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Effect of nano alumina on some properties of sustainable reactive powder concrete

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ABSTRACT

Reactive powder concrete (RPC) is an ultra-high-performance concrete. It consists of very fine powder including cement, sand, silica fume, quartz powder, steel fiber, superplasticizer, and very low water to cementitious ratio. Reducing the high cement content in RPC by replacing it with nano-Al_2O_3 to produce environmentally friendly RPC was the objective of this study. In this research, 10% of the weight of fine aggregate was replaced with quartz sand. After that, 0.5%, 1%, and 1.5% by weight of cement was replaced with nano-Al_2O_3. compressive strength, flexural strength, and splitting tensile strength tests were performed. The findings exhibited the optimal percentage of nano-Al_2O_3 was 1% where the compressive, flexural, and splitting tensile strengths at 28 days increased by 10.57%, 20.89% and 15.68%, respectively, in comparison to the reference mixture.

Keywords: reactive powder concrete, nano Al_2O_3, compressive strength, flexural strength, splitting tensile strength.

INTRODUCTION

Concrete is among of the most commonly employed construction materials globally [Shi et al., 2011; Muhsin & Fawzi, 2021]. Cement constitutes the primary component of concrete, with its production process yielding over two billion tons of (CO_2) emissions each year, representing nearly 7% of global (CO_2) emissions. The production of cement is projected to attain over six billion tons annually by 2050 [Pacheco-Torgal et al., 2013]. To reach sustainability in civil engineering, there is significant interest in producing reactive powder concrete (RPC) utilizing eco-friendly materials to reduce the CO_2 emissions from cement production facilities [Muhsin & Fawzi, 2021; Hussain & Aljalawi, 2022]. Substantial efforts were undertaken diminish the negative impacts of cement on both the climate and the environment. A multitude of studies has been undertaken to investigate alternatives to cement, including the use of pozzolans and nanoparticles. Nanoparticles are more precisely defined as innovative composites of concrete. Nano materials are employed in the cement-based materials as additions and substitutes for improving essential mechanical and durability features due to their more reactive nature and extensive surface area [Reches, 2018]. The relatively small particle size of the nanoparticles strengthens the microstructure of the concrete material by occupying voids in the cement paste, hence augmenting the packing density [Jo et al., 2007; Li et al., 2017]. Nanoparticles increase the strength of cementitious materials by optimizing the process of hydrating of cement, leading to the development of C-S–H [Reches et al., 2018; Monasterio et al., 2015]. RPC denotes a high-performance concrete type distinguished by its exceptional durability and strength [Qasim & Fawzi, 2024]. Enhancing the characteristics of RPC through modifications to its internal structure or the replacement or incorporation of aggregates is increasingly recognized as an effective approach to achieve RPC with specific qualities suitable for various purposes within the construction field [Luti & Abbas, 2024]. Constitution engineers exhibit a pronounced interest in augmenting the mechanical features of cementitious composite components within their current concrete applications. The enhancement of compressive, tensile, and flexural strength represents some of the most sought-after mechanical attributes in concrete construction. The integration of nanoparticles into cementitious matrices is instrumental in achieving concrete mixes characterized by superior mechanical strength [Prathebha et al., 2016; Bautista-Gutierrez et al., 2019]. Within the various categories of nanoparticles, the incorporation of nano-Al_2O_3 into cementitious materials has undergone analysis by multiple researchers. The application of nano-Al_2O_3 may accelerate the synthesis of (C-S-H) gel, particularly during early stages, thereby enhancing the strength of composite materials [Liu et al., 2015; Muzenski et al., 2019; Yang et al., 2019]. According to Salim et al. [2023], the compressive and flexural strengths of the control mixture (RPC) and RPC with three different proportions of nano-alumina (1.5%, 3%, and 5%) replacing silica fume by weight were assessed. The findings indicated that the maximum compressive strength was 140.32 MPa, while the maximum flexural strength was 30 MPa in the mixtures containing 3% of nano-Al_2O_3. The mixtures containing 1.5% and 5% of nano-Al_2O_3 exhibited improved compressive and flexural strengths relative to the standard concrete mix. Preeth & Mahendran [2019] partially replaced cement with 0.5%, 1%, 1.5%, 2%, and 3% of nano-alumina. The findings shown that the addition of nano-alumina decreases the current crossing the surface of the concrete and raises the electrical resistivity of UHPC, probably owing to the enhanced packing of nano-Al_2O_3, which minimizes porosity. Chu et al. [2022] examined the viability of manufacturing UHPC with an improved elastic modulus utilizing nano-alumina. When compared to UHPC without NA, the findings indicated that adding NA increased the flexural strength by 7.38–16.87%, compressive strength by 4.08–20.58%, and the elastic modulus by 2.89–14.08%. In addition, the essential pores and porosity of UHPC were negatively affected by NA addition, indicating that NA may improve its pore structure. The aim of this research was to replace the cement with nano-Al_2O_3 to produce sustainable RPC, reducing pollution of the environment resulting from the cement industry and to assess the impact of nano-Al_2O_3 on specific properties of RPC.

MATERIALS AND MIX DESIGN

Materials used

Cement

OPC (CEM I–42.5R) was employed in all mixes and it complies with [I.Q.S No.5, 2019]. The chemical and physical properties displayed in Tables 1 and 2.

Fine aggregate

The fine aggregate utilized was classified as zone 4, according to [IQS No.45, 1984]. Table 3 present the properties of the fine aggregate. Table 4 present the sand gradation.

Silica fume

Silica fume (SF) was employed as an additive for all mixtures and it complies with [ASTM C1240, 2015]. Tables 5 and 6 present the properties of silica fume.

Table 1. Chemical properties of OPC

Oxide compositions	Content (%)	[I.Q.S No. 5-2019] limits
CaO	62.7	–
SiO_2	20.3	–
Fe_2O_3	4.4	–
Al_2O_3	5.1	–
MgO	3.7	Max 5
SO_3	2.16	$SO_3 \leq 2.8$ if $C_3A > 3.5$ $SO_3 \leq 2.5$ if $C_3A \leq 3.5$
IR	0.6	Max 1.5
LOI	2.5	Max 4

Table 2. Physical properties of OPC

Property	Results	[I.Q.S No. 5-2019] limits
Specific surface area – Blaine approach (m^2/kg)	382	≥ 280
Initial setting time (min)	170	≥ 45
Final setting time (h)	4:25	≤ 10
Soundness (%)	0.15	≤ 0.80
Compressive strength (MPa)		
2-days	24	≥ 20
28-days	45	≥ 42.5

Table 3. Physical and chemical properties of fine aggregate

Property	Results	I.Q.S No. 45/1984	Standard test
Specific gravity	2.6	–	ASTM C128
Fineness modulus	1.62	–	I.R Guide No.500/3,2018
Dry rodded density (kg/m^3)	1520	–	ASTM C29/C29M
Absorption (%)	1.05	–	ASTM C128
Sulfate content (%)	0.23	Max 0.5	I.R Guide No.500/3,2018

Table 4. Fine aggregate grading

Sieve size (mm)	Cumulative passing (wt.%)	[I.Q.S No. 45/1984] (Zone 4)
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	95-100
0.6	100	95-100
0.3	35	15-50
0.15	3	0-15

Quartz owder

Quartz powder (QP) was used in this experiment as it had been adequately refined to comply with the requirements [ASTM C 311, 2015]. Tables 7 and 8 presents the properties of quartz powder in accordance with ASTM-C 618, 2018.

Quartz sand

The quartz sand (QS) used in this research was obtained from the Ardhuma deposit in the Iraqi Western Desert. The quartz sand utilized in this study was classified as zone 4, according to [IQS No. 45, 1984]. The gradation of quartz sand is shown in Table 9. Table 10 presents the properties of the quartz sand. In this research, quartz sand was used as partial replacement of fine aggregate.

Chemical admixtures

A superplasticizer was included into the mixture to lower the water content and increase the concrete strength. This enhancement broadened the flow abilities and it complies with [ASTM C494, 2019], type G. Additional information regarding this additive can be found in Table 11.

Table 5. Chemical properties of SF

Oxide	Content %	[ASTM C1240] Requirement
SiO_2	92.62	Min 85%
Al_2O_3	0.35	–
Fe_2O_3	1.24	–
CaO	0.52	–
MgO	0.93	–
L.O.I.	3.4	Max 6%

Table 6. Physical properties of SF

Property	Results	[ASTM C1240] Requirement
Retained on (No.325) sieve, %	3.5	Max. 10
Strength activities index at 7 days, %	115	Min. 105
Specific surface area (m^2/kg)	20	Min. 15
Color	Grey	–

Table 7. Chemical properties of quartz powder

Oxide	Content (%)	[ASTM C618] Requirement
SiO_2	99.18	Min 70%
Al_2O_3	0.32	–
Fe_2O_3	0.02	–
CaO	0.1	–
MgO	0.295	–
L.O.I.	0.010	Max 6%

Table 8. Physical properties of quartz powder

Property	Results	[ASTM C618] Requirement
Retained on (No.325) sieve,%	32	Max. 34
Strength Activities Index at 7 days,%	85	Min. 75
Specific surface area (m^2/kg)	19	Min. 15
Color	White	–

Table 9. Quartz sand grading

Sieve size (mm)	Cumulative passing (wt.%)	[I.Q.S No.45/1984] (Zone 4)
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	95-100
0.6	100	95-100
0.3	50	15-50
0.15	3	0-15

Table 10. Physical and chemical properties of quartz sand

Property	Results	I.Q.S No. 45/1984	Standard test
Specific gravity	2.65	–	ASTM C128
Fineness modulus	1.45	–	Iraqi Reference Guide No.500/3,2018
Dry rodded density (kg/m^3)	1540	–	ASTM C29/ C29M
Absorption (%)	1.17	–	ASTM C128
Sulfate content (%)	0.09	max 0.5	Iraqi Reference Guide No.500/3,2018

Table 11. Properties of superplasticizer

Property	Specification
Appearance	Light yellow
Specific gravity	1.07 ± 0.02
PH	5–7
Dosage	0.5–3.5 L/100 kg of cementitious materials
Chloride content (%)	Nil

Water

Potable water was employed to adequately combine and cure the samples used in this study. The water utilized must be suitable for its intended purpose and comply with the standard requirements specified in [IQS. No. 1703, 2018].

Nano Al_2O_3

Nano Al_2O_3 used in this work was obtained from the SkySpring-Nanomaterials company. It had a diameter of 50 nm, as shown in Figure 1. It was used as cement replacement. Table 12 shows the physical properties of NA that were used.

Figure 1. Sample of nano-Al_2O_3

Table 12. Properties of nano Al_2O_3

Property	Specification
Appearance	White
Type	Alpha
Purity	99.9%
Form	Powder
Average particle size	50 nm
Density	3.5–3.98 g/cm^3

MIX DESIGN

Two groups of mixtures were studied based on Richard and Cheyrezy [1995], the first group consisted of three RPC mixtures depending on fine aggregate replacement by 10%, 20%, and 30% of quartz sand by weight. The optimum percentage was 10 % of quartz sand. The second group consists of replacing the cement with 0.5%, 1%, and 1.5% of nano-Al_2O_3 by weight. For all mixtures, the water to cementitious ratio (w/cm) was 0.19, the silica fume was 219 kg/m^3, the quartz powder 371 kg/m^3 and the superplasticizer was 2.5 liter for 100 kg of cementitious material. Tables 13 and 14 present the details of concrete mixtures

Mixing procedure

In this investigation, the method of Al-Hassani et al. [2014] was used to make RPC. For RPC concrete, the cement, silica fume, quartz powder and nano-Al_2O_3 were combined in a dry state for approximately 3 minutes to achieve uniform distribution of silica fume, quartz powder, and nano-Al_2O_3 particles inside the cement matrix, followed by the incorporation of sand, and the mix was thereafter mixed for five minutes (Fig. 2). The superplasticizer has to dissolve in water, and the solution that results is gradually introduced during the mixing process, culminating in a total mixing period of 3 minutes. The mixer ceased operation, necessitating manual mixing, especially in the regions inaccessible to the mixer blades. The mixer functioned for 10 minutes to attain sufficient fluidity. The complete mixing of one batch needs around 15 minutes following the incorporation of water into the mixture.

PREPARATION OF SPECIMENS AND EXPERIMENTAL LAB TESTS

Upon completion of the mixing method, the steel molds were prepped and cleaned.

Table 13. Details of RPC mixtures in kg/m³

Mixes	Cement	Sand	QS	SF	QP	SP L/100 kg of cementitious materials	Water
MR	950	1045	–	219	371	2.5	222
*MS_{10}	950	940.5	104.5	219	371	2.5	222
MS_{20}	950	836	209	219	371	2.5	222
MS_{30}	950	731.5	313.5	219	371	2.5	222

Note: *After many trials with different percentages (10%, 20%, 30%) of quartz sand, this ratio has been selected due to its mixture giving higher compressive strength compared with other percentages.

Table 14. Details of RPC mixtures in kg/m³

Mixes	Cement	Sand	Nano Al_2O_3	QS	SF	QP	SP L/100 kg of cementitious materials	Water
MR	950	940.5	–	104.5	219	371	2.5	222
$MN_{0.5}$	945.3	940.5	4.7	104.5	219	371	2.5	222
MN_1	940.5	940.5	9.5	104.5	219	371	2.5	222
$MN_{1.5}$	935.8	940.5	14.2	104.5	219	371	2.5	222

Figure 2. Materials of RPC

Thereafter, the concrete was poured into the molds with vibration. Nylon covers were subsequently laid over the specimens. The molds were removed afterwards to a 24-hour interval. The specimens were then cured in hot water at 75 °C for 7 and 28 days.

Flow test

The flow of RPC calculated according to ASTM C1437, 2017, by using Eq. (1). The test stopped and the flow value calculated after 25 strokes during 15 s.

$$Flow = \left[\frac{D-100}{100}\right] \times 100 \tag{1}$$

where: D – represents spread rate on the base diameter for the concrete from 4 measurements in (mm) (Fig. 3).

Compressive strength test

The compressive strength of the RPC samples was found according to ASTM C 109/C 109M, 2020] by using a compression device. The cubes utilized in this test have dimensions of 50 × 50 × 50 mm. This test was conducted on concrete cubes aged 7 and 28 days. The compressive strength was established by mean (3) of the samples for each age. The compressive strength of each cube has been calculated based on Eq. (2).

$$F = \frac{P}{A} \tag{2}$$

where: F – compressive strength in (MPa), A – loaded surface area in (mm²), P – maximum load in (N).

Flexural strength test

Flexural strength of the RPC samples was found according to ASTM C293-19, 2019, using a flexural device. The prisms used in this test had

Figure 3. Steps for flow table test

Figure 4. Casting, testing, and failure of sample

dimensions of 250 × 50 × 50 mm. This test was conducted on concrete prisms aged (7 and 28) days. The flexural strength was established by mean (3) of the samples for each age. The flexural strength of each prism has been calculated based on Eq. (3) (Fig. 5).

$$Fr = \frac{3Pl}{2bd^2} \tag{3}$$

where: Fr – Flexural strength in (MPa), P – Failure load (N), L – The distance between the rollers of support in (mm), b – width of specimen in (mm), d – thickness of specimen in (mm)

Splitting tensile strength test

Splitting tensile strength of the RPC samples was found according to ASTM C496-17, 2017, using a compressive device. The cylindrical specimens used had dimensions of 100 × 200 mm. This test was conducted on concrete cylinders aged 7 and 28 days. The splitting tensile strength was established by mean (3) of the samples for each age. The splitting tensile strength of each cylinder has been calculated based on Eq. (4) (Fig. 6).

$$T = \frac{2P}{\pi dl} \tag{4}$$

where: T – splitting tensile strength (MPa), P – max applied load in (N), d – diameter in (mm), L – length in (mm).

RESULTS AND DISCUSSION

Flow test

The flow ability of mixes with nano-Al_2O_3 decreased in comparison to the flow ability of the

Figure 5. Casting, testing, and failure of sample

Figure 6. Casting, testing, and failure of sample

reference mixture. This arises from the large surface area of the nano-Al_2O_3 particles, allowing an increased rate of water absorption. The flow significantly decreases with a 1.5% replacement of nano-Al_2O_3 [Gowda et al., 2017], as shown in Table 15 and Figure 7.

Compressive strength

The compressive strength of the reference mixture increases with 0.5% and 1% nano-Al_2O_3 and then decreases, although the findings of 1.5% remain higher relative to the reference mixture. The use of 1.5% nano-Al_2O_3 particles reduces the compressive strength to a level close to that of the control concrete. This may be because of the additional amount of nano-Al_2O_3 particles in the mixture could exceed the necessary quantity needed to interact with the generated lime during hydrating, resulting in an excessive amount of silica leaking and a reduction in strength, since it substitutes some of the cementitious material without enhancing strength. Additionally, it may result from the defects produced during the spread of nanoparticles, leading to weak zones [Nazari et al., 2010], as illustrated in Table 16 and Figure 8.

Flexural strength

The flexural strength of the reference mix increases with 0.5% and 1% nano-Al_2O_3 replacement. This is because the incorporation of small particles will strengthen the structure of the concrete material by filling several voids within it [Fawzi & Fala, 2009; Alsaedy & Aljalawi, 2021]. Conversely, the flexural strength decreased with nano-AL_2O_3 1.5% replacement, but remained higher than the reference mix, owing to the potential for agglomeration formation, which resulted in a weak bond between nano-Al_2O_3 and the surrounding matrix [Mirjalili et al., 2009]. Also, this is due to the voids created by the agglomeration of nano-Al_2O_3 particles and the other constituents in the RCP mixture [Mahmood & Kockal, 2021]. This is illustrated in Table 17 and Figure 9.

Table 15. Effect of NA on the RPC mixtures flow

Mix type	Flow (%)
MR	110
0.5% NA	100
1% NA	90
1.5% NA	80

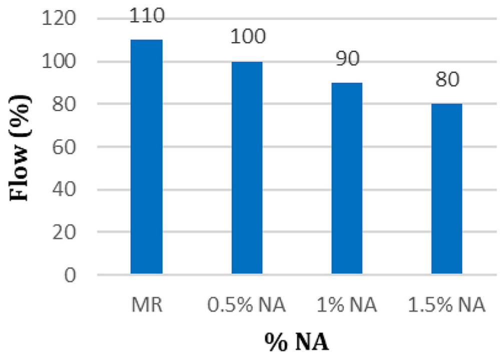

Figure 7. Effect of NA on the RPC mixtures flow

Table 16. Results of compressive strength

Mix type	Compressive strength (MPa)		Increase in compressive strength (%)	
	7 days	28 days	7 days	28 days
MR	85	104	–	–
0.5% NA	89	109	4.70	4.80
1% NA	95	115	11.76	10.57
1.5% NA	86	105	1.17	0.96

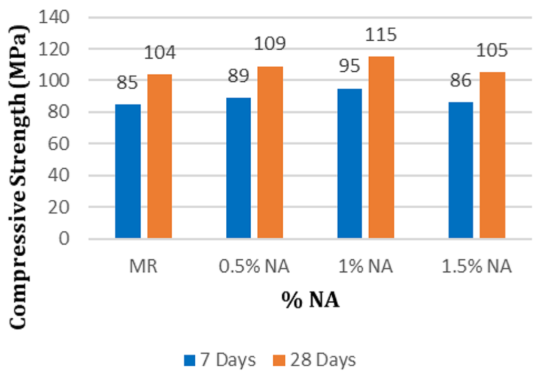

Figure 8. Effect of NA on the compressive strength of RPC

Table 17. Results of flexural strength

Mix type	Flexural strength (MPa)		Increase in flexural strength (%)	
	7 days	28 days	7 days	28 days
MR	11.2	13.4	–	–
0.5% NA	12.6	15.5	12.5	15.67
1% NA	15.3	16.2	36.60	20.89
1.5% NA	12.1	14.7	8.03	9.70

Splitting tensile strength

The splitting tensile strength of reference mix increases with nano-Al_2O_3 0.5% and 1% replacement this may arise from the extensive surface

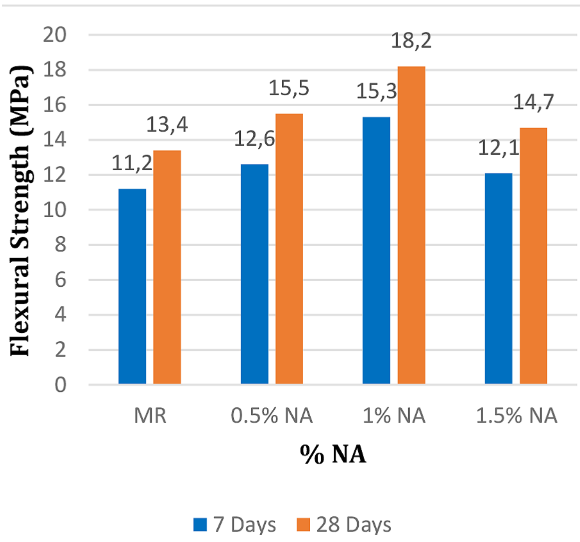

Figure 9. Effect of NA on the flexural strength of RPC mixtures

area of nanoparticles, which enhances pozzolanic reactions leading to the development of C-S-H gel and a comprehensive enhancement in strength [Atiq Orakzai, 2021]. Conversely, the tensile strength decreased with 1.5% nano-AL_2O_3 replacement, but remained higher than in the reference mix. The reduction in splitting tensile strength is due to the agglomeration of nanoparticles, which enhances concrete porosity and exacerbates stress concentration in the concrete under load [Chen et al., 2012]. Also, the presence of fine particles significantly hinders the ability of cement pasteto adequately cover all fine and coarse particles, resulting in a reduction of the reactive clinker component. It reduced the adhesion between cement and aggregate, this leads to a reduction in tensile strength [Aljalawi, 2021], as illustrated in Table 18 and Figure 10.

Table 18. Results of splitting tensile strength

Mix type	Splitting tensile strength (MPa)		Increase in splitting tensile strength (%)	
	(7 days)	(28 days)	(7 days)	(28 days)
MR	8.1	10.2	–	–
0.5% NA	8.9	11	9.87	7.84
1% NA	9.6	11.8	18.51	15.68
1.5% NA	8.6	10.6	6.17	3.92

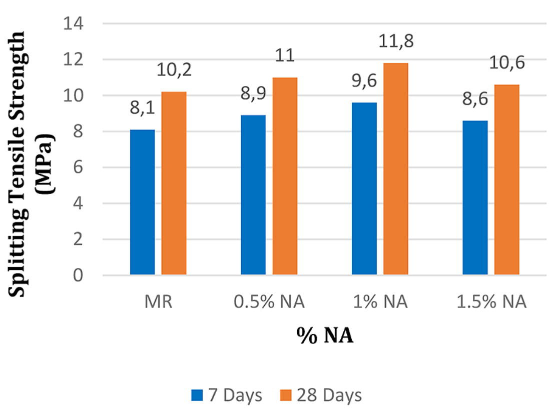

Figure 10. Effect of NA on the splitting tensile strength of RPC mixtures

CONCLUSIONS

As a result of the characteristics of reactive powder concrete, the most prominent of which is high cement content, this research focused on producing reactive powder concrete mixtures sustainably to reduce environmental pollution through decreasing cement consumption by replacing it with nano-Al_2O_3.

On the basis of the experimental results, replacing (10%) of the weight of fine aggregate with quartz sand increased the compressive strength. Nano Al_2O_3 enhances the mechanical properties of RPC because it fills the voids present in the concrete. The flow ability of reactive powder concrete decreased with nano-Al_2O_3 due its high surface area which led to higher water absorption. The compressive strength at 28 days with 0.5%, 1%, and 1.5% nano-Al_2O_3 replacing, increased by 4.80%, 10.57%, and 0.96% in comparison to the reference mix. The flexural strength at 28 days with 0.5%, 1%, and 1.5% nano-Al_2O_3 replacing, increased by 15.67%, 20.89%, 9.70% respectively. The splitting tensile strength at 28 days with 0.5%, 1%, and 1.5% nano-Al_2O_3 replacing increased by 7.84% 15.68% and 3.92% respectively.

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