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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Structural Sustainable Recycled Aggregate Concrete Production Under Environmental Conditions

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DOI: https://doi.org/10.30880/ijie.2023.15.06.007
Received 8 May 2023; Accepted 1 September 2023; Available online 28 November 2023

Abstract: The use of recycled aggregates (RA) in the concrete industry has become increasingly popular due to the reduction in natural aggregate (NA) consumption and the ability to reuse demolition waste. This research focuses on analyzing the performance of recycled aggregate concrete (RAC) cured with sodium sulfate (Na_2SO_4). Five different mixtures were created, varying from 0% RA without supplementary cementitious material (SCM), to 0%, 15%, 30%, and 45% substitution of NA with RA and SCM. The slump test was performed on all fresh RAC mixtures, which showed a decrease in slump with an increase in RA content. Both 5% Na_2SO_4 solution curing at 91 days and standard curing at 7, 28, and 91 days resulted in a reduction in compressive strength and ultrasonic pulse velocity (UPV) as the proportion of RA increased. Compared to standard curing, the compressive strength of specimens cured with 5% Na_2SO_4 solution at 91 days showed a decrease of approximately 5-7%. The UPV of SCM-based mixes showed 14-28% improvement with respect to normal aggregate concrete (NAC) in normal water curing. Furthermore, the SCM-included specimens have produced less deterioration in Na_2SO_4 immersion as SCM particles resist the severity of the dominant sulfate environment.

Keywords: Recycled aggregate concrete, construction waste, sulfate curing, ultrasonic pulse velocity, supplementary cementitious material, compressive strength

1. Introduction

Bangladesh's economy is now growing at a high rate, which has accelerated the development of the building industry and greatly expanded infrastructure. As concrete acts as a prime element of the construction sector, it puts pressure on limited resources like aggregate. The quantity of coarse aggregate (CA) needed to fill the volume of the concrete requires a significant amount of consumption, which has caused the worldwide demand to quadruple over the past five years [1]. Therefore, concrete aggregate from old or unusable buildings can be used in part as recycled aggregate (RA) to help reduce the rising demand for CA. Around three billion tons of globally produced demolished concrete waste can be utilized in a certain year [2]. According to Xiao et al. [3], The use of RA can preserve 60% of natural aggregate assets and reduce CO_2 emissions by up to 15-20%. On the other hand, concrete buildings may suffer damage if sulfate ions are present in soils, often below ground level [4]. When the structural element is exposed to water containing sulfate ions, the concrete infrastructure gradually loses strength over time and eventually collapses. However, silica fume and other supplemental cementitious materials (SCM) can significantly reduce the harm caused by sulfate assault [4].

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Despite the various benefits of RA, there are limited adverse effects for its wide application in conventional concrete. Several researchers observed the decreasing performance trend of RA with the increasing replacement percentage of normal aggregate (NA) by RA. According to Tabsh et al. [5], the strength of recycled aggregate concrete (RAC) achieved 10–25% less than the corresponding normal aggregate concrete (NAC). In addition, Jin et al. [6], Sobuz et al. [7], and Sobuz et al. [8] presented the decrement nature of compressive strength and workability of fresh concrete. On the contrary, Fonseca et al. [9] reported that a minor percentage inclusion of RA could enhance compressive strength by ensuring the better treatment of particles. However, several studies conveyed the ultrasonic pulse velocity (UPV) behavior of RAC for the representation of durability properties of the specimens [6], [10]. Investigation by Rao and Chakradhara [10] reported that concrete having RA as a partial replacement for normal aggregate results in 6% lower UPV readings than the matching standard concrete.

Structural concrete can experience an external sulfate assault when exposed to large amounts of sulfate ions in soils, seas, groundwater, industrial waste, and rivers [11]. As they move through the pore structure and participate in an interaction with solid hydration materials, sulfate ions are transported into the interior space [12]. The degradation of calcium silicate hydrate (C-S-H), which weakens the cement matrix, is caused by the transformation of cement's hydration products into harmful gypsum and ettringite particles [13]. Similar to the RAC, several types of research have been published to examine how sulfate immersion affects the characteristics of concrete [4], [11]-[15]. According to Park et al. [16], the mixed proportion and nature of sulfate solutions operate the compressive strength behavior. In addition, they also concluded that the compressive response of concrete tends to decrease as the immersion time of concrete increases. Conversely, Lee et al. [4] obtained that silica fume particles can resist extreme deterioration due to immersion in a 5% Na_2SO_4 solution. However, they observed a 15-20% strength loss of concrete with 5–10% silica fume replacement. Considering the prolonged experiment, Shannag & Shaia [17] observed that the UPV of specimens submerged in sulfate solution was about 30% less than that of conventionally cured concrete.

There have been several individual examinations of the effects of either RAC or sulfate solution curing on concrete specimens. In addition, the soil in Bangladesh's coastal region has an enhanced sulfate content, and an optimal solution for the use of RAC is also required for RA particle consumption. Concerning those aspects, this study represents the experimental investigation of the RAC under normal curing and 5% Na_2SO_4 solution curing to evaluate the impact of silica fume in controlling the harm due to sulfate attack. The slump test was conducted to evaluate the fresh behavior of the mixes. For RAC in regular water curing, the compressive strength and UPV were evaluated at 7, 28, and 91 days. In addition, 91 days of sulfate attack curing were completed, after which compressive strength and UPV were examined to determine the ideal sulfate-resistant RAC.

2. Materials and Experimental Methods

2.1 Materials

In this experiment, conventional Portland cement of the CEM-1 type was employed, which met the requirements of ASTM C150 [18]. Silica fume (SF) was also included as a 10% substitute for cement in the SCM. The stone chips were incorporated as natural coarse aggregate (NCA) having a nominal size of 20, whereas a similar nominal size series of RCA particles was used as the replacement of NCA. The fineness scenario of the NCA, RCA, and fine aggregate is represented in Fig. 1. The RCA fragments were collected from the waste from construction and broken down to the desired size and specification. Sand, RCA particles, and stone chips all have specific gravities of 2.62, 2.34, and 2.54, correspondingly. Furthermore, a superplasticizer was instigated as 1.3% of the binder to reduce the ratio of w/c.

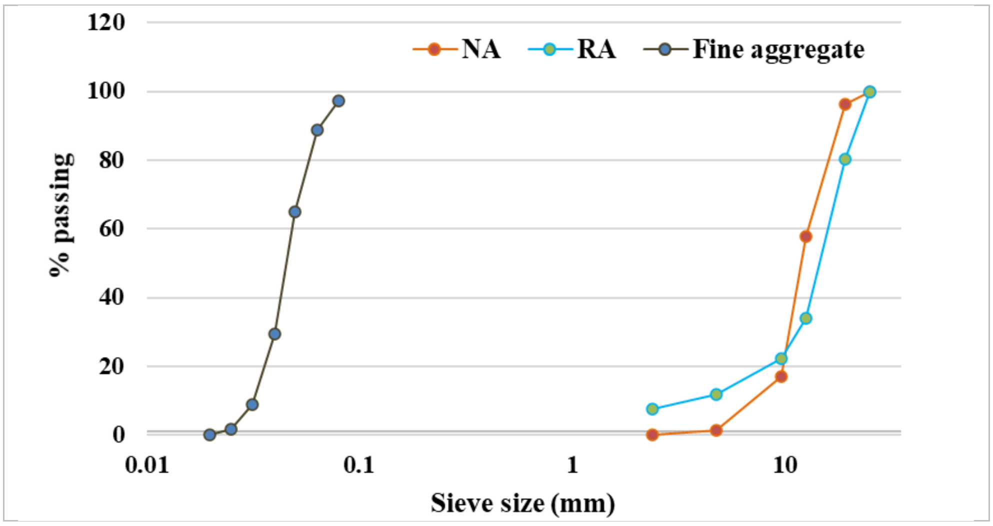

Fig. 1 - Particle size distribution of normal, recycled, and fine aggregate

2.2 Mix Preparation, Demarcation and Curing

Following ACI 363R Committee [19], the concrete mix design was conducted and the raw materials were mixed according to ASTM C192/192M [20]. To evaluate the RAC's qualities, five concrete mixtures were developed. The w/c ratio and the superplasticizer content were adjusted in this investigation by a number of trials of the mixtures. The water-binder ratio (w/b) was calculated from the provisional situations to be 0.33, and the mix ratio was calculated to be 1:1.54:2.41. The control mix is demarked as RAC0, having 0% concentration of RCA and the rest of the combinations are labelled as SRAC0, SRAC15, SRAC-30, and SRAC-45, comprising 15%, 30%, and 45% substitution of NCA by RCA. After the fresh state assessment, the fresh blend concrete was taken to 100 x 200 mm cylindrical moulds, which were submerged in water for 7, 28, 91 days. In addition, a few cylindrical specimens were submerged in 5% Na_2SO_4 solution for 91 days to evaluate the environmental effect. Consequently, the cylindrical specimens were removed from the curing tank a day before testing and stored outside.

2.3 Experimental methods

Fig. 2(a) demonstrates that the slump test was conducted following the ASTM C143 [21] to determine the workability of the concrete mixture and the impact of RCA particles on the slump value. Moreover, Fig. 2(b) shows that the compressive strength of cylindrical specimens was measured after 7, 28, and 91 days of maturity in accordance with ASTM C39 [22]. The non-destructive testing (NDT) assessment of the concrete specimens was performed using the ultrasonic pulse velocity test, following the ASTM C597 [23], as presented in Fig. 2(c).

(a) (b) (c)

Fig. 2 - Experimental set-up (a) slump test; (b) compressive strength, and; (c) UPV test

3. Results and Discussion

3.1 Workability

Fig. 3 characterizes the graphical illustration between the slump and percentage replacement of RCA of concrete mixes. In this study, an equivalent quantity of water and SP was incorporated to each mix. Therefore, the analysis specified a diminishing trend in a slump when the amount of RCA was amplified in the concrete mix. In addition, numerous researchers stated that water amounts have to be amplified for RCA to sustain the similar workability of NAC [24]. However, the roughness of blended concrete mix upturns attributed to the rough texture of RCA particles and thus condensed its flowability at a higher concentration [25]. On the other hand, the addition of SF as an SCM particle reduces the SRAC0 mix. Since SF is a finer powder than cement, the particles tend to fill the small vacuum spaces within the mixtures.

3.2 Compressive Strength

Assessing Fig. 4, it is obtained that the compressive strength development can be achieved by incorporating silica fume as the SRAC0 mix showed 33.7% strength improvement of the control mix (RAC0) after 28 days of normal water curing. The SRAC0 was found to have the greatest compressive strength among the mixes, although, at 7 and 91 days of testing, all the mixes exhibited a comparable improvement in compressive strength. The pozzolanic activity and space-filling ability of the ultrafine SF particles have significantly enhanced the concrete's ultimate strength characteristics. Thus, the formation of aggregate-paste linkages and an improved microstructure may both affect the strength properties. Additionally, the use of SF as a filler causes a thick transition zone to emerge between the cement matrix and the aggregate, which facilitates the production of calcium silicate hydrate (C-S-H) [26].

Fig. 4 illustrates that the normalized compressive response of concrete decreases as the proportion of RA particles increases over a period of 7, 28, and 91 days of normal water curing. The comparison with the control concrete mix stated that the compressive strength of the 28 days shows 33.67%, 8.64%, and 0.05% strength improvement for SRAC0, SRAC15, and SRAC30 mixes, respectively, whereas a 5.60% reduction is observed for the SRAC45 mix. The compressive strength following normal water curing at 7 and 91 days is evaluated in a similar way. The improving tendency declines as RA rises in proportion because there is a lower bonding force that exists between the RA interface and the matrix of concrete in the SRAC45 mix compared to the reference mix. The updated cement matrix and the old mortar attached to RA had a weaker binding due to the weakly adhered old mortar on the RA surface [27]. Furthermore, small internal cracks in the interfacial transition zone (ITZ) have an effect on the required RAC strength and outward stress assessment at the crack order owing to the transmission of the concrete's microcracks [7].

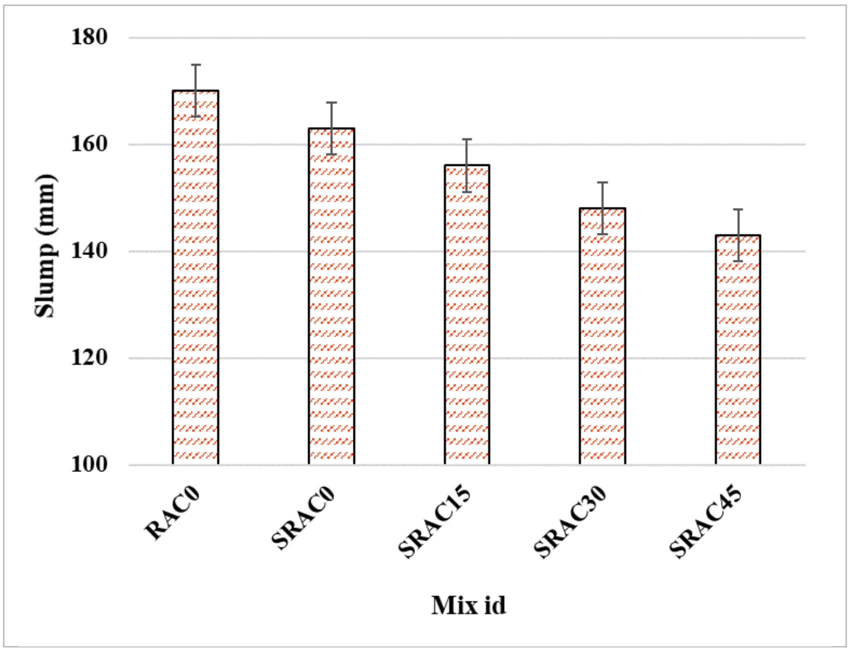

Fig. 3 - Slump value of the mixes

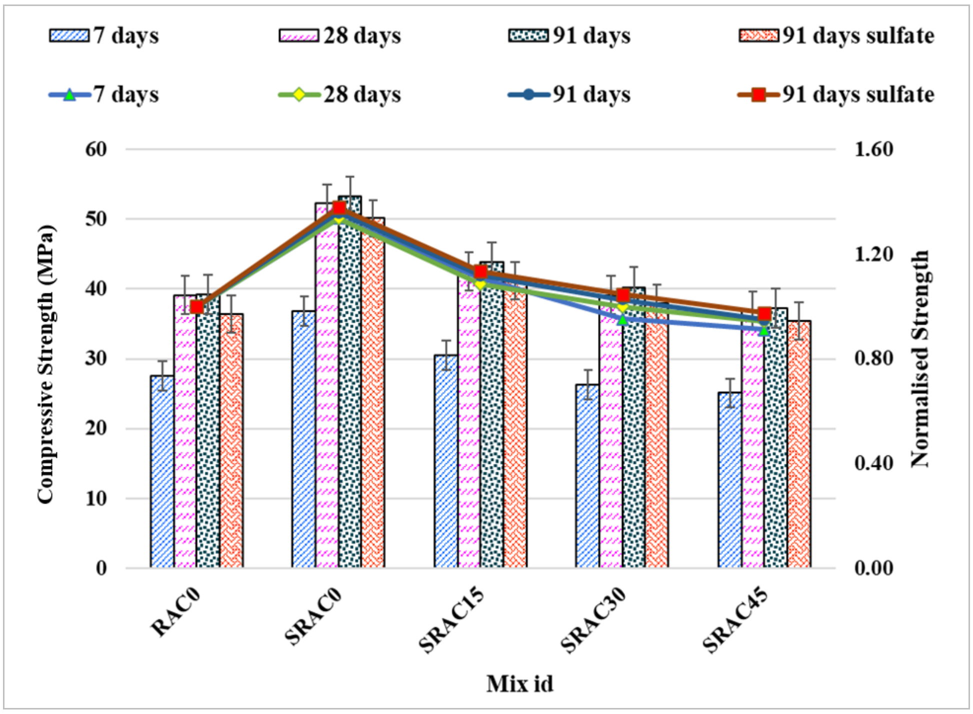

Fig. 4 - Compressive strength and normalized strength, along with the mix id

The results depicted in Fig. 4 indicate that the mixes subjected to immersion in Na2SO4 solution for a duration of 91 days exhibit a normalized strength that is inferior to the average strength value of the mixes that underwent water-curing after 28 and 91 days. Specifically, the strength of the normal water concrete at 91 days was 100.3-103.2% for the RAC0, SRAC0, SRAC15, and SRAC30 mixes relative to their 28-day normal curing strength. The tests also revealed that the specimens treated with Na2SO4 solution curing achieved 92.94%-97.16% strength at 91 days, compared to their 28-day normal curing strength. The observed softening and weakening of the sulfate-cured specimen can be attributed to the reaction between sulfate ions and calcium hydroxide as well as calcium aluminate hydrate, resulting in the creation of calcium hydroxide and gypsum. In addition, an internal sulfate attack is related to slower mobilization of cement sulfates, which results in the concrete's general degradation. The results also directed that the mixes holding silica fume exhibited good resistance to Na_2SO_4. In line with the study, Popovics [28] reported that the ultrafine SF's stuffing properties densified the pore space of the elements to increase their ability to withstand sulfate assault. This cohesive substance significantly contributes to the development of the aggregate-cement bond by densifying the transition zone via pozzolanic action and producing more calcium silicate hydrate [17].

3.3 UPV

Fig. 5 shows that the UPV value of SRAC0, SRAC15, SRAC30, and SRAC45 mixes exhibited 28%, 23%, 21%, and 15% enhancement from control concrete at 28 days. For cure times of 7, 91 days for regular curing, and 91 days for sulfate curing, a similar improvement pattern was seen. The presence of microcracks on the RA exterior impedes the pozzolanic reaction of the ITZ, resulting in a decrease in UPV values as the proportion of RA ingredients in concrete increases. Additionally, because the interior particle characteristics were not what was wanted, the pore structure form had an adverse effect on the UPV values. Therefore, RA's physical and mechanical properties can influence the decreasing percentage of UPV [10].

When comparing the UPV values for the basic water and sulfate water solutions at 91 days, Fig. 5 illustrates an intensifying pattern for the normal water solution and a declining trend for the sulfate solution. From the investigation, it is observed that RAC0, SRAC0, SRAC15, SRAC30, and SRAC45 mixes achieved 102.82%, 102.58%, 101.94%, 100.6%, and 101.44% of 28 days UPV at 91 days' water curing, whereas at 91 days' sulfate solution deep mixes of the identical concrete mixture obtained 95.46%, 97.77%, 97.21%, 96.12%, and 96.11% of 28 days UPV respectively. Ultrafine SF particles induced a reduction of the number of pores in the concrete, which slightly increased the transmission of the ultrasonic pulse. The results revealed that instead of SCM material, the concrete mixtures performed less efficiently than the SCM material mixes. As a result, SF resists the ingress power of sulfate substances to the concrete's interior. However, the filler and binding nature of SF particles also enhances the pulse durability of concrete under severe environmental action [17].

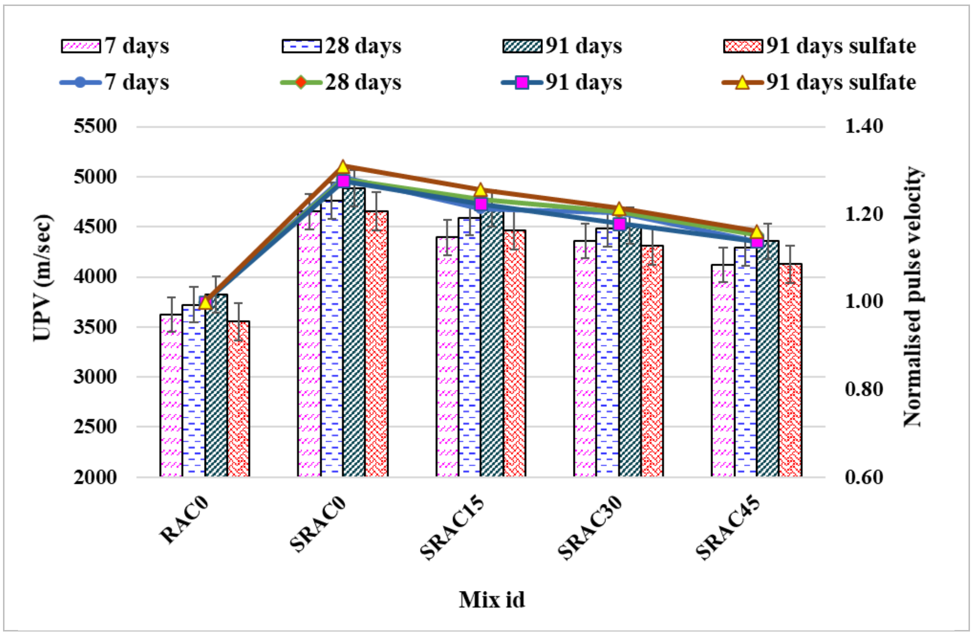

Fig. 5 - UPV and normalised pulse velocity along with the mix id

After 91 days of consistent water curing and 91 days of sulfate curing, Table 1 displays the concrete quality and UPV values (m/s) of the mixes. The quality of concrete was defined according to the range value of Malhotra [29] and IS:13311 [30]. The 91 days UPV value ranges between 3826 and 4883 m/s, which is in the concrete quality position of 'good' to 'excellent', while the UPV value at 91 days Na_2SO_4 solution varies from 3552 m/sec to 4654 m/sec with corresponding concrete quality of 'good' to 'excellent. Therefore, SF is efficient in decreasing or preventing sodium sulfate intrusion, owing to its involvement in lowering calcium hydroxide levels due to pozzolanic reactions.

It has been determined that there is a correlation between the RAC mixes' compressive strength from destructive testing and the UPV from NDT. The co-relation shown in Fig. 6 between compressive strength (f'_c) and UPV (v) is given as $f'_c = 0.0415v - 148.7$ ($R^2 = 0.81$). For concrete, it is possible to obtain ±20% of the absolute anticipated strength, but in the case of UPV measurement, the influencing parameter requirements are so frequent that it may be difficult to reach 95% confidence limits [31]. In this instance, UPV-compressive strength's co-relational behavior can be influenced by the physical characteristics of the aggregate, cementitious material, and water/cement content.

Table 1 - UPV specifications of RAC

Mix	UPV (m/s)		Concrete Quality	
	91 days (water)	91 days (Na_2SO_4)	Water Curing	Na_2SO_4 Curing
RAC0	3826	3552	Good	Good
SRAC0	4883	4654	Excellent	Excellent
SRAC15	4682	4465	Excellent	Good
SRAC30	4512	4311	Excellent	Good
SRAC45	4355	4126	Good	Good

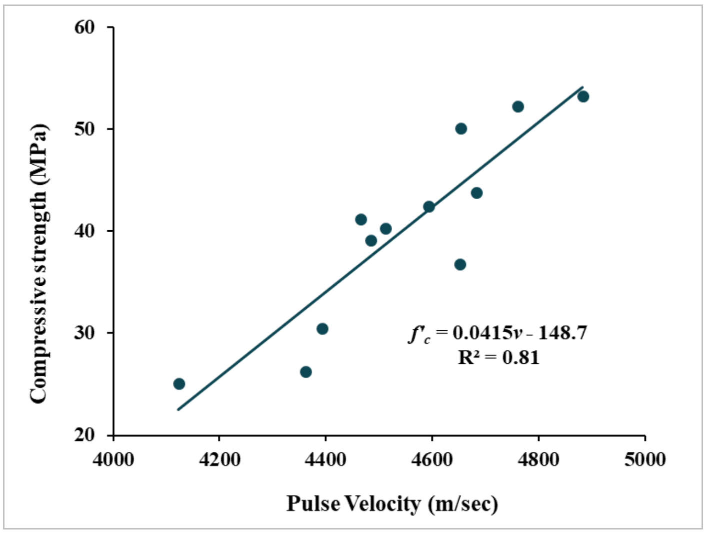

Fig. 6 - Relationship between destructive compressive strength and pulse velocity

4. Conclusion

This study presents a comprehensive investigation of several RA replacements on concrete specimens with or without silica fume in normal water curing and Na_2SO_4 solutions curing through strength and durability perspective. The particular curing was normal water and 5% Na_2SO_4 solutions, which were evaluated by taking into consideration the soil environment in Bangladesh. Therefore, the following concluding remarks can be obtained from the above-mentioned experimental results:

- With an increase in RA incorporation rate, the slump, compressive strength and UPV values of the RAC particle drop. Because of the high pozzolanic reaction and consequent reduction in $Ca(OH)_2$, the inclusion of SF in the Na_2SO_4 environmental action results in compressive strength that is beneficial and prevents the disproportionate loss of RAC specimens.
- Since only 5–10% strength loss was observed after 91 days of sulphate curing, the compressive strength losses may be kept to a minimum since the SF-cement matrix prevents the permeability and diffusion of SO_4^{2-} patenting from the Na_2SO_4 solution.
- The UPV values of 5% Na_2SO_4 solution curing at 91 days exhibit similar concrete quality with 91 days' of normal water curing. Therefore, excessive pulse velocity loss can be minimized by incorporating SCM-based material in concrete.

Acknowledgment

The authors would like to acknowledge the structural and materials engineering laboratory of the Department of Building Engineering and Construction Management at Khulna University of Engineering & Technology for providing facilities during material testing.

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