Research Article

Effect of aqueous sodium silicate on properties of recycled aggregate mortar

Babar Ali[1]

Abstract

This study investigates the influence of sodium silicate (Na_2SiO_3) (NS) on the strength and durability performance of recycled concrete aggregate bearing mortar (RAM). NS is used as 0%, 1%, 2%, 3%, 4%, and 5% by weight of cement in RAM. Natural aggregate mortar (NAM) serving as control mix is also produced using natural sand. Compressive strength, sorptivity coefficient, apparent porosity, chloride penetration, and mass loss due to H_2SO_4 are investigated at various ages. Experimental results indicate that RAM shows inferior strength and durability properties compared to NAM. RAM with 2–3% NS shows 4–9% higher compressive strength than NAM. 2–3% NS also improves the durability of RAM by significantly reducing water sorptivity and permeable porosity compared to corresponding blank mix. RAM shows significant mass loss due to H_2SO_4 attack compared to NAM, whereas, RAM with 2–4% NS shows acid attack resistance comparable to that of the NAM. Based on experimental results, it can be established that RAM with 2–3% NS can outperform NAM by noticeable margin in strength–durability–economic performance.

Keywords Recycled concrete aggregate (RCA) · Sodium silicate (Na_2SiO_3) · Compressive strength · Sorptivity coefficient · Chloride penetration · Acid attack on mortar

1 Introduction

In 2014, Freedonia group estimated that demand for world construction aggregates will reach up to the level of 51 billion tones per annum in 2019 [1]. Until 2012, the overall construction and demolition waste (CDW) generation reached the level of 3.0 billion metric tones per annum in 40 major countries [2] and this rate is constantly increasing. To solve sustainability issues, part of the total demand for construction aggregates can be satisfied by the using recycled concrete aggregates (RCA) from CDW.

Although incorporating high volumes of RCA in concrete/mortars may reduce the consumption of natural reserves of aggregates, but the strength and durability of product composite are usually jeopardized. Generally, RCA is less dense compared to natural aggregate owing to presence of less dense old cement paste. Water absorption of RCA is more than natural aggregates because during the crushing of old concrete most of the particles that contribute to RCA comes from sand and old cement paste [3]. In order to maintain workability of fresh RCA bearing mortar (RAM) or concrete additional water is required to satisfy the absorption capacity of aggregates [4–6], which in effect decreases the strength and durability of product composite [5, 6]. Aghabaglou et al. [7] reported that RAM shows lesser mechanical strength than natural aggregate mortar (NAM) but RAM exhibits more strength development rates than NAM after 28 days. They also reported that RAM shows significantly lower durability than NAM in terms of water absorption and chloride penetration. Although, data pertaining to effect of fine RCA on the performance of mortars is not widely available, most of drawbacks of using fine RCA in concrete/mortars are

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inferior mechanical performance and durability compared to natural aggregate composites [6, 8–11].

The lower strength of composites made with coarse/fine RCA can increase its cost to strength ratio [12, 13]. But studies conducted to evaluate the performance of RCA (as replacement of natural aggregates) in concrete have shown it as an economical and eco-friendlier practice than disposing of RCA in landfills and backfilling [14–17].

Sodium silicate (NS) has been used as a chemical activator in hybrid alkaline cement concrete/mortar systems and has become an essential component of alkaline solutions for manufacturing of geopolymers [18, 19]. Shayan et al. [20] used NS for surface treatment of coarse RCA and reported that the formation of calcium silicate hydrates on the surface of RCA improves its quality. NS has been proved as a most efficient activator in hybrid alkaline cements and has been used in various applications such as well cement, accelerator, waterproofer, acid resistant for concrete, etc. [21]. NS can also been used as surface impregnates to repair RC structures [22–25].

There are a limited number of studies available that dealt with the issue of lower strength and durability associated with incorporation of a high volume of fine RCA in concretes/mortars. Most of the research has focused on the treatment of coarse RCA, mainly because coarse aggregates comprise a major portion of concrete, generally 60–75%. Aghabaglou et al. [7] used binary and ternary binders to investigate their effects on properties of RAM in comparison to NAM, and they reported significant improvements in strength and durability parameters of RAM.

Present study is aimed at investigating the effect of NS on the performance of RAM. Compressive strength, permeable porosity, sorptivity, chloride penetration, acid attack resistance of NS modified RAM are evaluated and compared with NAM. This study also performs the cost to strength ratio analysis (CSR) in order to ascertain the combined economic and strength performance of NS modified RAM mixes with respect to NAM.

2 Research significance

Primary goal of CDW recycling plant is to produce coarse RCA because it will cost enormous energy to produce fine RCA directly. Apparently, fine RCA is produced as by-product containing old cement paste in significant amounts. Old cement paste increases the water absorption of RCA, therefore, when higher volume of fine RCA is used in mortar/concrete, fresh and hardened properties are badly affected. This is one of the main reasons why the use of fine RCA in cement-based composites is not recommended. Therefore, comprehensive studies are required to find appropriate application areas in cement-based composites for effective utilization of fine RCA. In the present study, an economical and environmental-friendly methodology is proposed in order to improve the properties of RAM using smaller dosages of NS. Results of experimental testing indicate that RAM with 2–3% NS shows comparable strenght and durability performance to that of the NAM without geopardizing economy.

3 Experimental program

3.1 Materials

3.1.1 Binder

General purpose cement of type I adhering to ASTM C150 [26] was used as binder. Details of the physical and chemical properties of cement are given in Table 1.

3.1.2 Fine aggregates

Natural aggregates used in this research was obtained from Lawrance Pur quarry. Concrete specimens of grade C30/37 were crushed intentionally to obtain coarse RCA. After screening the coarse RCA, the waste passing through 4.75 mm sieve was used as fine RCA in this research.

Table 1 General properties of Portland cement

Chemical characteristics	Result (%)	Physical characteristics	Result
SiO_2	22.5	Specific gravity	3.08
Al_2O_3	5	Specific surface (m^2/kg)	322
Fe_2O_3	4.0	Consistency	29.25%
CaO	64.25	Initial setting time	1 h, 53 min
MgO	2.5	Final setting time	3 h, 58 min
SO_3	2.9	Soundness	No expansion
Na_2O	0.2	28 days compressive strength	41.56 MPa
K_2O	1	–	–
Loss on ignition	0.64	–	–

General properties of fine aggregates are given in Table 2. Fine RCA is anticipated to contain high volume of hydrated cement paste and sand. RCA is finer than natural aggregates in terms of fineness modulus and is expected to absorb large quantities of water because of the presence of higher quantities of old cement paste.

3.1.3 Sodium silicate (NS)

Commercial grade NS having 50% water and 50% pure Na_2SiO_3 was used in this research. NS has $SiO_2/Na_2O = 2$, specific weight of 1.51 g/cm^3 and pH value of 12.04.

3.1.4 Water

No admixture was used to manipulate workability of mortars. Tap water free from organic impurities was used for all mortar mixtures.

3.2 Mix proportions

Seven different types of mortar mixtures were produced, as shown in Table 3. First mortar mix (NAM) is a control mix having natural aggregates. Whereas in remaining mixes (of RAM) fine RCA was used as aggregate with six different dosages of NS (0%, 1%, 2%, 3%, 4%, and 5% by weight of cement). Quantities of ingredients in each mix are also given in Table 3. 192 kg of water was used in each mixture to hydrate cement, whereas, additional water was also added to mortar mixes to compensate fine aggregates' absorption capacity. Fine RCA has higher water absorption compared to natural aggregates; therefore, large quantity of additional water was required by RAM mix. NS solution has 50% water, therefore deductions in total water were made for all the mixes involving NS.

3.3 Mixing procedure

Mixing of all mortar mixes was done in a mechanical mixer of Hobart type. For, NAM, RAM and NS modified RAM, different mixing procedures were adopted, see Fig. 1. For NAM, fine aggregates and binder were dry mixed for about 3 min and then actual amount of water required by NAM was added and mixing continued for about next 3 min. For RAM, firstly fine RCA was mixed with ½ of the total water for about 6 min to allow RCA enough time to absorb water. After that cement and remaining amount of water were added and mixed for about further 4 min. For NS modified RAM mixes, first fine RCA was mixed with ½ of total water for about 6 min, then cement and NS (required) were added with remaining ½ of water to mix and blending continued for about next 4 min. All RAM mixes were mixed for a total duration of 10 min, so that extra water required by fine RCA was properly absorbed. Rodrigo et al. [27] explained that most (80–90% of total moisture absorbed in 24 h) of the moisture required by RCA was absorbed in

Table 2 General properties of fine aggregates

Type of FA		Sieve aperture size (mm)						Fineness modulus	Bulk density (kg/m^3)	Sp. gravity	24-Hours water absorption (%)
		4.75	2.36	1.18	0.6	0.3	0.15				
Fine RCA	Passing (%)	100	96.43	74.23	45.32	21.57	8.92	2.678	1624	2.68	1.45
NFA[a]		100	94.56	81.34	41.57	27.56	11.54	2.432	1412	2.43	7.89

[a] *NFA* natural fine aggregates

Table 3 Nomenclature and composition of mortar mixtures

Mix ID	Mix proportions in kg per cubic meter of mortar							
	Type of aggregate	Cement	Fine aggregate	Water required by cement	NS	Water from NS	Extra water required by aggregates	Effective water
NAM/Ref-1	NFA	490	1470	245			21	266
RAM/Ref-2	RFA	490	1278	245			101	346
RAM/1%NS	–	490	1278	245	4.9	2.45	101	343
RAM/2%NS	–	490	1278	245	9.8	4.9	101	341
RAM/3%NS	–	490	1278	245	14.7	7.35	101	338
RAM/4%NS	–	490	1278	245	19.6	9.8	101	336
RAM/5%NS	–	490	1278	245	24.5	12.25	101	334

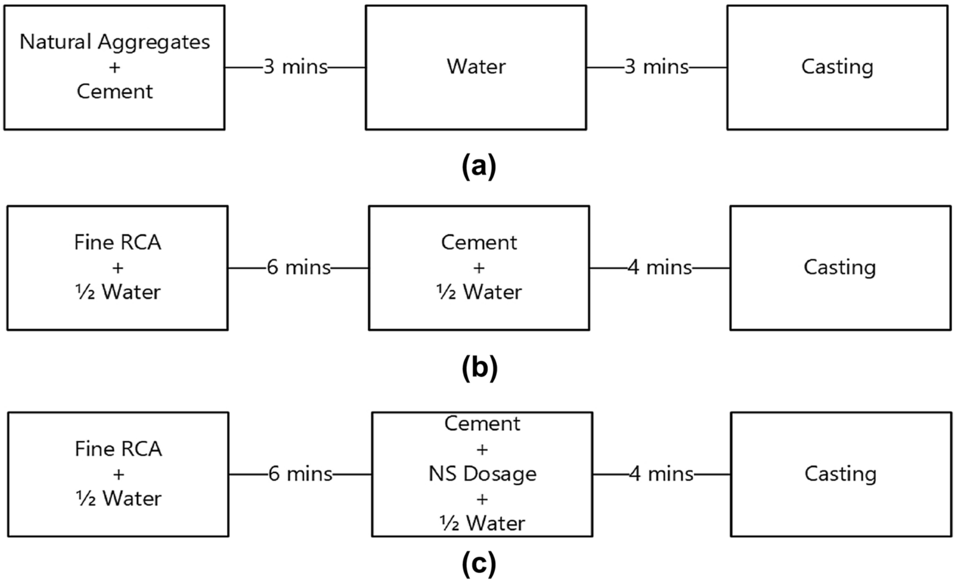


Fig. 1 Mixing procedure of **a** NAM, **b** RAM and **c** NS modified RAM

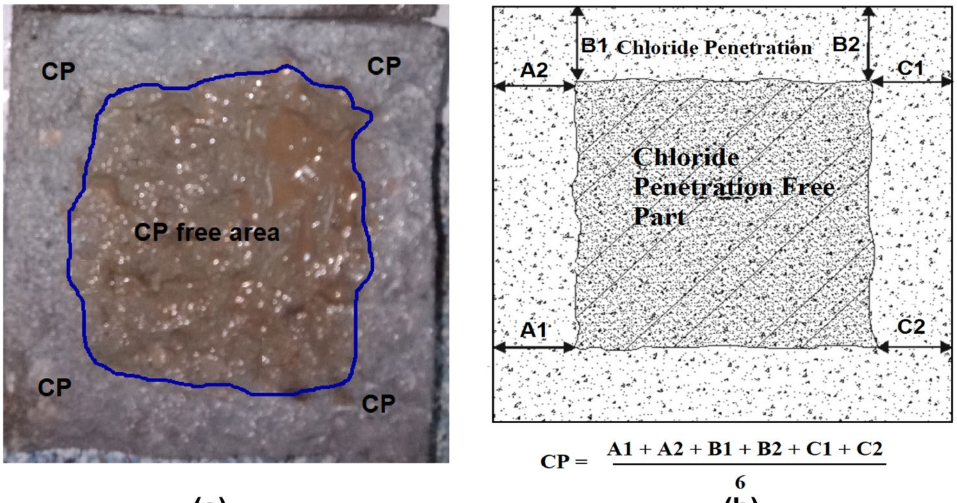
10 min of mixing. Kurda et al. [4, 9] also followed similar methodology and reported favorable results.

3.4 Preparation and testing of mortar specimens

In Table 4, methodology is given to evaluate the performance of RAM with varying dosage of NS. All specimens were cast following well-developed international standards. After casting, samples were allowed to set for 24 h and then cured in water tank after demolding until the age of testing reached. For compressive strength, $50 \times 50 \times 50$ mm^3 cubes of each mix were cast and tested following ASTM C109 [28]. For sorptivity coefficient and permeable porosity, mortar cylinders of 100 mm diameter and 200 mm height were cast, demolded after 24 h of casting, then cured in normal water until the age of testing. Then three discs of mortar were cut from each mortar cylinder using wet-stone cutter (after trimming 50 mm from both top and bottom of the cylinders). Each disc had a diameter of 100 mm and thickness of 50 mm. These mortar discs were tested for sorptivity and permeable porosity following the procedures under ASTM C1585 [29] and ASTM C948 [30], respectively. Compressive strength and both durability parameters (sorptivity coefficient and permeable porosity) were tested at four ages, i.e. 3, 28, 90 and 180 days for all mixes. Three replicate samples were tested for each strength and durability parameter presented in this paper. In order to calculate chloride penetration, $100 \times 100 \times 100$ mm^3 cubes were cast for each mix. After curing these mortar mixes in normal water for 7-days, these specimens were dried in oven for 3-days at 60 °C. After oven drying, specimens were immersed in 5% sodium chloride (NaCl) solution for 28-days. Then specimens were split into two halves, and 0.1 Normality solution of silver nitrate ($AgNO_3$) was sprayed over the failed surface. $AgNO_3$ reacted with penetrated chloride ions and produced white colored compound namely silver chloride (AgCl). Chloride penetrations were calculated as shown in Fig. 2. Similar methodology was adopted by Ali and Qureshi [31]. To study the sulfuric acid (H_2SO_4) attack resistance of mortar mixes, $100 \times 100 \times 100$ mm^3 cubical specimens of each mortar mix were cured in both normal water and 4% H_2SO_4 solution for 28-days. Loss

Table 4 Experimental testing and number of specimens used for evaluation of influence of NS on RAM

Properties	Mixture type						
	NAM/Ref-1	RAM/Ref-2	RAM/1%NS	RAM/2%NS	RAM/3%NS	RAM/4%NS	RAM/5%NS
Compressive strength (3, 28, 90, and 180-days)	3	3	3	3	3	3	3
Permeable porosity (3, 28, 90, and 180-days)	3	3	3	3	3	3	3
Sorptivity coefficient (3, 28, 90, and 180-days)	3	3	3	3	3	3	3
Chloride penetration (28-days)	3	3	3	3	3	3	3
Acid attack resistance (28-days)	3	3	3	3	3	3	3



(a) (b)

Fig. 2 **a** Visual observation of chloride penetration (CP) and **b** formula for calculation of CP

Table 5 Unit cost of different materials used in this research

Material	Unit price	
Cement	0.079	Dollars/kg
Cost of natural fine aggregate	0.00362	Dollars/kg
Cost of fine RCA	0.0021	Dollars/kg
NS	0.145	Dollars/kg

in mass and compressive strength of each mortar cube under 4% H_2SO_4 attack was calculated with respect to mortar cube cured in normal water.

3.5 Methodology for cost to strength ratio (CSR) analysis

CSR analysis of all mortar mixes was conducted by considering the cost of 1 m^3 of each mortar mix and its compressive strength at the age of 28 days. Costs of materials used in this research are given in Table 5. Cost of cement and natural were taken from suppliers, whereas, cost of fine RCA was measured by its quality, due to the absence of any CDW recycling plant in Pakistan and its price was taken as the price of cheap sand used for backfilling (having higher silt content). Another reason for assuming lower price for fine RCA than natural aggregates, is that fine RCA is often produced involuntarily in the manufacturing of coarse RCA from CDW [32]. Price of NS of laboratory grade was considered. Only material costs were used to estimate cost of 1 m^3 of each mortar mix and cost of mixing was not considered. CSR is calculated as given in Eq. (1).

$$\mathrm{CSR} = \frac{\text{Cost of 1 m}^3\text{ mortar mix}}{\text{28 - Days' compressive strength}} \tag{1}$$

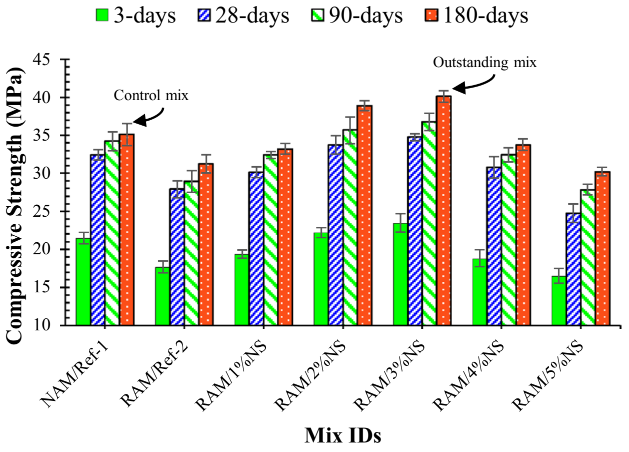


Fig. 3 Compressive strength of each mortar mixtures at the age of 3, 28, 90, and 180 days

4 Results and discussion

4.1 Compressive strength

Compressive strength is considered as the most effective material property of cement composites in determining their behavior under the action of different loads. Most of the characteristics of cement composites can be correlated with its compressive strength. Results of compression testing of each mix are illustrated in Fig. 3. Relative strength performance of mortar mixes with respect reference NAM (Ref-1) and reference RAM (Ref-2) is also presented in Table 6. Overall trend shows that replacement of natural aggregates with fine RCA reduces the compressive strength. Compressive strength of RAM increases 25–28% with 2–3% addition of NS compared

Table 6 Relative compressive strength of each mixture

Mix IDs	$f_{cMIXES}/f_{cRef\text{-}1}$				$f_{cMIXES}/f_{cRef\text{-}2}$			
	3-Days (%)	28-Days (%)	90-Days (%)	180-Days (%)	3-Days (%)	28-Days (%)	90-Days (%)	180-Days (%)
NAM/Ref-1	100.0	100.0	100.0	100.0	–	–	–	–
RAM/Ref-2	82.3	86.0	84.5	89.0	100.0	100.0	100.0	100.0
RAM/1NS	90.2	93.0	94.7	94.6	109.6	108.1	112.1	106.4
RAM/2NS	103.4	104.1	104.2	110.8	125.6	121.0	123.3	124.6
RAM/3NS	109.3	107.2	107.4	114.3	132.9	124.6	127.2	128.5
RAM/4NS	87.6	94.9	94.8	96.2	106.5	110.4	112.2	108.1
RAM/5NS	76.7	76.3	81.4	86.1	93.2	88.7	96.3	96.8

to Ref-1. At these dosages of NS, RAM outperforms conventional NAM.

The compressive strength of RAM reduces by about 17% compared to NAM. This is caused by presence of low density adhered mortar present in RCA as noted by researchers [6, 9] [33]. Whereas, at later ages reduction in compressive strength of RAM is about 11%, which can be attributed to hydration of old cement paste present in RCA [6]. It is noticed that RAM mixes develop higher compressive strength at higher rates between 28 and 180 days compared to NAM. Researchers agree that concrete with fine RCA obtained from crushing of old concrete carry higher amounts of calcium hydroxide (CH) than conventional concrete [3, 34, 35]. Generally, CH does not contribute to strength at early ages and it may leach out in curing water.

NS affects the strength parameters following chemistry explained by Eq. (2). Hydration of cement produces calcium hydroxide (CH) in addition to a durable cementing product known as calcium silicate hydrate gel (CSH) [36]. CH does not contribute to strength at early ages and it may drain out in curing water leaving small channels in microstructure. Therefore, as explained by Eq. (2) reaction of CH with NS produces CSH gel which can add to compressive strength of composite. Shayan et al. [20] used NS as surface treatment of coarse RCA and reported that CSH gel is produced on the surface of coarse aggregate. NS in RAM can also react with CH present in adhered mortar, which also contributes to strength development.

Increasing NS dosage 0–3% compressive strength of RAM improved sufficiently. At 3% NS compressive strength of RAM increases by about 14% with respect to NAM. This can be ascribed to increased consumption of CH by NS to produce CSH gel. Upon increasing the dosage of NS beyond 3% compressive strength begins to decrease. 3% NS can be considered optimum to improve compressive strength of RAM. No significant difference in the strength values of plain RAM and NS modified RAM is noticed at NS dosage greater than 3%. This is ascribed to increase in alkalinity level of mortar matrix, as NS releases NaOH when CSH gel is formed, see Eq. (2). This NaOH is suspected to decrease the compressive strength as reported by Martinez et al. [37] that alkali activation of hybrid alkaline cementing systems using NaOH showed reductions in compressive strength of concrete as equilibrium shifts towards the left side of Eq. (3). They also explained that as the alkaline concentration increases, it reduces the degree of hydration of CS-anhydrates. Due to this reason, compressive strength can be reduced at dosages of 4–5%. But reductions in compressive strength at 4–5% NS were not drastic compared to plain RAM (Ref-2), see Table 6, in which relative strength performance of each mixture is presented with respect to Ref-1 and Ref-2. Hence it can be concluded that 2–3% of NS can be used to enhance the compressive strength of RAM. Another reason for reduction in compressive strength of RAM at 4–5% NS can be blamed to lowered workability, as NS reduces the workability of concrete compared to plain concrete [18].

$$\mathrm{Na_2SiO_3} + \mathrm{Ca(OH)_2} \xrightarrow{\text{yields}} \text{CSH gel} + \mathrm{NaOH} \tag{2}$$

$$\mathrm{C_3A} + 2\mathrm{H_2O} \leftrightarrow \text{CSH gel} + \mathrm{Ca(OH)_2} \tag{3}$$

4.2 Permeable porosity and sorptivity coefficient

Results of permeable porosity and sorptivity coefficient testing are shown in Figs. 4 and 5, respectively. Deterioration of cement-based materials mainly depends on their permeability characteristics. Different gaseous ions and liquids by infiltrating the material of concrete react with durable cementing products which in effect significantly change the properties of material. Pore volume of the cement-based materials also affect its durability and strength characteristics.

As shown in Figs. 4 and 5, RAM (Ref-2) has lower durability in terms of permeable porosity and sorptivity coefficient. This can be blamed to lower density of fine RCA compared to natural aggregates, as shown in Table 2. When old concrete is crushed most of the particles which

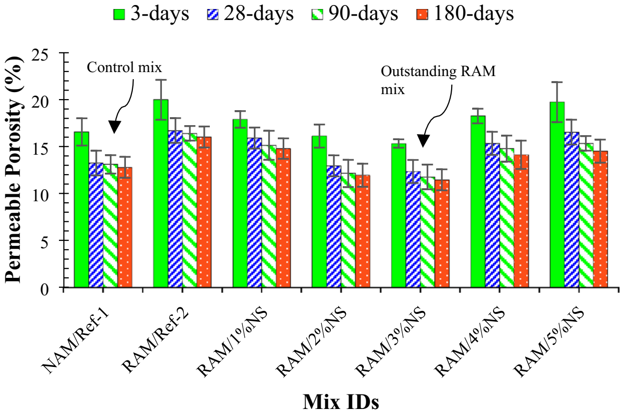


Fig. 4 Permeable porosity of each mortar mixtures at the age of 3, 28, 90, and 180 days

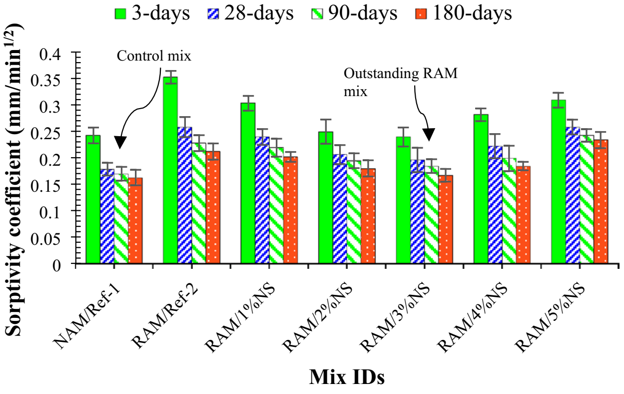


Fig. 5 Sorptivity coefficient of each mortar mixtures at the age of 3, 28, 90, and 180 days

contribute to fine RCA are from sand and old cement paste, both of these are less dense compared to particles which are contributed by stone aggregates. Therefore, the net increase in pores volume causes the increase in permeable porosity and sorptivity coefficient of the composite material. Kurda et al. [8] also reported that the inclusion of fine RCA was harmful to concrete in terms of water absorption characteristics of product composite.

NS up to 3% reduces both permeable porosity and sorptivity coefficient. Formation of additional CSH gel can be the reason for the reduction in porosity as explained by Eq. (2). Development of CSH gel can reduce the length of interconnected pores which consequently reduces the sorptivity and permeability of the material. NS act as both plasticizer and activator [21]. An activator like sodium sulphate is also known to increase the consumption of portlandite (CH) which also reported to reduce the permeability of mortar with binary blended cement [38]. RAM mixes have significant amounts of CH in both new and old mortar, means that RAM has a huge potential to develop CSH. With 2–3%NS, RAM mixes outperform Ref-2 by significant margin.

It is worth mentioning here that with the increasing age, all NS modified RAM mixes showed improvements in studied parameters i.e. strength, porosity, and sorptivity. This confirms that presence of NS is not harmful to the durability of mortar and can be used as a solution to improve durability properties of RAM.

4.3 Chloride penetration (CP)

Mortars are not used for steel-reinforced structures, but these are used as the matrix for holding coarse aggregates to produce concrete. Therefore, CP determination is the relevant durability parameter. CP is referred to the depth up to which Cl ions penetrate into the cement-based material from the environment (usually from soils, and seawater). Penetrated chlorides are the main cause of steel corrosion in RC structures; therefore, studying CP is very important to assess durability of cement-based materials. Chloride ion penetration mechanism is very complex and involves water diffusion, impregnation, and sorption. Results of CP testing are shown in Fig. 6. It is observed that RAM has significantly higher CP than NAM. The main reason for this behavior is the lower density of RAM compared to NAM. High volume of pores in RAM helps chloride ions to penetrate easily through specimen. Previous studies have also attributed high CP into concrete incorporating RCA due to its lower density [31, 39].

Inclusion of NS creates the CSH by reacting with CH. This leads to reduction in the length of interconnected pore volume of material; therefore, RAM with NS addition shows significant improvement in CP resistance. Results of CP follows trend of porosity and sorptivity testing with

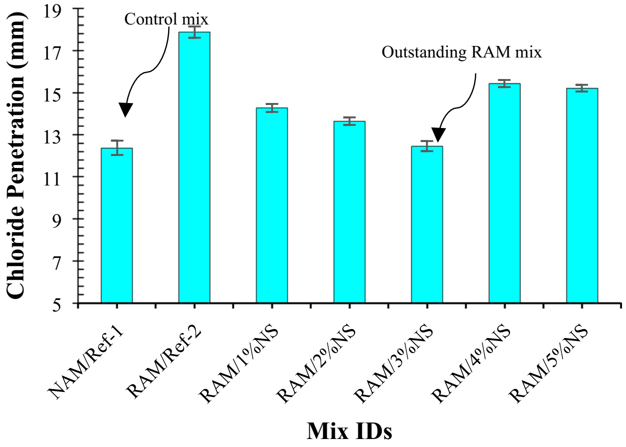


Fig. 6 Chloride penetration in each mortar mix after 28-days immersion in 5% NaCl solution

varying NS. It is worth mentioning here that none of the NS modified RAM mixes show CP resistance more than NAM. But RAM with 3%NS shows comparable CP resistance to that of the NAM.

4.4 Acid attack resistance

Like CP, measuring acid attack resistance is a relevant durability parameter because cement-based materials have numerous applications where they encounter highly acidic environments. In this research acid attack resistance of RAM modified with NS is reported as the loss in mass and compressive strength due to H_2SO_4 attack. $Ca(OH)_2$ is the most vulnerable component of cement-based materials that can easily react with H_2SO_4 leading to production of gypsum. Production of gypsum causes expansion due to increase in internal pressure and results in the loss of mass and strength reduction of material. Since RAM contains higher contents of $Ca(OH)_2$ (present in old RCA and new cement paste); therefore, it is more prone to acid attack. Loss in mass and compressive strength of NS modified RAM mixtures due to H_2SO_4 attack are shown in Fig. 7. NS modified RAM mixes show significant improvement in acid attack resistance over plain RAM. NS modified mixes show better resistance over the plain RAM due to consumption of $Ca(OH)_2$ by NS to produce CSH as explained by Eq. (2). Moreover, reduction in porosity of RAM due to NS inclusion can restrict the flow of sulfate solution into the microstructure of mortar.

4.5 Correlations

4.5.1 Correlation between compressive strength and permeable porosity

Exponential and power equations are derived to predict permeable porosity of mortar from its compressive strength, see Fig. 8. Both relationships indicate that compressive strength and porosity depends on each other, see Eq. (4). Compressive strength mainly depends on the gel density, and water absorption is the function of size

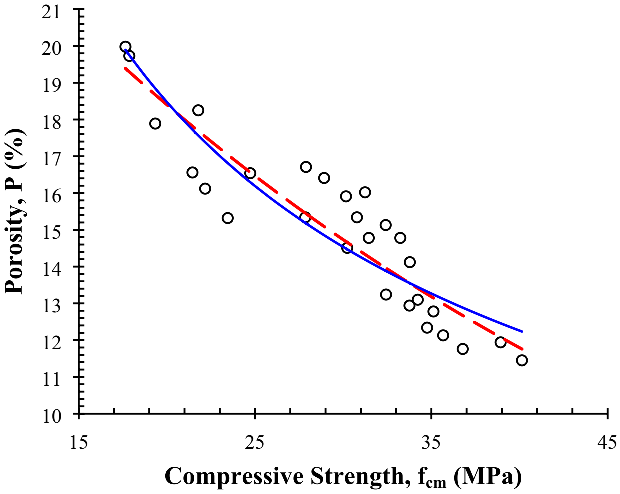
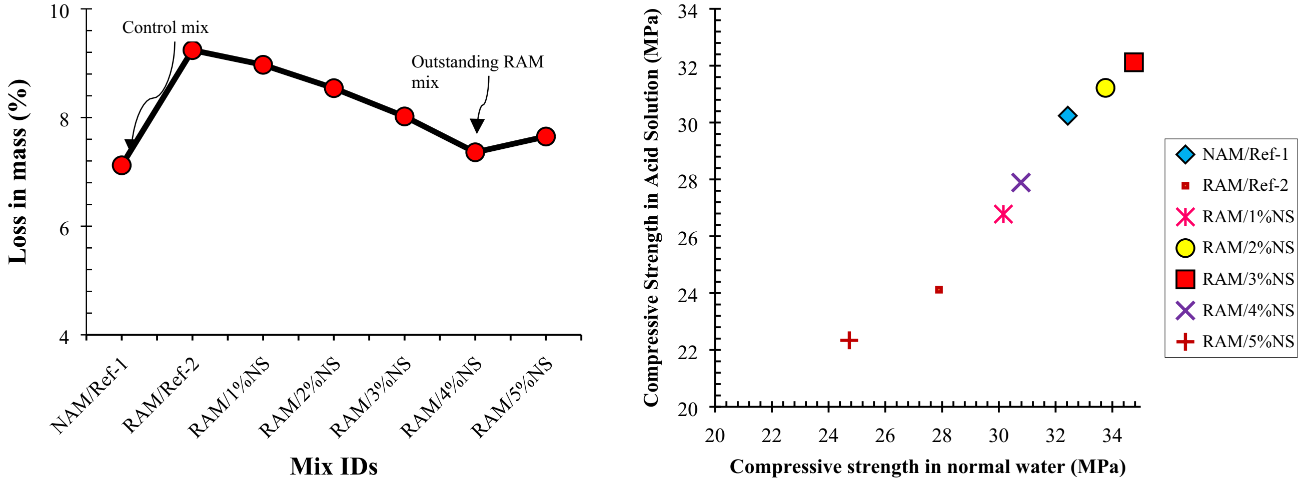


Fig. 8 Correlation between experimental values of porosity and compressive strength



(a) (b)

Fig. 7 **a** Mass loss due to acid attack and **b** comparison of compressive strength of mortar mixes cured in normal water and 4% H_2SO_4 acidic solution and distribution of pore volume. Generally, compressive strength improves with the reduction in pore volume, therefore, both parameters are inversely proportional to each other.

$$P\,(\%) = \begin{cases} 108.76 \times f_{cm}^{-0.6} \\ 28.71 \times e^{-0.022 f_{cm}} \end{cases} \left(3, 28 \text{ and } 90 \text{ and } 180\text{ - days, } R^2 \geq 0.80\right) \tag{4}$$

where P is the permeable porosity (%), and f_{cm} is the compressive strength (MPa).

4.5.2 Correlation between compressive strength and sorptivity coefficient

Correlation between experimental values of sorptivity coefficient and compressive strength is shown in Fig. 9. It is observed that sorptivity coefficient reduces with increasing compressive strength. Both power and exponential relationships are derived, see Eq. (5). These relationships have good degree of predictability ($R^2 > 0.80$).

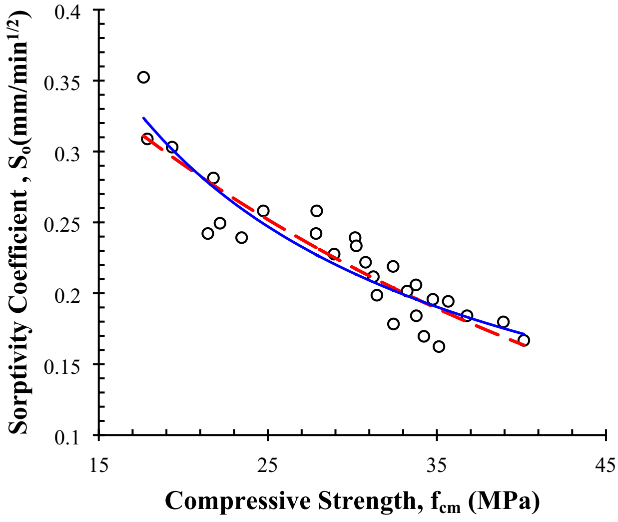


Fig. 9 Correlation between experimental values of sorptivity coefficient and compressive strength

The sorptivity coefficient mainly depends on the length and inter-connectivity of capillary pores in material of mortar. With the increase in the pore volume connectivity and length of pores may increase, hence both permeable porosity and sorptivity can be directly correlated. Compressive strength of material can be reduced with increasing porosity or sorptivity of material.

$$S_o = \begin{cases} 2.99 \times f_{cm}^{-0.78} \\ 0.515 \times e^{-0.029 f_{cm}} \end{cases} \left(3, 28 \text{ and } 90 \text{ and } 180\text{ - days, } R^2 \geq 0.80\right) \tag{5}$$

where S_o is sorptivity coefficient (mm/min$^{1/2}$), and f_{cm} is compressive strength (MPa).

Compressive strength and both permeability parameters exhibit a good relationship for power and exponential expressions. As explained by Basheer et al. [40] [41] that most of the of strength and permeability characteristics of cement-based materials depend on pore volume of the material, that's why both compressive strength and permeability properties showed decent values coefficient of determinations (> 0.8), see Figs. 8 and 9. Some studies [38, 42] have also shown that compressive strength can be correlated to permeability, chloride penetrability, and chloride diffusion with fair accuracy. These studies provided inverse relationships between strength and permeability indices of concrete.

5 Cost to strength ratio (CSR) analysis

The total cost of each mortar mix is shown in Table 7. Using the prices of material from Table 5 and quantities of different materials under a mix are given in Table 2, the cost of 1 m^3 of each mortar mix was calculated. It can be noticed in Table 7 that the replacement of fine RCA with natural aggregates does not bring a huge deal of economy as most of the cost of mortar relies on quantity and price of

Table 7 Total cost of each mortar mix in USD per cubic meter

Mix ID	Cement (USD)	Fine aggregate (USD)	NS (USD)	Total cost (USD)	Relative cost
NAM/Ref-1	38.71	5.32	0.00	44.0	1.00
RAM/Ref-2	38.71	2.68	0.00	41.4	0.94
RAM/1%NS	38.71	2.68	0.71	42.1	0.96
RAM/2%NS	38.71	2.68	1.42	42.8	0.97
RAM/3%NS	38.71	2.68	2.13	43.5	0.99
RAM/4%NS	38.71	2.68	2.84	44.2	1.00
RAM/5%NS	38.71	2.68	3.55	44.9	1.02

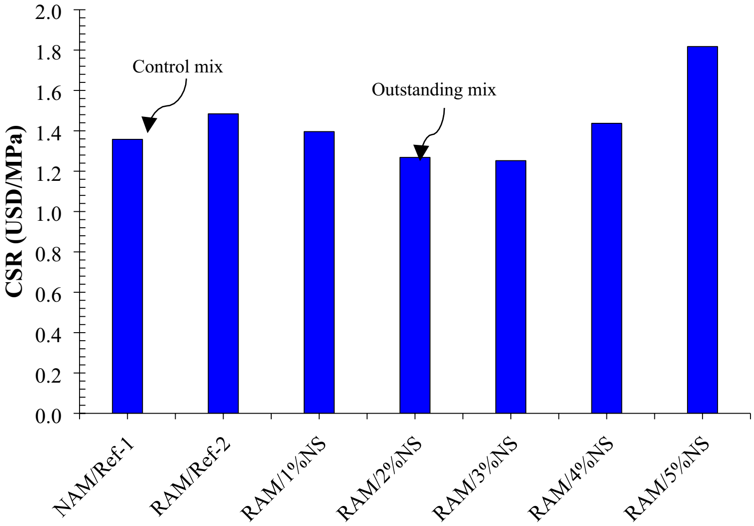


Fig. 10 CSR of all mixes at the age of 28 days

cement. CSR of each mix was calculated using Eq. (1) and results are presented in Fig. 10. CSR of RAM indicates that replacing fine RCA with natural aggregates is not a good option from combined strength and economic point of view. CSR of RAM increases mainly because of its lower strength. The inclusion of NS in RAM improves compressive strength that is why CSR is reduced. Minimum CSR value is associated to RAM with 2–3% ANS. Increasing NS dosage beyond 3%, does not affect the compressive strength of RAM that is why CSR is increased to the highest values. So, optimum dosage from CSR point of view can be considered as 2–3% of NS.

Although fine RCA does not bring the huge deal of economy but other benefits associated with the consumption of RCA cannot be neglected. Using the CDW waste materials can save valuable reserves of natural aggregates for the future. Problems related to the disposal of waste materials can be avoided. Increasing the consumption of fine RCA in cement composites will augment the life cycle of concrete structures.

6 Conclusions

Following conclusions can be drawn from this research paper:

1. 2–3% NS by weight of cement increases compressive strength of RAM by 20–28%. RAM with 2–3% NS has 4–6% higher compressive strength than conventional RAM.
2. Porosity and sorptivity of RAM is significantly higher than that of the NAM. RAM modified with 3% NS shows 21% and 29% reduction in sorptivity and porosity, respectively, compared to plain RAM.
3. CP of RAM is 45% higher than that of the conventional NAM. Maximum reduction in CP of RAM is noticed at 3% NS dosage, where, RAM exhibits durability comparable to that of the conventional NAM.
4. RAM is extremely vulnerable to H_2SO_4 due to its high porosity and increased $Ca(OH)_2$ content. NS modified RAM mixes show acid attack resistance comparable to that of the NAM. At 2–3% NS, acid attack resistance of RAM increases by 13% and 7% in terms of mass and compressive strength loss, respectively.
5. Both power and exponential expressions are derived between experimental values of permeability-related durability parameters (i.e. porosity and sorptivity) and compressive strength. Microstructural developments that increase the compressive strength, also contributes to durability enhancement of mortars.
6. CSR analysis concludes that despite lower cost, RAM has lower performance than NAM. 2–3% of NS can significantly reduce the CSR of RAM compared to that of the NAM.
7. Considering economic-strength-durability performance of mortars, RAM with 2–3% NS offers optimum results; therefore, can be considered as a better substitute of conventional RAM.

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Compliance with ethical standards

Conflict of interest Author has no conflict of interest to declare.

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