is an increase of split tensile strength by about 52%. (Tawfik et al., 2018) studied the effect of different nano particles on mechanical properties of concrete and observed that split tensile strength and flexural strength of concrete using nano particles has improved significantly and also observed that it may be due to at early ages, Ca(OH)2 consumption is the main reason of increasing the splitting tensile strength in mixtures containing nanoparticles. Fig 3 & 4 shows the split tensile strength and flexural strength results observed by various researchers. Most of the studies reported an increased trend up to certain limit of nano particles after that there is a decrease trend which is may be due to agglomeration.

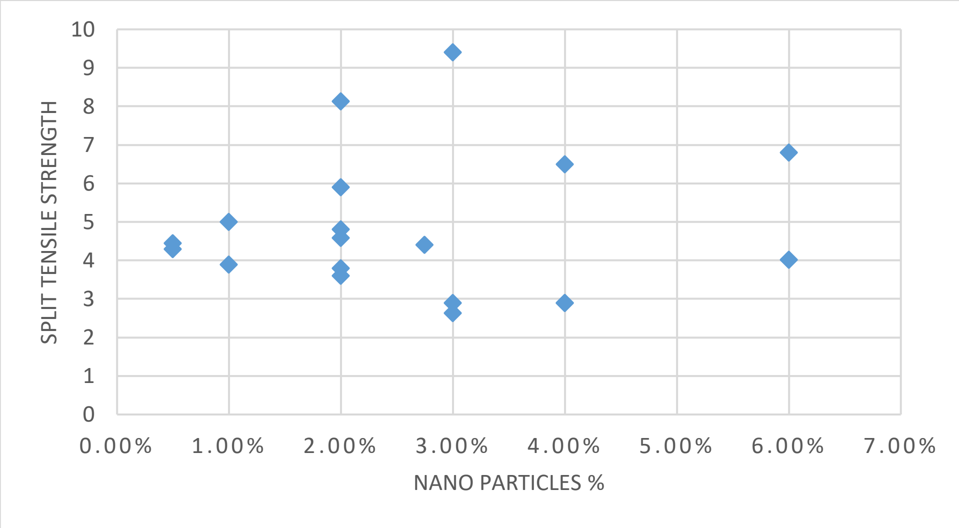

Fig. 3 Influence of nano particles % on Split tensile strength

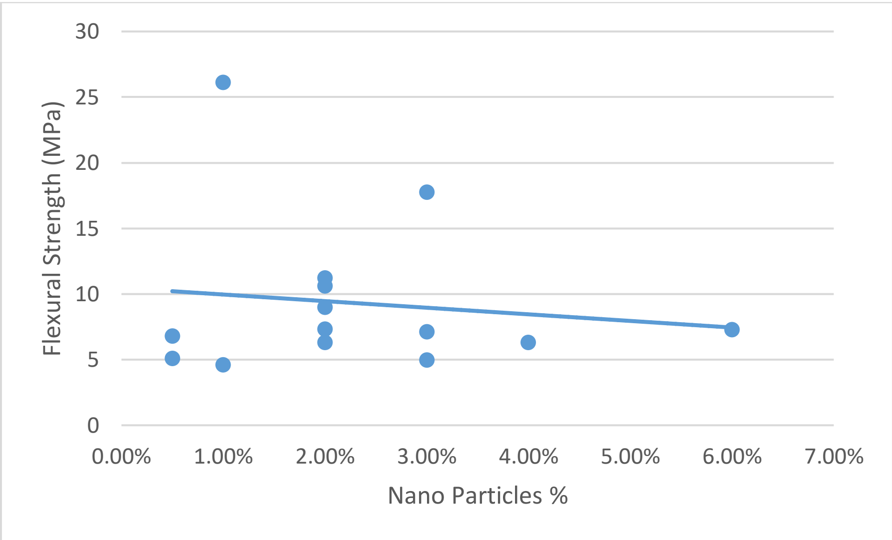

Fig. 4 Influence of nano particles % on Flexural strength

2.3. Correlation between compressive strength, split tensile strength and flexural strength

Generally, compressive strength is used to predict its split tensile strength and flexural strength. Several authors have studied and proposed a model to predict relation between Compressive strength, Split tensile strength and flexural strength (Ashwini & Srinivasa Rao, 2021; Jaber et al., 2018; Varghese Lincey et al., 2017). Fig. 5 & 6 shows the relation between compressive strength, split tensile strength and compressive strength, flexural strength. There is an increase in both split tensile strength and flexural strength with increase of compressive strength. (Katz, 2003) reported that the ratio of flexural strength to compressive strength ranges from 16-23% and that of split tensile strength to compressive strength is 9 – 13%.

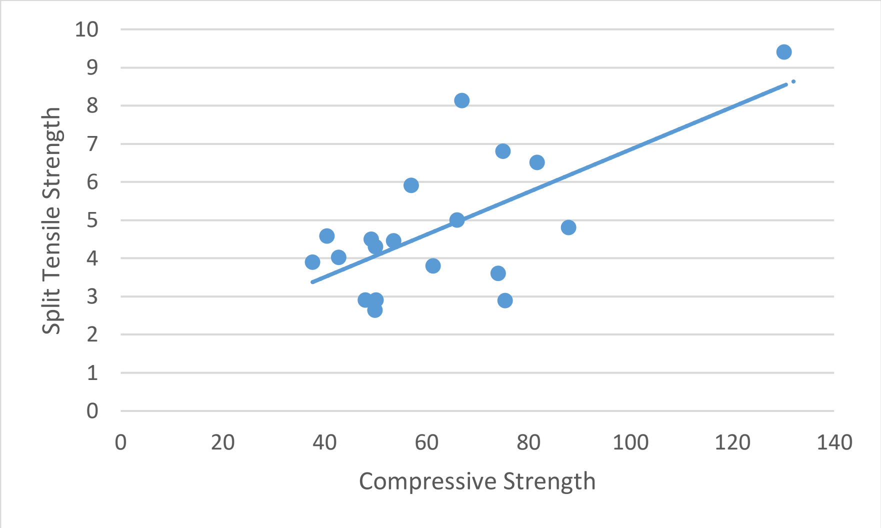

Fig. 5 Correlation between compressive strength and split tensile strength

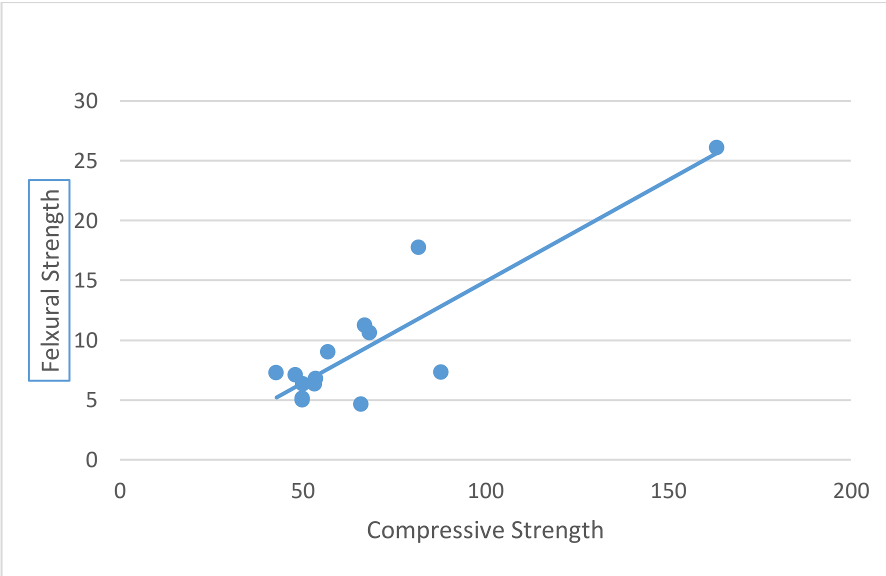

Fig. 6 Correlation between compressive strength and Flexural strength

2.4. Existing Studies on Durability of concrete using nano particles

Most of the studies has observed that adding nano particles to concrete improves the durability performance of concrete. This may be due to rapid formation of hydration products in the presence of nano particles. Adding nano materials reduced the pores there by reducing the water absorption (Madandoust et al., 2015). Similar to mechanical properties there will be great influence of water cement ratio, influence of nano particles and their size, influence of adding mineral admixtures on durability of concrete. There are many studies on durability characteristics of concrete using nano materials. Table 4 shows various durability studies done by various researchers.

Similar to compressive strength, improvement in pore structure improved the durability properties significantly for various researchers. (Madandoust et al., 2015) able to achieve enhanced durability properties by incorporating nano silica in concrete. (Jahangir & Kazemi, 2014) studied the durability properties of concrete and observed that addition of nano particles reduced porosity and improved resistance against sulphate attack.

Table 4: Durability properties studied by various researchers

Source	Permeability	Corrosion Resistance	Water Absorption	Freeze - thaw resistance	Sorpitivity	Chloride ion penetration resistance	HCL acid resistance
(Praveenkumar et al., 2019)	N	N	N	N	N	Y	Y
(Thangapandi et al., 2020)	Y	N	N	N	N	Y	N
(Rao et al., 2015)	N	Y	N	N	N	N	N
(Gamal et al., 2021)	N	Y	N	N	Y	Y	N
(Chithra et al., 2016)	N	N	Y	N	Y	Y	N
(Gowda et al., 2017)	N	N	Y	N	N	N	N
(Palla et al., 2017)	Y	N	Y	N	N	Y	N
(Madandoust et al., 2015)	N	Y	Y	N	N	Y	N
(Shekari & Razzaghi, 2011)	N	N	Y	N	N	Y	N
(H. Du & Pang, 2019b)	N	N	Y	N	Y	N	N

Note: Y – Studied; N- Not Studied

(Supit & Shaikh, 2015) studied the durability properties of high-volume fly ash concrete containing nano silica and he concluded that addition of nano silica reduced the sorptivity by about 20% - 40%. Also, there observed a significant reduction in chloride ion penetration by adding nano silica in concrete. (Campillo I et al., 2004) were able to achieve enhanced properties with the use of colloidal suspension types compared to the dry grain ones. The use of nano silica to improve the durability of concrete is as a result of its pozzolanic reaction and acceleration of the hydration reaction. Addition of nano particles improved the resistance to freeze and thaw this sis may be due to dense and more compacted microstructure. Improving the resistance to freeze and thawing helps the structure to not deteriorate in cold climates. (S. Du et al., 2019).

The use of nano particles has improved the properties of microstructure. Adding 1% nano alumina microstructure of cement mortar improved, become denser and voids also decreased but large crystals of $Ca(OH)_2$ were observed. With increasing the % of nano alumina $Ca(OH)_2$ has reduced thus microstructure of cement mortar became denser (Arefi et al., 2011).

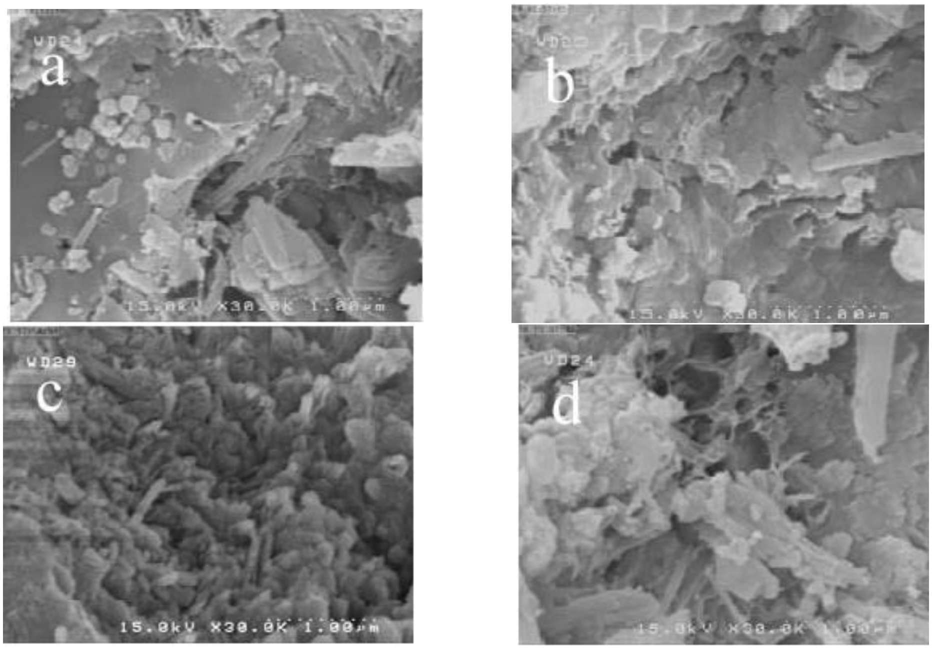

Fig.7 Microstructure samples of
a) Sample of CO. b) Sample of 1NA.
c) Sample of 3NA. d) Sample of 5NA.

3. Conclusion

This article summarizes the use of Nano particles for sustainable concrete development. By using Nano particles, we can reduce the contributions of the construction industry to global warming while using the accumulated amount of industry by-products in the correct mechanism and the industry can overcome these deficits and achieve a stronger and durable concrete. Based on the literature reviewed below are the points can be drawn for the use of nano particles.

- Nano particles are very finer in size. It has high surface area to volume ratio therefore consistent mix is possible.
- Mechanical properties have been increased by using nano particles in concrete however there is a limit of dosage.
- Nano particles improve the durability properties.
- Nano particles help concrete to set quickly.
- Nano particles increased rate of hydration there by attaining high early strength.
- Nano particles reduces calcium hydroxide, increases C-S-H gel which improves strength and durability.

- Microstructure analysis showed that by adding nano particles less or no voids or pores found in the microstructure. This may be due to formation of C-S-H.
- For higher dosage, as nano particles size is less, they may form agglomeration and poor dispersion of particles that affects the strength of concrete.

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