Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 9610317, 12 pages
https://doi.org/10.1155/2023/9610317

Research Article

Experimental Investigation on the Influence of Superplasticizer on Mechanical Behavior of Recycled Aggregate Concrete

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Received 27 September 2022; Revised 30 September 2023; Accepted 6 October 2023; Published 31 October 2023

Academic Editor: Afaq Ahmad

Needs for renovation and efficient use of available land space have led to the destruction of numerous deteriorated civil structures. Consequently, a huge amount of concrete demolished waste is generated annually worldwide. This demolished concrete waste has created an extra burden on the environment and landfills, making the development projects unsustainable. Demolished waste can be recycled and reused for sustainable development and to reduce the demand for fresh natural aggregates (NA). However, the poor performance of recycled aggregate concrete (RAC) compared to natural aggregate concrete (NAC) may be a significant drawback in the recycling and reusing of demolished concrete wastes. This limitation can be overcome by using a superplasticizer, which has the ability to improve different mechanical properties of concrete. The objective of this paper is to assess the effects of the superplasticizer on the mechanical characteristics of RAC. Concrete specimens were prepared to have replacement ratios (0%, 25%, 50%, and 100%) of fresh NA by recycled stone aggregates (RSA) and recycled brick aggregates (RBA). Half of the prepared concrete specimens were admixed with the superplasticizer, having 15% water reduction for concrete mixes. The obtained test results encourage the use of superplasticizers for improving the mechanical properties of RAC. It is observed that fresh, natural coarse aggregates in a concrete mix can be replaced with 50% RSA and 25% RBA with the addition of the superplasticizer without compromising the mechanical performance.

1. Introduction

The demand for concrete is surprisingly increasing due to the rapid rate of urbanization. Concrete is an extensively used construction material because of its low cost and the flexibility to be cast in any shape in many developing countries. Demolitions of deserted and aged structures have resulted in the generation of millions of tons of concrete waste [1–3]. A significant part of the demolished waste is being dumped in the land, which creates major concerning issues for the environment and makes the land imperfect for cultivation. Fine dust from the demolished waste is also creating air pollution and raising health problem issues. Moreover, there is a scarcity of natural resources, which is used as ingredients to prepare fresh concrete. Each year, around 30 billion tons of concrete are utilized globally [4, 5]. Construction aggregates have a global demand of more than 26.8 billion tons annually [6]. Aggregate demand has increased due to rapid growth and the need for large-scale civil infrastructure. To reduce the demand for fresh natural aggregates (NA) and to make development sustainable, recycling and reusing concrete waste have become indispensable [7]. Natural resources can be conserved and environmental pollution can be reduced by using recycled aggregate concrete (RAC) [8]. However, the poor mechanical performance of RAC is a significant issue in recycling and reusing concrete demolished waste [9–12]. Several researchers showed that the service life of RAC decreases with the increase of the replacement ratio of NA by recycled concrete aggregate (RCA) [13–15].

A study by Alqarni et al. [16] reported that three treatment methods such as cement–silica fume slurry, sodium silicate solution, and Los Angeles (LA) abrasion treatment for RCA could enhance the concrete slump by 15%–35% and a noticeable increase in compressive strength. Li et al. [17] claimed that the mechanical properties of recycled aggregate could be improved by the chemical enhancements and subsequently, the properties of RAC can also be improved. Tang et al. [18] showed that the uniaxial compressive strength of concrete decreases significantly with the increase in temperature but the negative effect can be eliminated by adding recycled aggregate and recycled rubber particles.

The adhered mortar wrapped around the surface of natural aggregate controls different properties of RCA [19–21]. RCA differs from fresh NA because of this adhered mortar. The amount of adhered mortar in RCA and its quality have a direct influence on the mechanical performance of RAC. The crushing process involved during the preparation of RCA also affects the quality of adhered mortar [22–24]. Different studies suggested that the amount of attached mortar reduces as the RCA grows larger [25, 26]. RCA formed from crushed demolished concrete contains almost one-third volume of adhered mortar from parent concrete, according to a statistical study [27]. RCA's low relative density, high water absorption, and high porosity are due to the adhering mortar [28–31]. A high percentage of adhered mortar in RCA results in high water absorption and decreased mechanical performance of RAC [32, 33]. RCA can be used in structural concrete if it contains adhered mortar of less than 44% [23]. Jang et al. [34] conducted research on the effect of aggregate size on RAC and found that with the increase of RCA size, mechanical strength improves.

Previous studies reported a large reduction in the mechanical performance of concrete when NA is replaced by RCA at different percentages. It was also observed that the service life of recycled aggregates influences the mechanical performance of RAC [35]. Several researchers observed a reduction of compressive strength of RAC up to 25% for 50% replacement of NA by RCA [36–38]. Splitting tensile strength was found to be decreased by up to 39% for 100% replacement of NA by RCA and follows the same pattern as compressive strength [39–41]. The modulus of elasticity of RAC can be as low as 60% of NAC [42, 43]. Many studies have shown that NA can be replaced by RCA for up to 30% without a significant decline in the mechanical performance of concrete [44–46]. Thomas et al. [47] reviewed the works of many researchers on RAC. They suggested that different factors like properties of RCA, workability preferred in the mix design, quantity of fines in RCA, etc., are involved in optimum replacement percentages of NA by RCA.

Reduction in the water-to-cement ratio increases the mechanical performance of concrete but decreases workability. Moreover, high water absorption of RCA also reduces the workability of RAC. Superplasticizer is used in concrete to allow a reduction in the w/c ratio for a given workability or slump value. The addition of superplasticizers results in a modest improvement of mechanical strength, as well as a reduction in water content in the mixes [48–50]. Verma and Dev [51] reported that a 1% superplasticizer dosage resulted in optimum enhancement of the strength of geopolymer concrete with increasing workability. Schutter et al. [52] claimed that the rheology of fresh cementitious materials could be actively controlled by a responsive superplasticizer where the polycarboxylic ether (PCE)-based superplasticizer was given extra functionalities by adding specific chemical groups. de Hita and Criado [53] found that the workability of cementitious mixtures increased with the use of PCE-based superplasticizers and is linked with the structural parameters. However, they reported that the compressive strength decreased by 17% on average due to adding superplasticizer in alkali-activated cementitious mixtures. Altun et al. [54] found that the shortest side chain length of PCE-based superplasticizer negatively affects the fresh and time-dependent performance of concrete. Kumar et al. [55] reported that although the compressive strength of concrete increases due to the addition of superplasticizer but the overdosage of superplasticizer results in the segregation of concrete and decreases the compressive strength.

Although the effect of superplasticizer on NAC is well-established, its performance on both recycled stone aggregate concrete (RSAC) and recycled brick aggregate concrete (RBAC) has yet to be properly investigated. In the abovementioned context, the effect of superplasticizer on the mechanical performance of RAC, made with two different types of recycled aggregates, has been studied and experimental results are presented in this paper with an aim to encourage the use of concrete demolished wastes in the construction industry.

2. Materials and Methods

An extensive laboratory testing has been carried out to obtain the properties of fresh natural stone aggregate, recycled brick aggregate, recycled stone aggregate, and fine aggregate (sand), which are provided in the following subsections. In addition, commercially available cement and superplasticizers have been used in different concrete mixes collected from the local market.

2.1. Cement and Water. In this research, BDS EN 197-1:2003 CEM II/B-M (S-V-L) 42.5 N or Portland Composite Cement (PCC) has been used as a binding material. Freshwater suitable for drinking is used as mixing water in different concrete mixes.

2.2. Coarse and Fine Aggregates. Locally available "Sylhet sand" having a yellowish color was used as fine aggregate. The granules of the fine aggregate were slightly coarser in size. Three types of coarse aggregate have been used, which are shown in Figure 1. They are natural aggregate (black Indian stone), recycled stone aggregate (RSA), and recycled brick aggregate (RBA). RSA was collected from laboratory waste concrete, and RBA was collected from the demolished waste of an old residential building. Different physical properties of aggregates were investigated, and sieve analysis was done. The gradation of aggregates is shown in Figure 2, and physical properties are shown in Table 1.

2.3. Superplasticizer. La Hypercrete, a third-generation superplasticizer made of PCE, has been used in concrete

Figure 1: Different types of coarse aggregate used for concrete mixes.

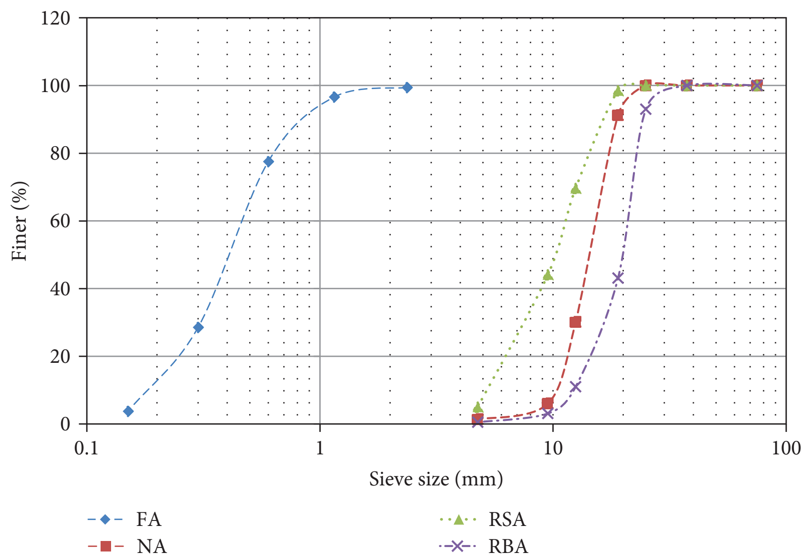


Figure 2: Particle size distribution of different types of aggregate.

Table 1: Physical properties of different types of aggregate.

Types of aggregate	FM	Unit weight (kg/m^3)	Bulk specific gravity (OD)	Absorption capacity (%)
Fine aggregate (FA)	2.94	1,542	2.59	0.73
Natural aggregate (NA)	6.97	1,535	2.78	1.86
Recycled stone aggregate (RSA)	6.47	1,285	2.23	7.53
Recycled brick aggregate (RBA)	7.51	1,038	1.89	11.55

mixtures. It conforms to IS:9103-1999 (reaffirmed 2004), Edition 2.2 (2007–2008), ASTM C494, Type F&G.5. A fixed dose of 0.7% of the weight of dry cement was considered for all the concrete mixes, assuming a 15% reduction in mixing water.

2.4. Concrete Mix Proportion. In the current study, a mix design of concrete with a target strength of 20.7 MPa (3,000 psi) having fresh stone chips aggregates is taken as the control mix as it is widely used in the local area as the design strength of concrete. Fourteen different concrete mixes are prepared varying the type and percentages of coarse aggregates. RAC having replacement ratios (0%, 25%, 50%, and 100%) of NA by RCA was prepared. In all of the concrete mixes, the water-to-cement ratio was kept constant. Half of the mixes have been admixed with superplasticizer, and the water content of these concrete mixes has been reduced by 15%. The quantity of superplasticizer used was 0.7% of the weight of cement content in the concrete mixes. Tables 2 and 3 show the quantity of different constituent materials of the concrete mix design.

2.5. Test Methods. The compressive strength test was done by following the procedures specified in ASTM C39. The prepared concrete cylinders were tested at 7, 28, and 90 days of

Table 2: Details of concrete mixes considered in this study.

Mix	Specimen ID	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)			Superplasticizer (kg/m^3)
					Natural stone	Recycled stone	Recycled brick	
Mix-01	NAC	345	179.4	732	1,195	0	0	0
Mix-02	RSAC100	345	179.4	732	0	1,195	0	0
Mix-03	RSAC50	345	179.4	732	597.5	597.5	0	0
Mix-04	RSAC25	345	179.4	732	896.25	298.75	0	0
Mix-05	RBAC100	345	179.4	732	0	0	1,195	0
Mix-06	RBAC50	345	179.4	732	597.5	0	597.5	0
Mix-07	RBAC25	345	179.4	732	896.25	0	298.75	0
Mix-08	NACA	345	152.5	732	1,195	0	0	2.415
Mix-09	RSACA100	345	152.5	732	0	1,195	0	2.415
Mix-10	RSACA50	345	152.5	732	597.5	597.5	0	2.415
Mix-11	RSACA25	345	152.5	732	896.25	298.75	0	2.415
Mix-12	RBACA100	345	152.5	732	0	0	1,195	2.415
Mix-13	RBACA50	345	152.5	732	597.5	0	597.5	2.415
Mix-14	RBACA25	345	152.5	732	896.25	0	298.75	2.415

Table 3: Quantity of different type of coarse aggregates used for preparation of concrete specimens.

Specimen ID	Coarse aggregate (%)		
	Natural stone aggregate (NA)	Recycled stone aggregate (RSA)	Recycled brick aggregate (RBA)
NAC	100	–	–
RSAC100	–	100	–
RSAC50	50	50	–
RSAC25	75	25	–
RBAC100	–	–	100
RBAC50	50	–	50
RBAC25	75	–	25
NACA	100	–	–
RSACA100	–	100	–
RSACA50	50	50	–
RSACA25	75	25	–
RBACA100	–	–	100
RBACA50	50	–	50
RBACA25	75	–	25

curing age. The splitting tensile strength test, as specified in ASTM C496, was performed at the curing age of 28 days. The stress–strain diagram of the concrete cylindrical specimen was determined first, and then the modulus of elasticity was calculated as per ASTM C469 at 28 days of curing. Figure 3 shows the laboratory test setup of the compressive strength test, splitting tensile strength test, and modulus of elasticity test.

3. Results and Discussions

Superplasticizer was employed in RAC to eliminate its specific weaknesses, and the primary aim of the study is to investigate its impact on the mechanical characteristics of RAC. In the following subsections, the effects of the superplasticizer on fresh and hardened properties of concrete are presented with experimental findings.

3.1. Effect of Superplasticizer on Fresh Concrete Properties. Workability in terms of fresh properties of concrete made with and without superplasticizer was determined by slump test. This test is done to assess the consistency of fresh concrete. The experiment was performed as per ASTM C143/C143M. Table 4 shows the results of different types of concrete mixes used in the research. It is observed that the mixes with superplasticizer resulted in greater slump values. Maximum slump value was seen in Mix-08 where 100% natural stone aggregates were used as coarse aggregate, and the superplasticizer was used in that mix. It is also observed that the mixes containing greater percentages of natural

(a) (b) (c)

Figure 3: Test setup for (a) compressive strength, (b) splitting tensile strength, and (c) modulus of elasticity.

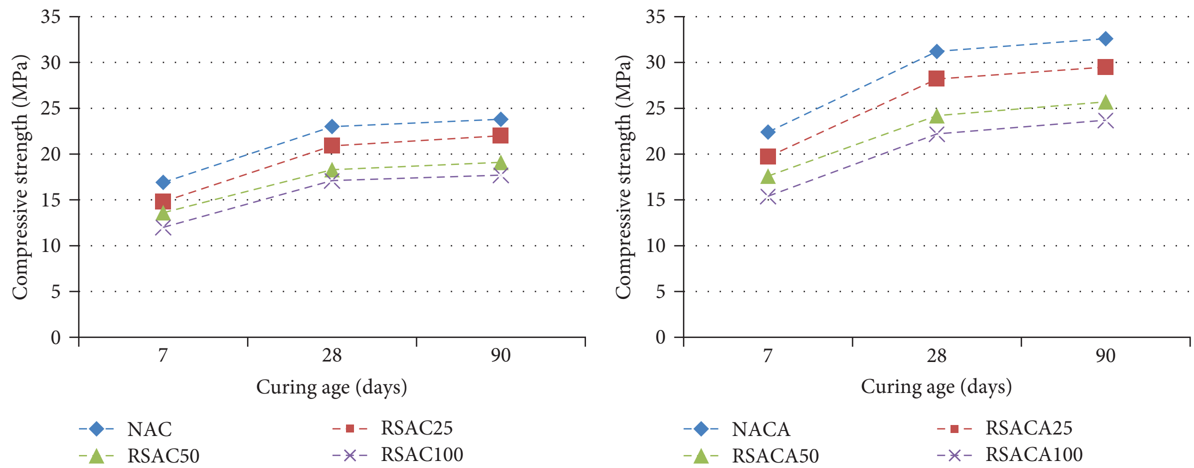
Table 4: Slump values of different concrete mixes.

Mix		Specimen ID	Slump, mm (inch)
Without superplasticizer	Mix-01	NAC100	88 (3.5)
	Mix-02	RSAC100	73 (2.9)
	Mix-03	RSAC50	75 (3.0)
	Mix-04	RSAC25	83 (3.3)
	Mix-05	RBAC100	70 (2.8)
	Mix-06	RBAC50	75 (3.0)
	Mix-07	RBAC25	80 (3.2)
With superplasticizer	Mix-08	NACA100	125 (5.0)
	Mix-09	RSACA100	100 (4.0)
	Mix-10	RSACA50	100 (4.0)
	Mix-11	RSACA25	120 (4.8)
	Mix-12	RBACA100	113 (4.5)
	Mix-13	RBACA50	100 (4.0)
	Mix-14	RBACA25	88 (3.5)

stone aggregates resulted in greater slump values. On the other hand, mixes containing greater percentages of recycled brick aggregates resulted in lower slump values.

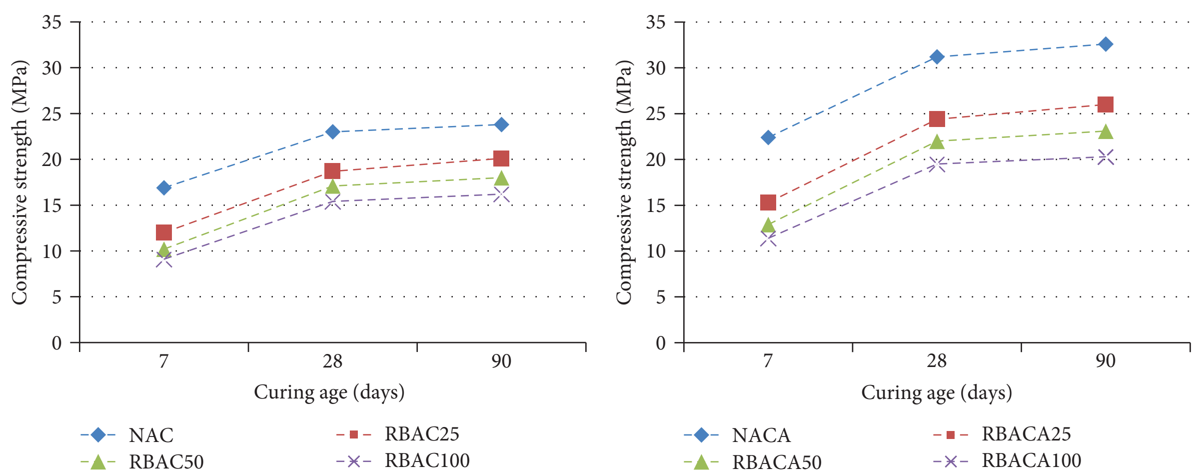
3.2. Effect of Superplasticizer on Hardened Concrete Properties. Three types of tests have been conducted in this study to evaluate the hardened properties of concrete and to assess the effect of the superplasticizer. These are as follows: compressive strength of concrete (f'_c), split tensile strength (f_{st}), and modulus of elasticity (E) of concrete. The results of the experimental investigation are given in the following subsections.

3.2.1. Effect of Superplasticizer on Concrete Compressive Strength. The compressive strength of RSAC and RBAC with and without superplasticizer at different curing ages is presented graphically in Figures 4(a), 4(b), 5(a), and 5(b). The results show the optimistic effect of the superplasticizer on RAC. Control specimens containing 100% natural stone aggregate without and with superplasticizer (NAC and NACA) have achieved maximum compressive strength. For RSAC without superplasticizer at 28 days, compressive strength has decreased by 9.1%, 20.4%, and 25.6%, corresponding to 25%, 50%, and 100% replacements of NA by RSA. For RBAC without superplasticizer at 28 days, compressive strength has decreased by 18.7%, 25.65%, and 33.04%, corresponding to 25%, 50%, and 100% replacements of NA by RBA. For RSAC with superplasticizer at 28 days, compressive strength has decreased by 9.6%, 22.4%, and 28.8%, corresponding to 25%, 50%, and 100% replacements of NA by RSA. For RBAC with superplasticizer at 28 days, compressive strength has decreased by 21.8%, 29.5%, and 37.5%, corresponding to 25%, 50%, and 100% replacements of NA by RBA. A similar trend is observed for 7 and 90 days of curing age. With the rising RCA amount, compressive strength steadily declined in RAC. Adhered mortar presents around recycled aggregates, which creates a weak aggregate–matrix interface bond, could be the possible reason for the compressive strength reduction. Figures 6(a) and 6(b) show the effect of



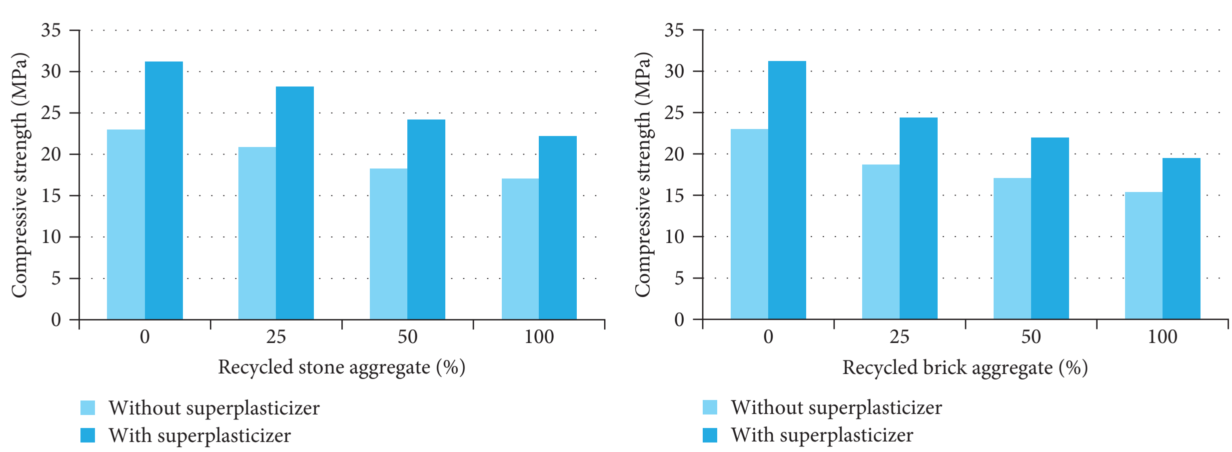
(a) (b)

Figure 4: Compressive strength of RSAC (a) without superplasticizer and (b) with superplasticizer at different ages of cylinder specimens.



(a) (b)

Figure 5: Compressive strength of RBAC (a) without superplasticizer and (b) with superplasticizer at different ages of cylinder specimens.



(a) (b)

Figure 6: Effect of superplasticizer on compressive strength of (a) RSAC and (b) RBAC for 28 days cylinder specimens.

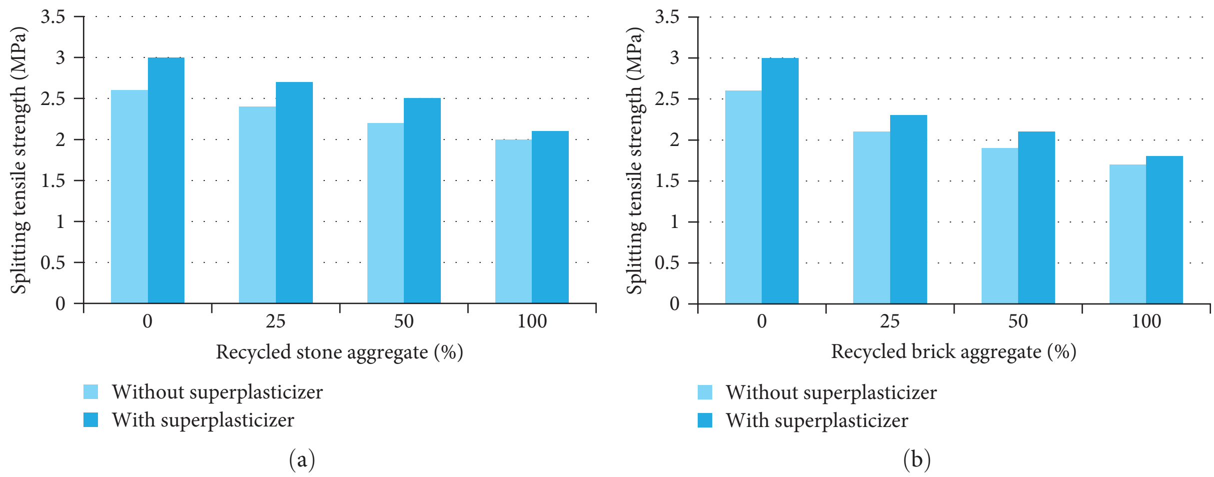


FIGURE 7: Effect of superplasticizer on splitting tensile strength of (a) RSAC and (b) RBAC at 28 days of curing age.

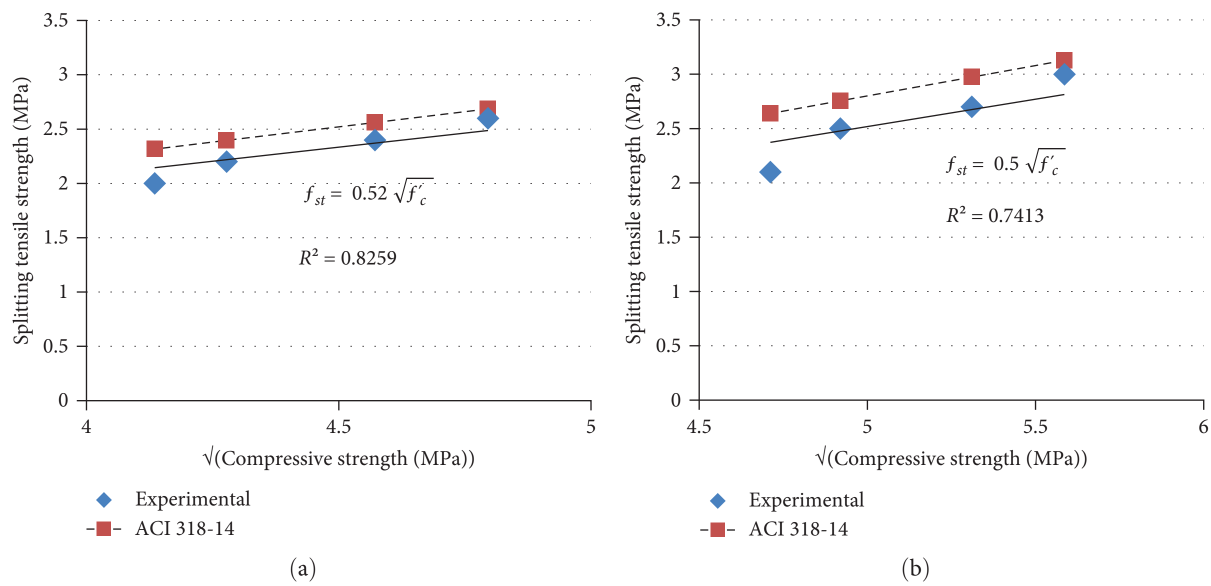


FIGURE 8: Relationship between compressive and splitting tensile strength of RSAC (a) without superplasticizer and (b) with superplasticizer at 28 days.

superplasticizer on the compressive strength of RSAC and RBAC at 28 days of curing age graphically. For NAC containing 100% natural stone chips, the compressive strength increases by 32.5%–36.9% due to the superplasticizer at different curing ages. For RSAC containing 25%, 50%, and 100% recycled stone chips, the corresponding compressive strength increases by 33.1%–34.9%, 29.4%–34.5%, and 28.3%–33.9%, respectively, due to superplasticizer at different curing ages. For RBAC containing 25%, 50%, and 100% recycled brick chips, the corresponding compressive strength increases by 27.5%–30.5%, 26.5%–28.6%, and 25.2%–26.6%, respectively, due to superplasticizer at different curing ages. From the literature [56], it is observed that superplasticizer increases the compressive strength of concrete by enhancing the effectiveness of compaction to produce denser concrete. Superplasticizer has a strong steric hindrance effect due to the ultra-long side chain in their structure, which can increase the contact area between cement particles and water, accelerating cement hydration and forming dense C–S–H gel. The pores in cement paste are then filled by this C–S–H gel, leading to its compactness with better mechanical and durability performance.

3.2.2. Effect of Superplasticizer on Splitting Tensile Strength. Splitting tensile strength and the effect of superplasticizer on it for RSAC and RBAC are represented graphically in Figures 7(a) and 7(b) at 28 days. For NAC containing 100% natural stone chips, splitting tensile strength increases by 15.38% due to the superplasticizer. For RSAC containing 25%, 50%, and 100% recycled stone chips, corresponding splitting tensile strength increases by 12.5%, 13.6%, and 5.0%, respectively, due to the addition of superplasticizer. For RBAC containing 25%, 50%, and 100% recycled brick

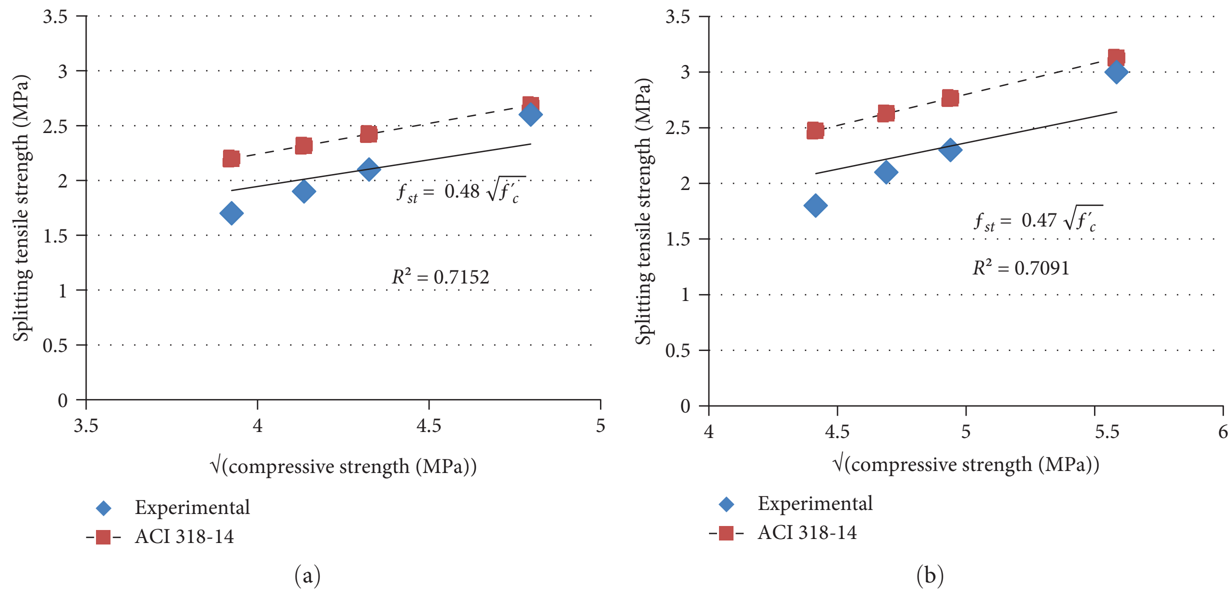


Figure 9: Relationship between compressive and splitting tensile strength of RBAC (a) without superplasticizer and (b) with superplasticizer at 28 days.

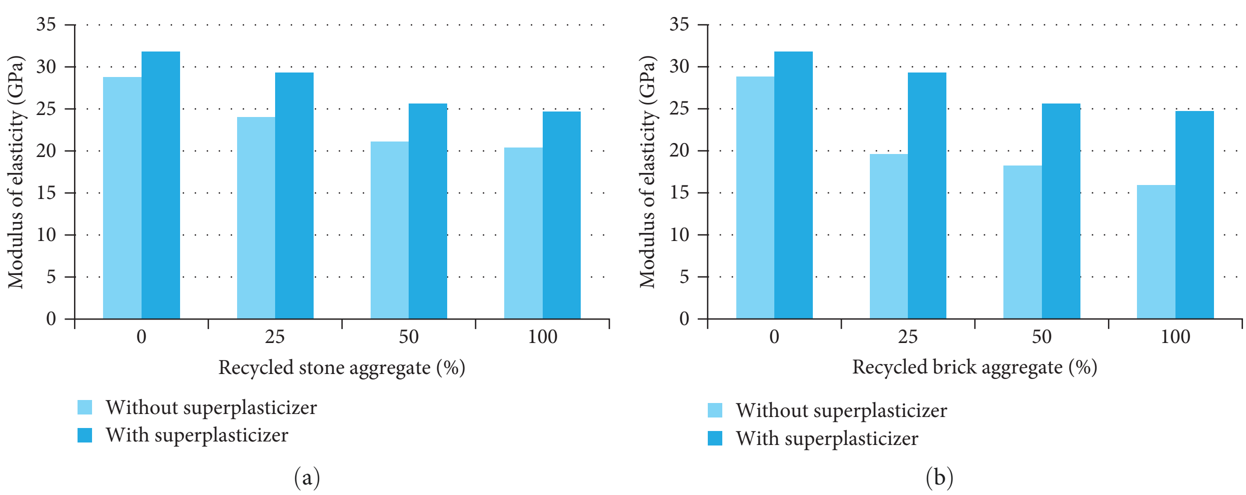


Figure 10: Effect of superplasticizer on modulus of elasticity of (a) RSAC and (b) RBAC at 28 days of curing age.

chips, corresponding splitting tensile strength increases by 9.5%, 10.5%, and 5.8%, respectively due to the superplasticizer at 28 days of curing age. Superplasticizer produces higher quality cement paste having a higher density, which results in increasing splitting tensile strength. Splitting tensile strength follows the same trend of decreasing compressive strength with an increased replacement of NA by RCA.

A linear relationship is derived between experimental results of compressive strength and splitting tensile strength of RAC and is presented graphically in Figures 8(a), 8(b), 9(a) and 9(b), including the relation proposed by ACI 318-14. Graphs show that the experimental splitting tensile strength values are less than the proposed values by ACI 318-14 due to using RCA. Derived equations signify that the compressive strength level of concrete has an influence on the splitting tensile strength. Developed equations and corresponding values of coefficient of determination for RAC with and without superplasticizer are also shown in respective figures.

3.2.3. Effect of Superplasticizer on Modulus of Elasticity of Concrete. Concrete with high compressive strength shows better elastic performance. Figures 10(a) and 10(b) present graphically the effect of the superplasticizer on the static modulus of elasticity of NAC, RSAC, and RBAC. For NAC containing 100% natural stone chips, the static modulus of elasticity increases by 10.4% due to the superplasticizer. For RSAC containing 25%, 50%, and 100% recycled stone chips, the corresponding static modulus of elasticity increases by 22.1%, 21.3%, and 21.1%, respectively, due to superplasticizer. For RBAC containing 25%, 50%, and 100% recycled brick chips, the corresponding modulus of elasticity increases by 36.2%, 28.5%, and 22.0%, respectively, due to the inclusion of

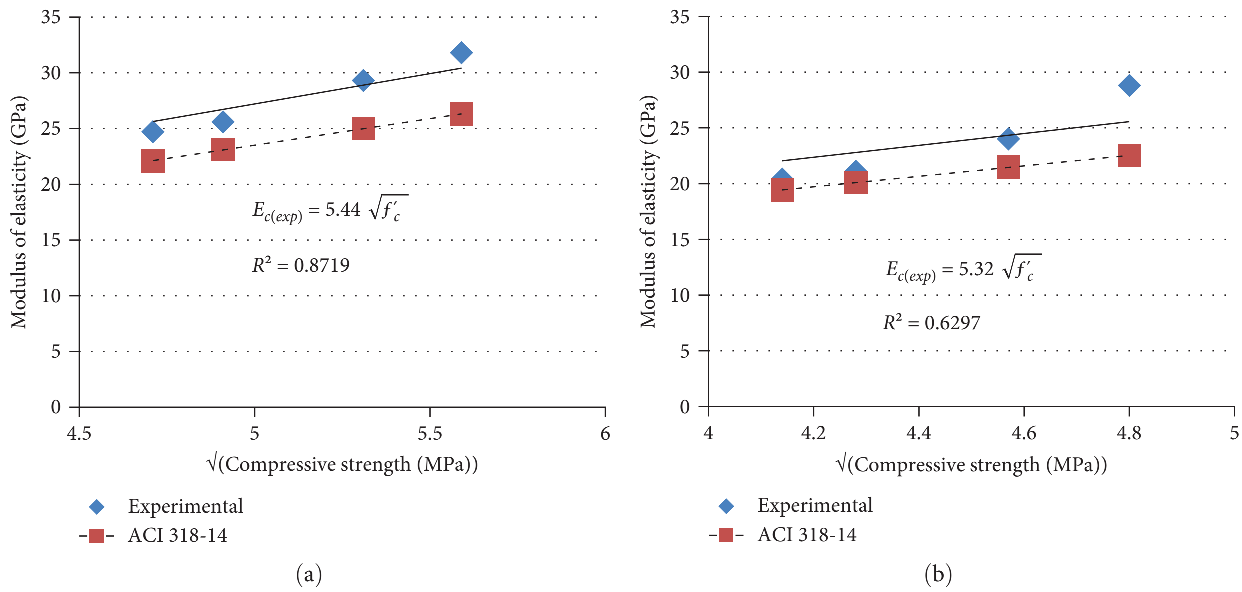


Figure 11: Relationship between compressive strength and modulus of elasticity of RSAC (a) without superplasticizer and (b) with superplasticizer at 28 days.

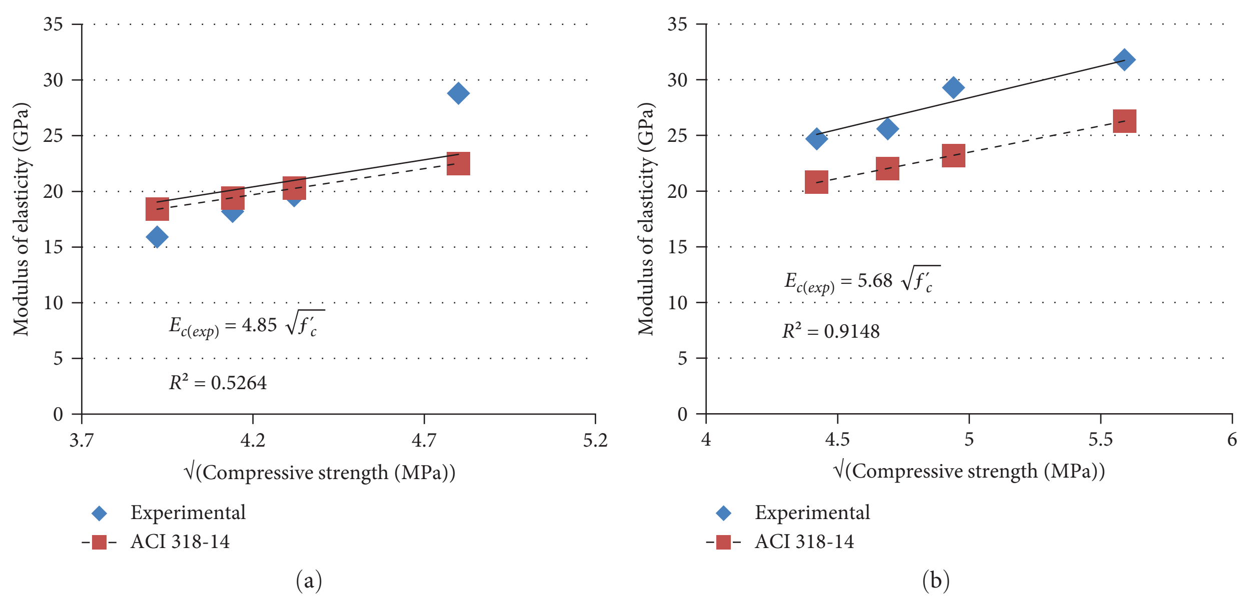


Figure 12: Relationship between compressive strength and modulus of elasticity of RBAC (a) without superplasticizer and (b) with superplasticizer at 28 days.

superplasticizer. Superplasticizer produces self-consolidating concrete, increasing its density and the modulus of elasticity of concrete is inextricably linked to its density. It is also observed that the static modulus of elasticity has decreased with the increasing amount of recycled aggregate percentages in the concrete specimens. A linear relationship is also derived between the experimental static modulus of elasticity and compressive strength of concrete, which is presented graphically in Figures 11(a), 11(b), 12(a), and 12(b), including the relation proposed by ACI 318-14. The graphs show that the experimental static modulus of elasticity is more than those proposed by ACI 318-14 for RSAC. On the other hand, the experimental static modulus of elasticity is lesser than that of the proposed by ACI 318-14 for RBAC. Corresponding values of the coefficient of determination for RAC with and without superplasticizer are also shown in respective figures.

4. Conclusions

An experimental investigation is conducted to assess the influence of the superplasticizer on the mechanical properties of RAC. Two types of RCA such as RSA and RBA were considered in the experimental program and compared NA. Four types of coarse aggregate replacements such as 0%, 25%, 50%, and 100% were used and half of the concrete specimens were admixed with superplasticizer collected from the local market to assess its effect on concrete mechanical performance. Fresh property in terms of slump value and hardened properties such as compressive strength, split tensile strength, and modulus of elasticity was tested at 28 days. The main conclusions that can be drawn from the experimental study are stated below [57]:

(1) Significant improvement of compressive strength was achieved due to the addition of superplasticizer in RAC.
(2) Splitting tensile strength of RAC also showed optimistic results for the addition of superplasticizer. However, experimental splitting tensile strength is found to be less than that of the value as per ACI 318-14.
(3) Static modulus of elasticity has been enhanced for RSAC and RBAC, respectively, for different aggregate replacement ratios due to the addition of the superplasticizer. In general, elasticity for RASC is found to be more than that of the value as per ACI 318-14. But the same trend is not followed by RBAC.
(4) Mechanical performance of RAC degraded with the increasing replacement of NA by RCA.
(5) Noticeable enhancement in splitting tensile strength and modulus of elasticity was obtained for RSAC and RBAC when the superplasticizer was used.
(6) It is observed that NA in a concrete mix can be replaced with 50% RSA and 25% RBA with the addition of the superplasticizer without compromising the mechanical performance. This clearly demonstrates the promising effect of the superplasticizer on the mechanical properties of RAC.

Data Availability

The data used to support the findings of this study are included in the article.

Disclosure

Experimental studies of this research were carried out under the postgraduate program at Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh and subsequently published on their website as a thesis.

Conflicts of Interest

The authors declare that they have no conflicts of interest or personal relationships that could have appeared to influence the work reported in this article.

Acknowledgments

The authors are thankful to all lab technicians/assistants of the Civil Engineering Department, BUET for their assistance during the experimental study.

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