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ORIGINAL ARTICLE

Effect of mineral additives and two-stage mixing on the performance of recycled aggregate concrete

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Abstract
There is an increasing tendency to use recycled aggregate to produce concrete due to diminishing sources of natural aggregate. The properties of recycled aggregate concrete (RAC) are inferior to that of normal aggregate concrete. Several strategies including the use of supplementary cementitious materials (SCMs) are adopted to improve the properties of RAC. The two-stage mixing approach (TSMA) is also used as an improvement strategy. The present study was aimed to examine the individual and combined effects of using SCMs and TSMA on the fresh and hardened properties of RAC. Three SCMs, namely, fly ash, ground granulated blast furnace slag, and silica fume were used with and without TSMA. The experimental data indicated the beneficial effect of SCMs and TSMA on workability, strength, shrinkage, and durability of RAC. Further, the cost per unit strength of the RAC with SCMs and TSMA was less than that of RAC without any treatment. The use of developed RAC will lead to technical, economic, and environmental benefits.

Keywords Mineral additives · Supplementary cementitious materials · Two-stage mixing approach · Recycled aggregate · Concrete · Mechanical properties · Durability

Introduction

Coarse aggregate is one of the ingredients that is used in highest amount for producing normal concrete mixtures. However, the depleting natural sources of coarse aggregates necessitates to find alternative sources [1, 2]. At the same time, the disposal of construction and demolition waste is often costly and hazardous for the environment [3]. To address these issues, several studies have been carried out towards utilizing coarse aggregates extracted from the construction and demolition wastes in producing concrete. The coarse aggregate extracted from the construction and demolition wastes to produce new concrete is commonly termed as recycled aggregate (RA) [4–7]. The studies conducted to evaluate the performance of recycled aggregate concrete (RAC) [8–12] indicated that the quality of RAC is inferior to that of natural aggregate concrete (NAC), mainly due to the weak interfacial transition zone (ITZ) between the old mortar on the surface of the RA and the new mortar. The main reason behind a weak ITZ is the pesence of microcracks and pores in the old mortar adhering on the surface of RA. Notwithstanding this trait, efforts have to be made to identify methods that can improve the properties of RAC at least on par or above that of NAC. Research is being carried out globally to develop strategies to improve the performance of RAC [13–19].

The strategies for improving the quality of RAC can be broadly categorized as: (i) grading or proportioning, (ii) mixing, (iii) improvement of RA, and (iv) improvement of concrete matrix (mortar). A brief review of the strategies

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used to improve the quality of RAC is presented in the following paragraphs.

Bui et al. [20] used a proportioning technique that improved the mechanical properties of RAC by replacing larger size particles of natural aggregate (NA) with RA. By adopting this strategy, replacement of NA with RA could be increased up to 50% from the conventional replacement limit of 30%. Pradhan et al. [21] used a grading technique known as particle-packing method to lessen the voids of concrete which eventually yielded significant improvements of resulting RAC.

Tam et al. [22] developed a two-stage mixing approach (TSMA) to improve the properties of RAC. In the TSMA, coarse aggregates are first mixed with cement mortar for sealing the cracks on the RA surface as well as for improving the bond between RA and new cement mortar [23]. The TSMA approach helps in shifting the ITZ outwards and helps in sealing the cracks on the surface of RA [23]. Two other mixing approaches, namely, mortar mixing approach (MMA) and sand enveloped mixing approach (SEMA) were also reported in the literature to enhance the mechanical properties of RAC [24, 25]. However, the TSMA is regarded as better than other mixing approaches due to its cost effectiveness as well as its simple implementation [24].

Several researchers focused on the improvements of RA itself through primarily coating RA with slurries to improve the qualities of RAC. Junak and Sicakova [26] used geopolymer slurry to coat the RA to produce good quality RAC. They reported that coating during mixing produces better RAC than that with pre-coated RA. Some researchers [27] used nano-slurry to improve the surface of RA. In another instance, a combination of normal Portland cement and nano-slurry was employed to improve the quality of RA [28]. Shi et al. [29] used slurries of three different supplementary cementitious materials (SCMs): fly ash, silica fume and natural pozzolan, and CO_2 treatment to modify the RA. They reported that silica fume slurry treatment was better than other treatments. Similarly, Kou et al. [30] used CO_2 treatment to modify the properties of RA. RAC produced using CO_2-treated RA exhibited good durability and mechanical properties. The performance of RAC can be further enhanced by combining limewater treatment with CO_2 treatment, as it will result in extra calcium in the mortar pores that increases the quality of RA [31].

A number of reported studies concentrated on the concrete matrix (mortar) to improve the performance of RAC. The matrix improvement was primarily initiated by replacing part of Portland cement with different SCMs (fly ash, silica fume, and natural pozzolan) while preparing fresh RAC. The inclusion of ground-granulated blast-furnace slag (GGBFS) and silica fume in RAC through mixing was reported to improve the microstructural properties of RAC, thereby improving the durability and mechanical properties significantly [32–37]. Use of fly ash in RAC is also reported to be beneficial in the long run [38, 39]. Akter and Sarmah [40] used silicon-rich char instead of SCMs and found significant performance enhancement of RAC. Senaratne et al. [41] used 0.6% steel fiber with 30% RA to improve the quality of RAC. Some researchers used crumb rubber [42] or a combination of crumb rubber and silica fume [43] along with steel fibers to improve the compressive and the flexural properties of RAC. A combination of 10% silica fume and 5% crumb rubber was recommended for steel fiber reinforced RAC [43].

Recently, a trend of combining one or more of the above-mentioned strategies has been adopted to further enhance the performance of RAC. Rajhans et al. [44, 45] combined the TSMA with concrete matrix improvement techniques, by adding silica fume and fly ash in the concrete mixture and obtained RAC of higher compressive strength than the with individual application of improvement strategies. Similarly, Pradhan et al. [21] used particle-packing method along with the conventional TSMA and was able to produce satisfactory RAC with 100% RA. Most recently, the use of biomaterials, such as calcium precipitating bacteria, are being investigated to enhance the performance of RAC [46, 47]. Although bacterial treatment has shown promising results, further research is required for its practical applications [48].

Although some studies, as summarized earlier, have been conducted to improve the properties of RAC, most of them require pre-treatment of RA. The pre-treatment of RA often requires additional setup and time, which makes them inconvenient for practical applications. On the other hand, the use of SCMs is convenient as it does not require additional setup. The use of TSMA approach is reported to have good effect on the improvements of RAC and, additionally, it does not require extra materials. A few studies reported in the literature considered use of both mineral additives and TSMA together for improving the quality of RAC [44, 45]. Further, there is lack of detailed information regarding the effect of the treatment of RA on the durability of RAC mixtures. Some researchers considered the durability aspects; however, they focused only on some indirect durability indices without considering the direct evaluation of the resistance of RAC mixtures (prepared using mineral additives and TSMA) against corrosion of steel reinforcement. In the present study, the effect of mineral additives (fly ash, GGBFS, and silica fume) used as SCMs and the application of TSMA on the mechanical properties, durability characteristics, and drying shrinkage behavior of RAC were evaluated, followed by comparative cost analysis of the developed RAC mixtures. Specifically, this study features indirect assessment of durability of RAC, through water absorption and chloride permeability, and a direct assessment of qualitative corrosion behavior through monitoring corrosion potentials of steel rebars embedded in the developed RAC mixtures.

Experimental work

For the experimental investigation, four sets of concrete mixtures were prepared where each set had two identical concrete mixtures, one prepared using the normal mixing approach (NMA) and the other using two-stage mixing approach (TSMA). In this research, twenty groups of three replica specimens each—10 groups of 100 mm cubes, 8 groups of cylinders having 75 mm diameter and 150 mm height, and 2 groups of prisms having 50 mm square cross section and 250 mm length—were prepared for each set. Thus, for the four sets of test specimens, a total of eighty groups of three replica specimens were used. The specimen preparation procedure along with the fundamental characteristics of the used materials is described below.

Materials

The natural aggregate (NA) was crushed limestone, sourced from a local quarry. The recycled aggregate (RA) was prepared from concrete members of an old demolished building. The local desert dune sand was used as fine aggregate (sand). The water absorption and specific gravity of sand, NA, and RA were determined as per relevant ASTM standards. Those physical properties of aggregates are presented in Table 1, while their particle size distribution is shown in Fig. 1. Both RA and NA were sieved and blended to produce the same particle size distribution, as done in the study reported by Li et al. [23].

Potable water was used for mixing and curing the concrete specimens. A liquid proprietary sulphonated naphthalene polymer superplasticizer (SP), conforming to ASTM C494, was used to achieve the targeted workability.

The ordinary Portland cement (OPC) used in this study was ASTM Type I cement. Three different SCMs, namely, a Type F fly ash (FA), ground-granulated blast-furnace slag (GGBFS), and silica fume (SF), were used to partially replace the OPC. The key oxide composition and physical properties of all the cementitious materials used in this study are presented in Table 2.

Table 1 Water absorption and specific gravity of aggregates

Type	Water absorption (%)	Specific gravity
Fine aggregate (sand)	0.6	2.50
Natural coarse aggregate (NA)	1.1	2.60
Recycled coarse aggregate (RA)	6.1	2.62

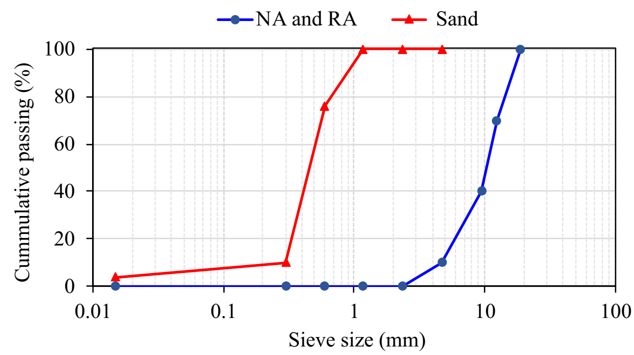


Fig. 1 Particle size distribution of aggregate

Strategies for improving quality of RAC

Two-stage mixing approach (TSMA)

The TSMA is a strategy that does not require any extra materials for the improvement of the quality of RAC. Instead of the normal procedure of mixing coarse and fine aggregate together with cement paste, this method involves mixing coarse aggregate with cement paste prior to adding fine aggregate. This causes inclusion of the cement paste in the micro-cracks and pores on the surface of RA, which in turn acts to fill the cracks and pores and improves the quality of the ITZ between RA and new mortar [23]. A number of variations of TSMA are reported in the literature. In the present study, a simple TSMA was used. A schematic presentation of TSMA used in the present work, is presented in Fig. 2a. The normal mixing approach (NMA) is presented in Fig. 2b. The word "MCA" represents a mixture of NA and RA in Fig. 2b.

Use of supplementary cementitious materials (SCMs)

SCMs are commonly used to improve the microstructure of concrete that influences both strength and durability of concrete. There are different types of SCMs, namely silica fume, natural pozzolan, fly ash, ground-granulated blast-furnace slag etc. that are used for this purpose. In the present study, ASTM Type I cement was partially replaced with the

Table 2 Oxide composition and physical properties of the binders

Item	OPC	FA	GGBFS	SF
Silicon dioxide (SiO_2) %	20	53	33	91
Aluminum oxide (Al_2O_3) %	6	34	14	1
Ferric oxide (Fe_2O_3) %	4	4	1	0.25
Calcium oxide (CaO) %	65	4	43	0.20
Specific gravity	3.15	2.25	2.90	2.08
Surface area, m^2/kg	365	300	600	20,200–21,200

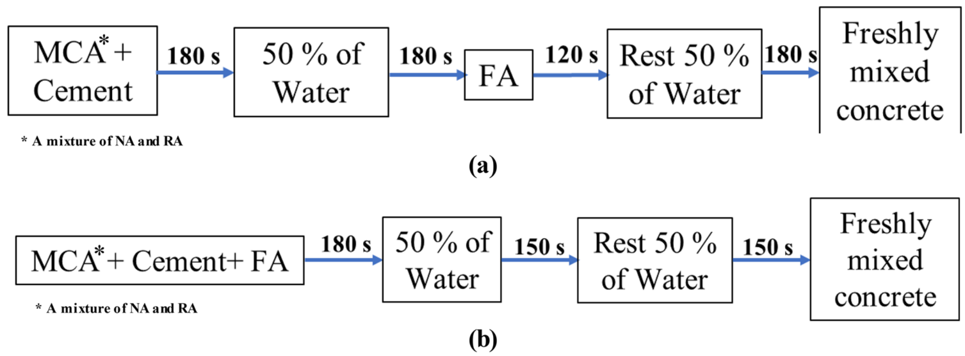


Fig. 2 Schematic representation of **a** two-stage mixing approach (TSMA) and **b** normal mixing approach (NMA)

selected SCMs that included silica fume (7%), fly ash (20%), and GGBFS (20%).

Mixture proportions

Considering different combinations of the treatment strategies, four sets of concrete mixtures in NMA-TSMA pairs were prepared, as stated earlier. The cementitious material content, water to cementitious materials ratio, and coarse to total aggregate ratio were kept invariant at 375 kg/m^3, 0.4 (by mass), and 0.6 (by mass), respectively, in all the concrete mixtures. The levels of these key parameters were chosen to produce high strength RAC mixtures. The replacement of NA with RA was kept at an optimal level (in terms of both mechanical and durability characteristics) of 40% (by mass), as suggested by Zaben [49]. Additionally, a concrete mixture was prepared with 0% RA and 100% OPC while maintaining the same cementitious materials content, water to cementitious materials ratio, and coarse to total aggregate ratio of abovementioned RAC mixtures. This additional mixture was only used as a slump control mixture for the purpose of comparing the workability of RAC and NAC prepared with normal mixing approach. The weights of ingredients calculated using the absolute volume method for producing 1 cubic meter of the RAC and NAC are presented in Table 3.

Casting and curing

The RAC and NAC mixtures were prepared in a tilting drum-type mixer. The freshly mixed concrete was poured in molds and consolidated on a laboratory vibrating table. The specimens were demolded after 24 h of casting and subsequently kept in a water tank for curing until the time of testing. The temperature of the water in the curing tank was maintained at 23 ± 2 °C.

Evaluation of hardened properties of concrete mixtures

To assess the net enhancement in the key material properties of different RAC mixtures due to techniques applied to treat the RA in this research, the hardened properties of concrete

Table 3 Quantities of ingredients for producing 1 m^3 of the RAC and NAC mixtures

Set no	Mixture description	Mixing approach	*Gross* water (kg)*	Cementitious materials (kg)		Sand (kg)	NA (kg)	RA (kg)	SP (kg)
				OPC	Mineral additives				
1	100% OPC†	NMA†	189	375	0	750	675	450	5.3
		TSMA							
2	20% FA–80% OPC	NMA	189	300	75	740	666	444	4.7
		TSMA							
3	20% GGBFS–80% OPC	NMA	189	300	75	748	673	449	4.7
		TSMA							
4	7% SF–93% OPC	NMA	189	349	26	745	671	447	4.7
		TSMA							
Additional	100% OPC–0% RA	NMA	167	375	0	748	1122	0	5.3

*Gross water includes the effective water and water absorbed by the aggregates

†100%OPC-NMA (i.e., without mineral admixture and TSMA) is the control RAC mixture

mixtures were determined by testing the specimens after curing for specific durations. Mechanical properties of concrete mixtures were evaluated in terms of their compressive and tensile strengths. While the compressive strength is the central mechanical property of any concrete, the tensile strength is also important as it gives direct indication of the quality of ITZ. As emphasized earlier, improving the quality of ITZ around RA particles is the main target of RA improvement strategies, especially the application of TSMA. In addition, previous studies indicate that RAC exhibits lower tensile strength, especially for high strength RAC [21] considered in the present research, further highlighting the need to study the tensile properties of the RAC mixtures. In this study, the compressive strength was measured after 3, 7, 14, 28, and 90 days of curing, while the splitting tensile strength was measured after curing for 28 days. For the type of RA used in this research, the reduction of elastic modulus in RACs incorporating the raw 40% RA was only about 10% compared to NAC, as reported by Zaben [49]. However, the positive effect of the supplementary cementitious materials (SCMs) on enhancing the elastic modulus as well as compressive strength of various RAC is well reported in the existing literature [33, 38]. On this ground, the improved version of the RAC was projected to produce elastic modulus greater than the RAC without treatment. Therefore, elastic modulus was not investigated for the improved version of RAC considered in this research.

In addition to mechanical properties, durability properties of RAC are of interest [24]. The main characterization parameters to evaluate the performance of concrete from the perspective of durability are permeability and deformation [24, 50–52]. In this study, the permeability characteristics of RAC were assessed in terms of water absorption, rapid chloride permeability, and reinforcement corrosion potentials. Water absorption and chloride permeability were directly measured after 28 days of curing. Corrosion of steel reinforcements embedded in concrete is one of the major concerns for which permeability properties of concrete are studied as indirect indications of physical protections offered by concrete to steel rebars. This study features a direct assessment of qualitative corrosion behavior by monitoring the corrosion potentials of steel rebars embedded in the studied concrete mixtures. The specimens used for the corrosion potential testing were first moist-cured for 28 days and then partially immersed in 5% NaCl solution. This was followed by the measurements of corrosion potentials, via saturated calomel electrode (SCE), at different intervals of time up to 140 days. The drying shrinkage of moist-cured specimens of RAC mixtures were measured for about 100 days. Details of all the tests conducted on the RAC mixtures are presented in Table 4.

Results and discussion

Workability

As mentioned earlier, the workability of the RAC mixtures was evaluated by measuring the slump. The slump of RAC and NAC mixtures is summarized in Table 5. The workability of RAC was more than that of NAC at the same dosage of the SP. The increased workability of RAC may be attributed to addition of extra water to the mixture to compensate for the absorption of the RA [32]. The extra water in RAC mixture remains available on the surface of the aggregate for some time before being absorbed by RA and this leads to a decrease in inter-particle friction thereby increasing the workability. However, the workability of RAC with TSMA decreased in all cases. This observation is consistent with the given explanation along with the fact that the adopted TSMA required 20% longer time than the NMA.

Table 4 Summary of tests conducted on the RAC mixtures

Property	Test standard	Shape and size of the test specimen	Testing time
Workability	ASTM C143	Freshly mixed RAC	Immediately after mixing and before initial setting time
Compressive strength	ASTM C39	100 mm cube	After 3, 7, 14, 28, and 90 days of water curing
Splitting tensile strength	ASTM C496	Cylinder having 75 mm diameter and 150 mm height	After 28 days of water curing
Water absorption	ASTM C642	Cylinder having 75 mm diameter and 150 mm height	After 28 days of water curing
Chloride permeability	ASTM C1202	Cylinder having 75 mm diameter and 150 mm height	After 28 days of water curing
Drying shrinkage	ASTM C157	50 × 50 × 250 mm prism	Up to 98 days of air exposure after 28 days of water curing
Corrosion Potential	ASTM C876	Cylinder having 75 mm diameter and 150 mm height	Up to 140 days of chloride solution exposure after 28 days of water curing

Table 5 Slump of RAC produced using selected strategies

Mixture description	SP dosages (% of cementitious materials)	Slump (mm)
100% OPC-NMA (control RAC)	1.40	100
100% OPC-TSMA		88
100% OPC–0% RA		75
20% FA–80% OPC-NMA	1.26	106
20% FA–80% OPC-TSMA		94
20% GGBFS–80% OPC-NMA		125
20% GGBFS–80% OPC-TSMA		100
7% SF–93% OPC-NMA		100
7% SF–93% OPC-TSMA		81

Nevertheless, the workability of the TSMA mixtures was more than that of NAC.

The addition of SCMs to RAC increased the workability, even at a low dosage of SP. This can be attributed to the lubricating effect or ball bearing effect, texture, and shape [53] of the added SCMs. The increase in workability in case of RAC containing SF was slightly less than that containing FA and GGBFS due to the high surface area of SF compared to that of FA and GGBFS. However, the workability of all RAC mixtures (with and without SCMs) decreased when TSMA was adopted instead of NMA. This reduction in workability when RAC mixtures were prepared using TSMA can be attributed to the fact that the mixing was carried out for a longer period in case of TSMA. The extra mixing time allows more water absorption by the aggregates, thus reducing the lubricating effect and decreasing the workability [54]. Although there is a reduction in the workability due to preparation of the RAC mixtures by TSMA, the net effect of the use of SCMs and TSMA on the workability is beneficial. The workability of all RACs at a significantly lower SP dosage was higher compared to the workability of NAC.

Compressive strength

Figure 3 depicts the compressive strength of RAC mixtures with 100% OPC (without SCM), prepared separately using the NMA and TSMA. The beneficial effect of TSMA on compressive strength of RAC at all ages is evident from the data in Fig. 3. The positive effect of TSMA is due to the improvement in the bond between RA and the fresh mortar. The RA particles bear partial/full coating of the old mortar that consists of pores and cracks, which weaken the bond between the RA and fresh mortar, i.e., a weak ITZ in the RAC mixture. The TSMA improves the quality of the ITZ by sealing the cracks and pores on the surface of the RA particles [23]. This is also termed as 'shifting of ITZ' that provides a better bond between the fresh mortar and RA,

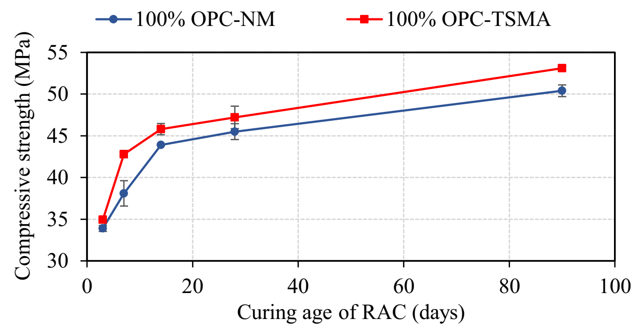


Fig. 3 Effect of TSMA on the compressive strength of RAC

thereby resulting in a densified microstructure of the RAC prepared using TSMA. The RAC mixture with denser microstructure helps in achieving better mechanical properties and durability characteristics [22, 55].

The morphology of RAC specimens prepared using NMA and TSMA (100% OPC-NMA and 100% OPC-TSMA) was evaluated using a scanning electron microscope (SEM) to examine the improvement in the ITZ due to TSMA. The SEM micrographs for RAC (100% OPC-NMA and 100% OPC-TSMA) are shown in Fig. 4, which indicated that the ITZ between old mortar and new mortar contained cracks and pores when the RAC was mixed using NMA (Fig. 4a). However, the ITZ between old mortar and new mortar became dense when TSMA was adopted for mixing the RAC (Fig. 4b). The improved interfaces between the old mortar on the surface of the RA particles contributed to the enhanced strength in RAC prepared using TSMA.

The effect of incorporating FA and application of TSMA on the compressive strength of RAC is depicted in Fig. 5. The initial strength development (before 28 days of curing) of RAC containing FA is notably lower compared to that of control RAC (100% OPC-NMA). The lower early strength of RAC with FA may be attributed to a decrease in the quantity of silica and high water to binder ratio. The silica in FA takes time to react with the calcium hydroxide (liberated from the primary hydration of the OPC). However, the formation of secondary calcium silicate hydrate gel contributes to the strength gain at later stage of hydration [56] as is evident from the higher strength of RAC mixture containing FA after 90 days of curing. It matched the strength of control mixture after around 28 days curing and surpassed it significantly at 90 days of curing. The combined effect of adding FA and mixing using TSMA increased the 28 and 90 day compressive strength as compared to that of control RAC.

The effect of GGBFS, silica fume, and TSMA on compressive strength of RAC is shown in Figs. 6, 7. Unlike the case of FA, the early strength was not affected by the addition of GGBFS and SF, rather their presence in the RAC improved the early strength compared to the control RAC

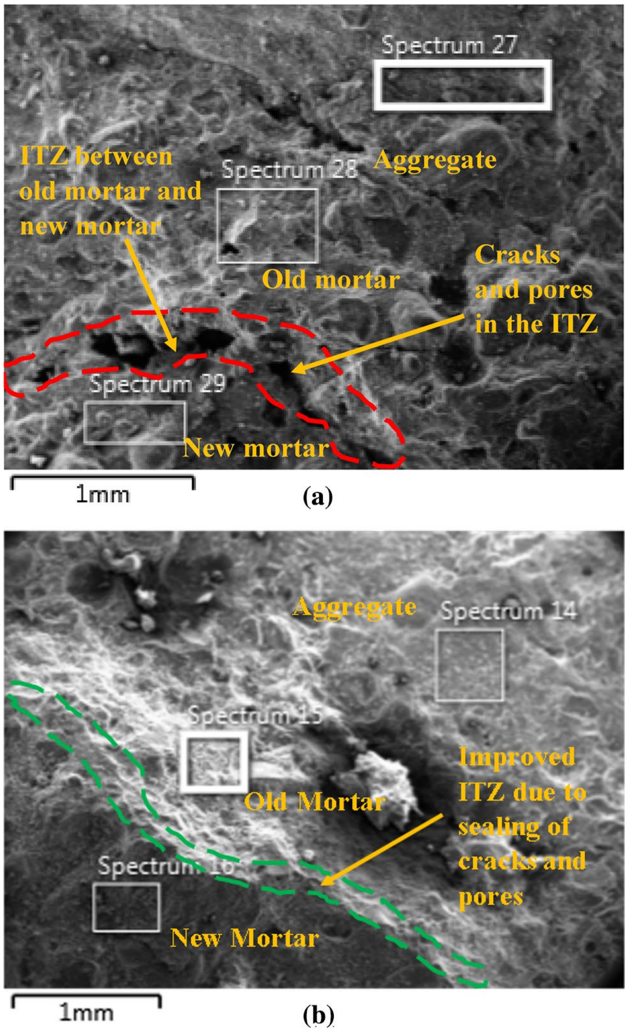


Fig. 4 SEM of RAC produced with: **a** NMA; **b** TSMA

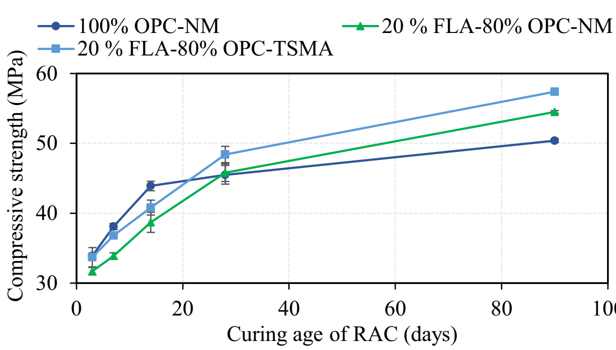


Fig. 5 Effect of FA and TSMA on the compressive strength of RAC

(100% OPC-NMA). The early strength gain due to the addition of GGBFS may be attributed to the presence of enough lime and silica that makes the hydration of GGBFS similar to that of OPC. The addition of a small amount of SF

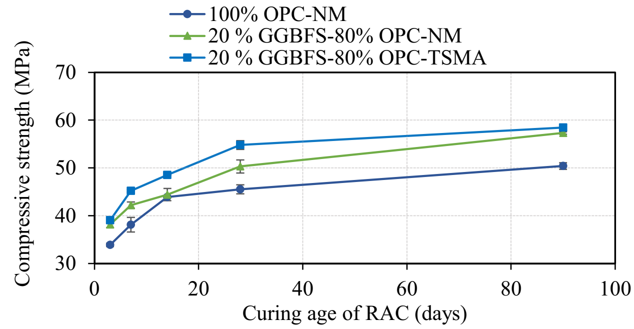


Fig. 6 Effect of GGBFS and TSMA on the compressive strength of RAC

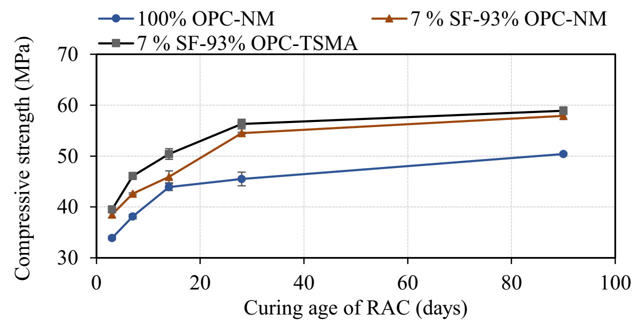


Fig. 7 Effect of SF and TSMA on the compressive strength of RAC

(7% only) resulted in a higher compressive strength of RAC containing SF even at early ages due to its pore-filling ability by virtue of its very fine particle size. Similar findings pertaining to the concrete mixtures containing GGBFS and SF are reported in the literature [57]. The use of TSMA in presence of GGBFS and SF (20% GGBFS–80% OPC-TSMA and 7% SF–93% OPC-TSMA) further improved the compressive strength at all ages due to denser ITZs compared to normal mixing.

A summary of the combined effect of addition of mineral additives (SCMs) and TSMA on the 28-day compressive strength of RAC is presented in Fig. 8. It can be observed that the combined effect of SCM and TSMA has resulted in a significant increase in the 28-day compressive strength compared to the control RAC mixture (100% OPC-NMA). While the increase in the 28-day strength of RAC (20% GGBFS–80% OPC-TSMA and 7% SF–93% OPC-TSMA) was 20% and 24%, respectively, it was only 6% in the RAC mixture containing FA (20% FA–80% OPC-NMA) due to slow hydration in presence of FA.

Splitting tensile strength

Figure 9 depicts the effect of treatment strategies on the 28-day splitting tensile strength of RAC. It can be

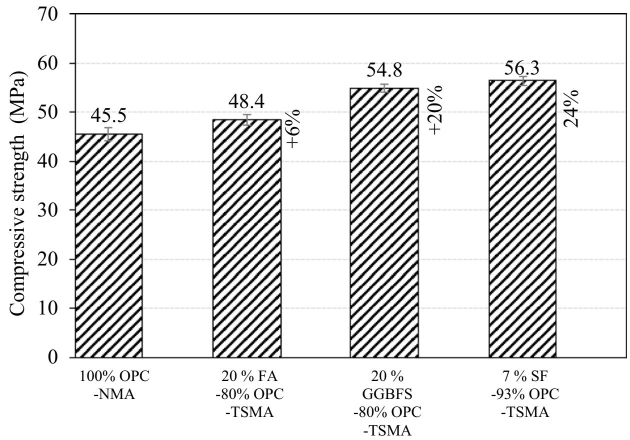


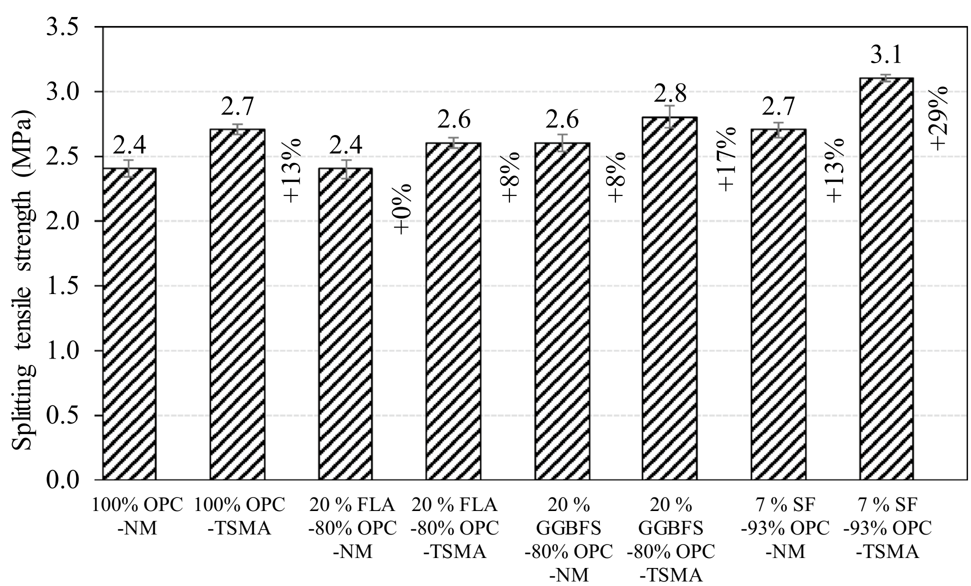
Fig. 8 Combined effect of SCMs and TSMA on the 28-day compressive strength of RAC

observed from the data presented in Fig. 9 that the TSMA resulted in a significant increase in the splitting tensile strength of all the RAC mixtures including the control mixture. Similarly, the addition of GGBFS and SF also increased the splitting tensile strength significantly in line with the results reported in the literature [58, 59]. However, the addition of FA did not increase the splitting tensile strength due to the slow formation of secondary C–S–H. The splitting tensile strength increased in mixtures incorporating SCMs and prepared with TSMA (8, 17 and 29% in the RAC mixtures with 20% FA–80% OPC-TSMA, 20% GGBFS–80% OPC-TSMA and 7% SF–93% OPC-TSMA, respectively) because of the combined positive effects of the addition of SCMs and the use of TSMA. Modification of hydration process due to SCMs results in densification of ITZ [60]. TSMA is also responsible for producing densified ITZ of RA as a result of sealing microcracks and voids in the mixing process [23]. The tensile strength of concrete primarily depends on the bond between the concrete matrix and aggregate. Densified ITZ contributes to develop good bonding between the concrete matrix and aggregate [61]. As a result, the improvements of ITZ due to SCMs and TSMA primarily play role in enhancing the splitting tensile strength. The mechanism of improved ITZ in enhancing the splitting tensile strength is depicted in Fig. 10. The improved ITZ is represented by red border. The improved ITZ requires larger separating (tensile) forces to separate RA from cement matrix, leading to a higher splitting tensile strengths [61].

Water absorption

The effect of different treatment strategies on the 28-day water absorption of RAC is presented in Fig. 11. The 28-day water absorption in the RAC with SCMs decreased by 2–8%, compared to the control RAC mixture. The reduction in the water absorption in the presence of SCMs may be attributed to the development of a dense microstructure due to two effects [62, 63]. The first one is the filling of the pores with SCM, while the second one is the chemical contribution by the formation of additional C–S–H gel that decreases the porosity of concrete. In addition, the use of TSMA further decreased the water absorption of RAC with SCMs. The sealing of cracks and pores in the old mortar on the surface of RA due to TSMA has probably contributed to a reduction in the water absorption of the RAC. The lowering of water absorption due to use of TSMA and addition of SCMs indicate that the durability of the resulting RAC improved significantly.

Fig. 9 Effect of selected treatment strategies on the 28-day splitting tensile strength of RAC



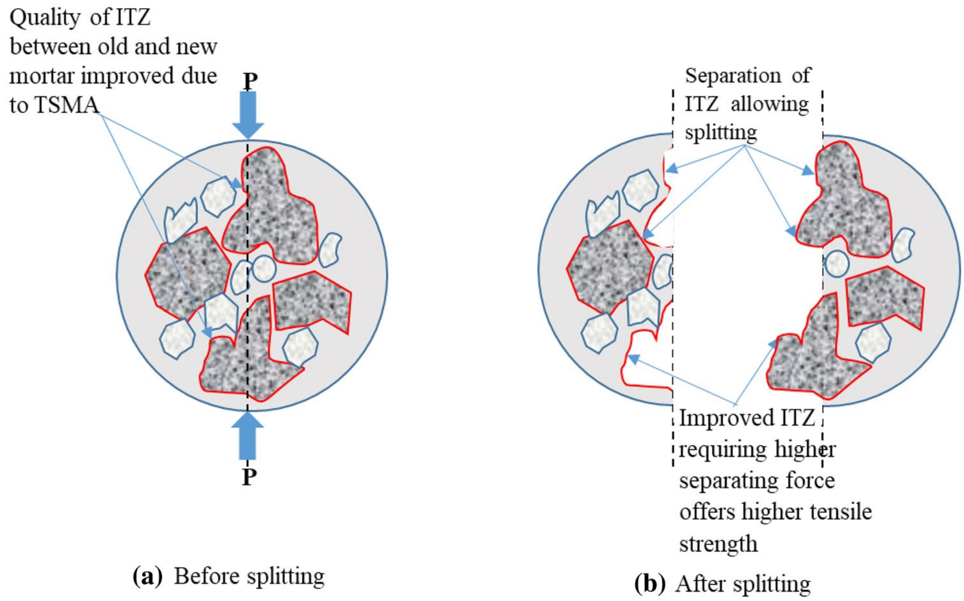


Fig. 10 Mechanism of enhancement of splitting tensile strength due to TSMA

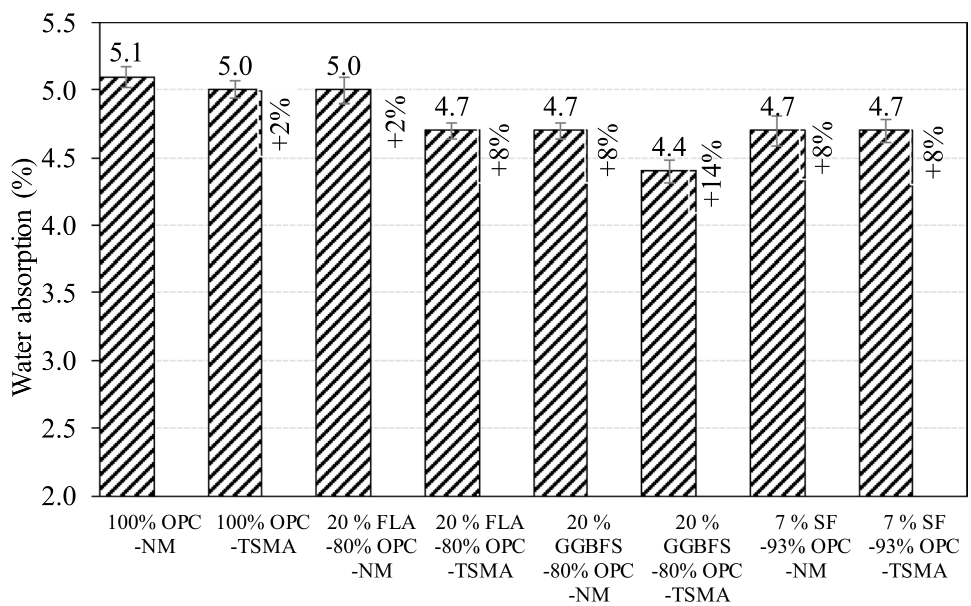
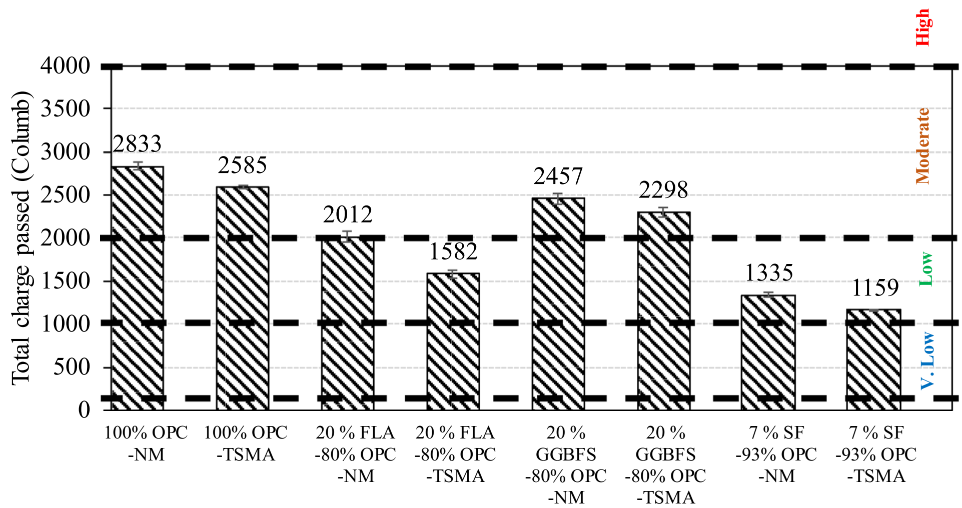


Fig. 11 Effect of selected treatment strategies on the 28-day water absorption of RAC

Rapid chloride permeability

The rapid chloride permeability of RAC prepared using different treatment strategies is shown in Fig. 12. A significant reduction in the rapid chloride permeability (in the range of 13%–53%) was noted in RAC with SCMs compared to the control RAC (100% OPC-NMA). With a 13% reduction in the rapid chloride permeability, GGBFS was the least effective, whereas, SF was the most effective causing 53% reduction in the rapid chloride permeability. Similar effects of the SCMs on the chloride permeability was reported in the literature [64–66]. The efficiency of SCMs against chloride permeability depends on their effect on the electrical resistivity of concrete in two different ways. First, an increase in the electrical resistivity due to pore-filling effect and second, decrease in the electrical resistivity due to a decrease in the free chloride ions because of chemical reaction between chloride ions and tri-calcium aluminate. The highest reduction in the chloride permeability in case of SF addition is mostly due to pore-filling effect of SF owing to its very small particle size compared to that of OPC, FA, and GGBFS. The decrease in the chloride permeability (29%) of RAC with FA compared to that in GGBFS (13%) may be attributed to the fact that the FA with high alumina content can bind more chloride ions thereby increasing the electrical resistivity of concrete more than that in case of the GGBFS. Furthermore,

Fig. 12 Effect of selected treatment strategies on the 28-day rapid chloride permeability of RAC



the plots in Fig. 12 clearly indicate the beneficial effects of TSMA on the chloride permeability of RAC. The reduction in the chloride permeability due to the combined effect of SCMs and TSMA ranged from 19 to 59%. The positive effect of TSMA may be attributed to the sealing of pores and cracks in the old mortar that decreases the porosity of the RAC. The reduction of the rapid chloride permeability due to use of TSMA and addition of SCMs indirectly indicates that resulting RAC has higher resistance against the incursion of harmful ingredients like chloride in the concrete, hence better durability is expected from the modified RAC.

Drying shrinkage

The drying shrinkage of RAC mixture with TSMA but without SCM (100% OPC), is depicted in Fig. 13a. The mixing of RAC ingredients using TSMA caused a significant reduction in the dying shrinkage after 28 days of exposure to air. The positive effect of TSMA may be attributed to the sealing of cracks and pores on the surface of RA leading to refinement of the pores at ITZ [67].

The data in Fig. 13b, c, d show the individual effect of the SCMs as well as the combined effect of the SCMs plus TSMA. The addition of FA has caused a very significant reduction in the drying shrinkage particularly after 28 days of exposure to the air, as shown in Fig. 13b. The addition of other SCM (SF) has also caused a reduction in the drying shrinkage after 28 days of exposure to air, as depicted in Fig. 13d, but not to the extent of FA addition. Unlike the incorporation of FA and SF, the addition of GGBFS has not caused any noticeable reduction in the drying shrinkage, rather the shrinkage is higher in the early stages of the exposure to air, as can be noted from the data in Fig. 13c. The reduction in the drying shrinkage due to addition of SCMs (FA and SF) may be attributed to the lower chemical shrinkage in presence of pozzolanic additives because of the formation of the extra C–S–H gel that enables refinement of the pores [64, 68–74]. Although both the SCMs decreased the drying shrinkage significantly, FA showed more pronounced reduction in the drying shrinkage compared to SF. This may be attributed to the fact that the addition of SF causes autogenous shrinkage due to its very fine size, particularly at a low water to cementitious materials ratio. This additional shrinkage in the presence of SF causes a reduction in the ability of the SF to offer resistance against shrinkage compared to FA [68]. Further, the inability of GGBFS to resist the drying shrinkage [59, 75] is due to its hydration almost similar to that of the OPC resulting in the formation of almost similar quantity of C–S–H gel causing pore refinement at almost similar level. Unlike the effect of addition of SCMs on the reduction of drying shrinkage, adoption of TSMA did not exhibit any significant improvement, except in case of RAC with SF. The reduction of drying shrinkage due to improvement techniques used here is liable to enhance the durability of resulting RAC [24].

Corrosion potential

The plots of corrosion potential versus exposure duration for RAC without addition of any SCM (100% OPC), as shown in Fig. 14a, clearly indicate the beneficial effect of using TSMA instead of using NMA. The initiation of reinforcement corrosion has occurred in case of RAC with NMA prior to that in RAC with TSMA due to a reduction in the porosity of concrete with latter treatment.

The data in Fig. 14b showing the individual effect of addition of FA as well as combined effect of FA and TSMA on the corrosion potential indicates that the FA and TSMA are jointly more effective in improving the corrosion resistance of RAC compared to RAC with FA only. While addition of FA alone increased the time to corrosion initiation by a few days, the use of TSMA along with FA suppressed the

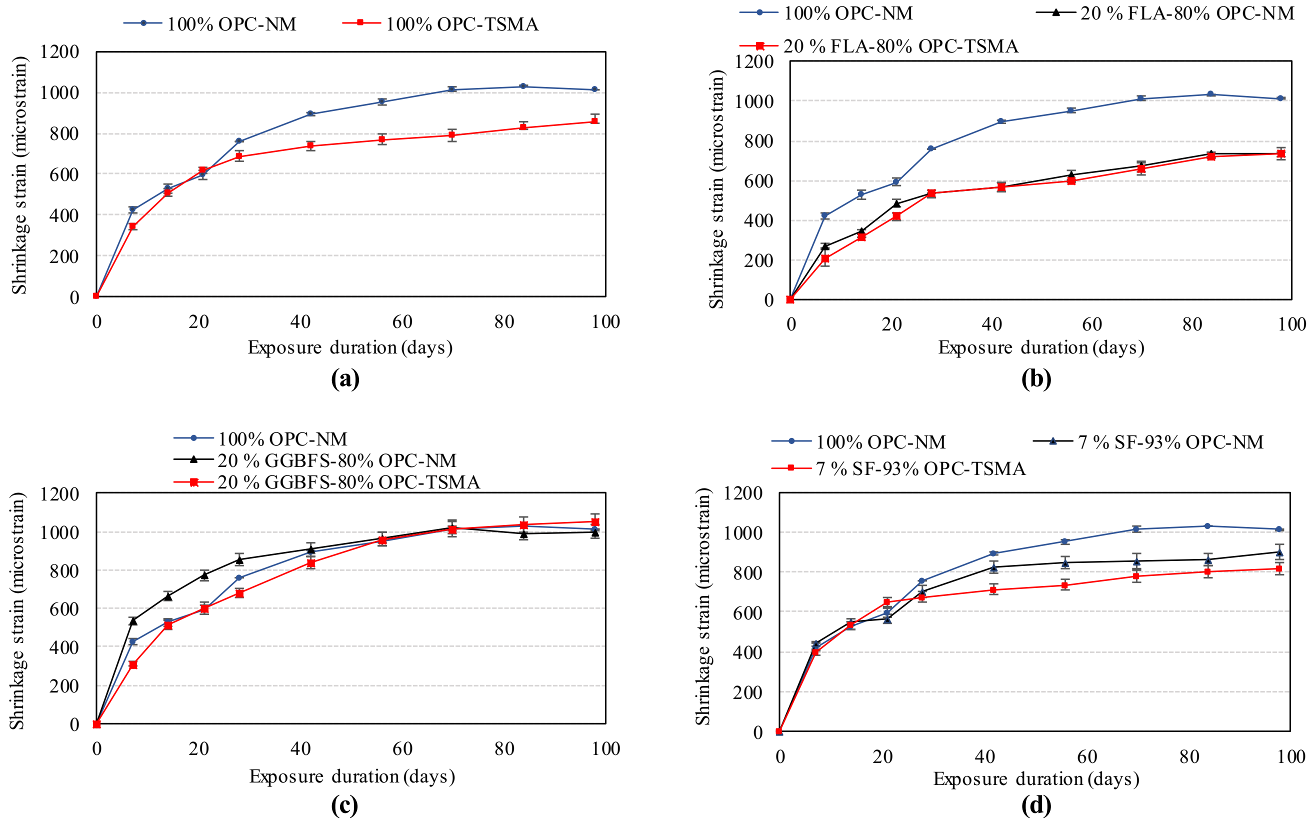


Fig. 13 Effects of two-stage mixing and SCMs on the dry shrinkage

reinforcement corrosion to be in a stable passive state (i.e., the corrosion potential is more positive than the threshold corrosion potential of -270 mV SCE). This highly beneficial effect of the TSMA against reinforcement corrosion may be attributed to the reduction of the porosity and pore connectivity due to sealing of pores and cracks at ITZs due to the TSMA.

The beneficial effect of GGBFS and SF (without and with TSMA) on reinforcement corrosion is shown in Figs. 14c and d, respectively. It can be observed that the addition of GGBFS as well as SF resulted in a stable passive state of reinforcement corrosion, whether mixed using NMA or TSMA. The insignificant effect of TSMA on resistance against reinforcement corrosion of RAC mixtures containing GGBFS and SF may be attributed to the fact that the GGBFS with a higher lime content and SF with very high pore-filling ability compared to the FA, have a higher resistance against reinforcement corrosion even without using TSMA [12, 76, 77]. As corrosion potential is an electrochemical tool to monitor the corrosion of steel bars embedded in concrete, the delayed initiation of the reinforcement corrosion because of using TSMA and addition of SCMs indicates reduction in the permeability of the resulting RAC, hence better durability of improved RAC is expected [78].

Cost analysis

To estimate the cost for producing 1 cubic meter of each of the RAC mixtures considered in the present work, the unit costs of all the ingredients were collected including unit cost of energy required for mixing using NMA and TSMA. The cost of mixing is considered as the cost of energy consumed while mixing to include the cost variation in the normal mixing approach (NMA) and the two-stage mixing approach (TSMA). The cost per cubic meter, estimated for producing all the RAC mixtures, is presented in Table 6. The cost per unit strength of each RAC mixture, as shown in Table 6, was calculated as the ratio of cost per cubic meter of RAC divided by the 28-day compressive strength. Compared to the cost per unit strength of the control RAC mixture, a significant reduction in the cost per unit strength is observed when the SCMs were added (a reduction of 6.5, 10.6, and 17.1%, in the case of FA, GGBFS, and SF, respectively). The cost per unit strength of the RAC mixtures was reduced further by adopting TSMA.

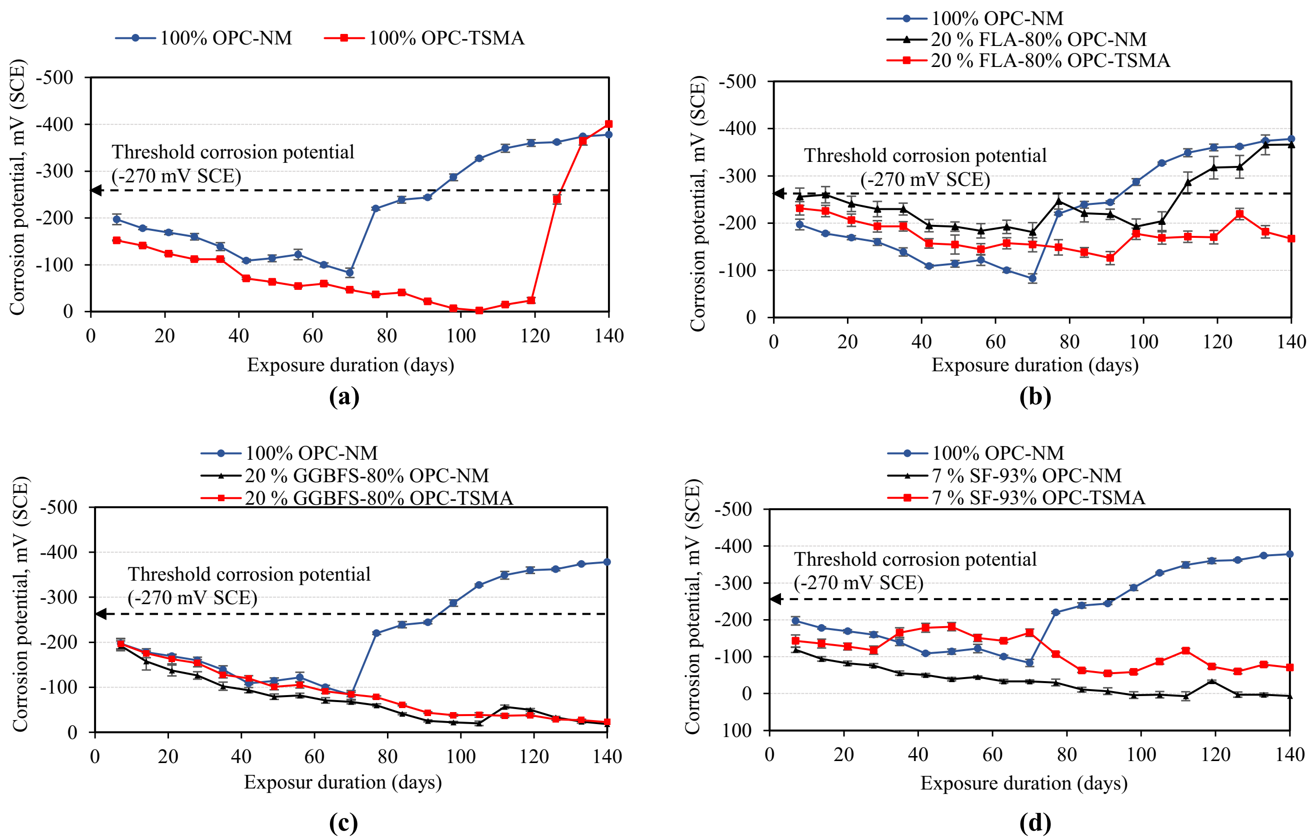


Fig. 14 Effects of two-stage mixing and SCMs on the corrosion potentials of steel in RAC

Table 6 Cost comparison of different RAC mixtures

Item	Unit cost $/ton	100% OPC-NMA (control)	100% OPC-TSMA	20% FA–80% OPC-NMA	20% FA–80% OPC-TSMA	20% GGBFS–80% OPC-NMA	20% GGBFS–80% OPC-TSMA	7% SF–93% OPC-NMA	7% SF–93% OPC-TSMA
OPC	48.5	18.2	18.2	14.6	14.6	14.6	14.6	16.9	16.9
FLA	33.0	0.0	0.0	2.5	2.5	0.0	0.0	0.0	0.0
GGBFS	65.0	0.0	0.0	0.0	0.0	4.9	4.9	0.0	0.0
SF	97.5	0.0	0.0	0.0	0.0	0.0	0.0	2.5	2.5
Sand	12.2	9.2	9.2	9.0	9.0	9.1	9.1	9.1	9.1
NA	10.5	7.1	7.1	7.0	7.0	7.1	7.1	7.0	7.0
RA	3.9	1.8	1.8	1.7	1.7	1.8	1.8	1.7	1.7
*SP($/lt)	3.7	19.5	19.5	17.5	17.5	17.4	17.5	17.5	17.5
Water	1.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Energy for mixing ($/kWh)	0.09	0.20	0.28	0.20	0.28	0.20	0.28	0.20	0.28
Total ($)/m^3	–	56.1	56.2	52.8	52.8	55.2	55.4	55.3	55.4
Cost ($) / MPa (28 day)	–	1.23	1.19	1.15	1.09	1.10	1.01	1.02	0.98
% Reduction in cost/MPa (28 days)	–	–	3.3	6.5	11.4	10.6	17.9	17.1	20.3

Conclusions

Following conclusions can be drawn based on the results of the present experimental investigation conducted with the main objective of exploring the possibility of improving the quality of RAC (40% recycled coarse aggregate and 60% natural coarse aggregate) through a combined strategy that consisted of the addition of three selected SCMs (FA, GGBFS, and SF) and use of TSMA:

1. The workability of RAC mixture was more than that of NAC at the same dosage of the SP due to the addition of extra amount of water to the mixture to compensate the water absorption by the RA. The extra water in RAC mixture remains available on the surface of the aggregate for some time before being absorbed that enables in decreasing friction and, therefore, in increasing the workability. The workability of RAC mixtures was higher due to the addition of SCMs even at a lower dosage of the SP. The TSMA caused a reduction in the workability; however, the workability of RAC with TSMA was more than that of concrete mixture without RA.
2. The addition of the SCMs resulted in densifying the microstructure with more binding capacity and the use of TSMA improved the quality of the interfacial zones between the old mortar on the surface of the RA and the new mortar, as is evident in the SEM micrographs. This combined strategy caused a significant improvement in the strength of RAC.
3. The drying shrinkage was significantly reduced due to the addition of FA and SF to RAC prepared with or without TSMA. The drying shrinkage of RAC with GGBFS was initially more than that of control RAC. However, its overall shrinkage in the long-run was similar to that of control RAC mixture.
4. The water absorption and chloride permeability of RAC mixtures decreased and corrosion resistance increased due to the addition of the SCMs and the use of TSMA. The densification of the concrete microstructure due to pozzolanic and pore-filling action of the SCMs and improvement in the quality of ITZs due to TSMA contributed to the enhancement of the durability of the RAC mixtures.
5. The production cost per unit strength of the RAC mixtures (incorporating SCMs and prepared using TSMA) was less than that of the control RAC mixture due to the positive effect of the SCMs and TSMA on the compressive strength.
6. RAC prepared with the addition of SCMs and use of TSMA increased workability at a lower dosage of SP. This joint strategy improved strength and durability, lowered shrinkage, reduced consumption of OPC due to the use of the SCMs, and lowered cost per unit strength. The RAC mixtures with these advantages may be considered as environment friendly (due to lower OPC consumption with lower CO_2 emission), sustainable (due to resource conservation using recycled coarse aggregate and waste materials as SCMs), and cost effective (due to improvements in the quality of RAC).

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