Sulfate Resistance and Alkali-Silica Reaction of Recycled Aggregate Concrete

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Abstract

In this research article laboratory investigations of sulfate resistance and alkali-silica reaction of recycled aggregate concrete are presented. A total of eighteen prisms of 25mm x 25mm x 286mm were prepared using a 1:3 (cement: fine aggregates) mix and 0.4 water to binder ratio. The specimens were prepared in three batches using recycled aggregates, conventional aggregates, and sand. An equal number of samples was used to evaluate sulfate resistance and alkali-silica reaction. The change in length of specimens was measured in a standard way from 1- to 28 days. The results at 14- and 28-days show that the percentile change in length of all specimens is less than the specified limit of concerned standards. The length change recorded at 14 days (in accordance with ASTM C1260 recommendations) of recycled aggregates is 342% (for alkali-silica reaction) and 57% (for sulfate resistance) better than conventional aggregates and sand. Therefore, the performance of recycled aggregates is concluded better compared to conventional aggregates and sand for both alkali-silica reactivity and sulfate resistance.

Keywords—Recycled aggregate concrete, demolishing waste, sulfate resistance, alkali-silica reaction, concrete deterioration.

1 Introduction

Several factors need to be considered to ensure good performance of concrete not only in a fresh state, immediately after hardening but also during service life. Among several factors and hazards that concrete faces during its service life; alkali-silica reaction is one. The reaction in concrete is identified as the second most dangerous after the corrosion of steel. As corrosion deteriorates the concrete around the steel resulting in loss of bond strength and cracking, alkali-silica reaction occurs between the reactive silica present in the aggregates and alkali present in the cement. The reaction forms alkali-silicate gel which sits in the pores and on the absorption of water its volume increases. The increase in volume results in the length change of the specimen. Also, the increase in turn builds up pressure in the concrete and causes internal cracking. To avoid the phenomenon; thus, to ensure better serviceability of concrete low-alkali cement is used but it cannot guarantee zero occurrences of the reaction. ASTM provides guidelines and testing of the aggregates for alkali presence[1]-[4] to avoid deterioration of concrete throughout life. ASTM C295[4] defines the procedure of testing alkali reactivity of cement-aggregate combination, and ASTM C227 [3] gives the procedure of petrographic examination of aggregates. ASTM C1260[1] and ASTM C1293[2] define the procedure for testing alkali-silica reactivity of aggregates throughout 2 weeks and 52 weeks respectively. Based on the results of the tests the aggregate sources are approved or sweeteners are suggested to reduce the reaction. ASTM C 1293 requires one complete year of examination of the material to reach a suitable conclusion, which in turn is a long time, therefore accelerated ASTM C1293[10] is proposed. The process requires the examination of samples at 60°C for thirteen weeks.

ISSN: 2523-0379 (Online), ISSN: 1605-8607 (Print)
DOI: https://doi.org/10.52584/QRJ.2002.16.

2 Literature Review

The literature review of a topic not only provides the benchmark information about the already done work in the field but also explains the procedures, hurdles, and obtained results. It in turn provides adequate information for further work in the field. This section summarizes the available relevant state-of-art related to the proposed topic of the research presented in this article.

A good quantum of effort has been devoted by scholars around the world to studying the alkali-silica reaction and sulfate resistance of concrete. Lindgård et. al.[7] published a review of the parameters with respect to factors affecting laboratory testing and emphasized giving due attention to internal humidity, extent of alkali leaching, and storage temperature for proper examination of the parameters. In another attempt, Sutter. [8] overviewed the alkali-silica reaction for concrete pavements. Among several factors affecting the alkali-silica reaction pH of the solution used for the curing of specimens is an important factor as it helps the formation of gel in the concrete[9].

To reduce the alkali-silica reaction different additives/sweeteners have been attempted in concrete. In an attempt, Aguayo et. al.[11] used foundry sand as a replacement for reactive sand to develop high-strength concrete and study its alkali-silica reaction. The authors used 7-, 14- and 28-day cured samples for the purpose and observed that replacement with foundry sand by up to 30% increased the reaction in the concrete. Latifee[12] used different dosages of class C and F fly ash as a sweetener to study the reaction with respect to lime content in fly ash. From the results, the author observed a linear relationship between the reaction and dosage of sweetener for both low and high-lime-content fly ashes. The author also coined the numerical expression to predict the length change based on the lime content. Choi and Yand.[13] used steel slag as an additive in concrete. Based on the results the authors argued that monitoring crack patterns along with length change is necessary. They observed cracks in the concrete even when the length change was within the specified limits of ASTM C1293. Reactive aggregate powder obtained by grinding reactive aggregates has been used by Andre´ et. al..[14] Based on the observations of 88 weeks authors concluded that the powder helped to reduce the alkali-silica reaction and cracking. William and Rodney[15] attempted different additives to check the validity of ASTM C1567 for testing alkali-silica reactions in concrete with combined aggregates. Based on the results author argued that for aggregate sources other than approved sources, 30% sweetener i.e., limestone, calcinate, cemented sandstone, coarse gravel or granite may be used for better performance of the concrete. Lucero[16] used electron microscopy to check the formation and release of ASR gel in existing structures and pointed out that alkalis present at the time of construction contribute a lot to the process. Synder and Lew[17] studied the degradation of the concrete of nuclear power plants due to the alkali-silica reaction. From the observations, the authors argued that the process is a complex phenomenon as several materials and environmental factors affect it. They also put forward recommendations to fill the knowledge gap and tools to evaluate the structural capacity of ASR-affected structures. Recycled aggregates from waste, black rock, and knife river aggregates were used by Tanner and Fiore[18] to study the alkali-silica reaction and validate FHWA limits. From the obtained results of the length change of mortar bars, authors concluded that recycled aggregates perform better than others against alkali-silica reaction. But the length change limits for the aggregates are higher than specified by ASTM C1293 therefore, recommended that the standards should consider the aggregates and revise the limits accordingly.

In the research article [27] the authors evaluated the alkali-silica reaction with respect to the applicability of the mortar bar test. The research used one batch of samples with a constant volume of water equal to 50% of absorbed water by the aggregates and another batch with pre-saturated aggregates. Based on the expansion tests of mortar bars authors concluded that the constant volume samples performed well than the samples of the second batch. The authors like Tanner and Fiore[18] observed that the ASTM C1260 specified ranges for expansion are too high for fine recycled aggregates therefore may be revised to consider the recycled fine aggregates. Another attempt by Mariakova et. al. [28] studied the alkali-silica reaction in recycled aggregate concrete by replacing sand with waste glass. The research program verified the chemical composition of the aggregates and used various samples cured at 1, 5, 9, 14, 21, and 28 days. The obtained results showed the authors better performance of the material used against alkali-silica reaction in recycled aggregate concrete. Adams and Idekar [29] on other hand studied alkali-silica reactions in concrete fly ash, silica fume, and metakaolin as cement replacement. The authors used binary and ternary blending of the materials to study ASR in the concrete and observed that with supplementary cementitious materials, the performance of the concrete against alkali-silica reaction was in good agreement with that of conventional concrete.

Recycled aggregates from demolishing waste or locally available material have also been checked for alkali-silica reactions and used in the development of ultra-high strength concrete [24], their influence on mechanical properties [25] and overall assessment of alkali-silica reaction affected recycled aggregates as building material [26].

Sulfate resistance is another quality of concrete that it should possess to counter the sulfate attack in aggressive environments during service life. Otherwise, its structural capabilities of it will be severely affected due to the reaction between sulfate ions and calcium hydroxide and/or calcium aluminate hydrate to form gypsum and ettringite. Ferraris et. al.[19] in their research program reviewed existing procedures adopted for the evaluation of sulfate attacks on concrete. They developed the test method to evaluate the resistance of fully and submerged concrete specimens for sulfate, which is three to five times shorter in time length than existing procedures. Like ASR control sulfate resistance of concrete may also be improved by using the additives in concrete. To this end, Lopez et. al.[20] used slag from steel manufacturing as an additive in mortar bars. They used different proportions of the slag and two different granularities. After ensuring the compressive strength of the specimens cured from 1 to 118 days, the authors evaluated the sulfate resistance of the mixes up to 36 weeks. From the results, they observed that slag with smaller particle sizes performs better than coarse sizes and showed improvement in the sulfate resistance of the concrete. Portland limestone cement containing higher quantities of limestone act as a sweetener for sulfate control. But its use in a sulfate environment is uncertain therefore, Ramezanianpour[21] performed laboratory investigations to check its performance. The author used five different limestone cement and their combination with and without slag. Based on the results he concluded that the use of 30% slag in the concrete shows better performance of the concrete. On the other hand, Emmanuel et. al.[22] insists on performance-based tests for the evaluation of the sulfate resistance of the concrete.

Vesna et. al. [30] also studied the resistance of concrete against sulfate attack. The research study used different proportions of recycled aggregates to produce eight different concrete mixes. The prepared samples were cured for 90-, 180-, and 365 days The test results of compressive strength and length change of the concrete showed the authors good resistance to sulfate attack. Hewayde et. al. [31] also studied the resistance of recycled aggregate concrete against magnesium and sodium sulfate subjected to drying-wetting cycles. The authors for their research program prepared concrete samples with 0, 25%, 50%, 75%, and 100% replacement of conventional aggregates with recycled aggregates. The samples were partially kept in solution with 2.5%, 4.5%, and 6.5% concentrations of sodium sulfate solution. The weekly recording of mass loss showed the authors that it was higher with the increase in dosage of recycled aggregates. It was almost double with 100% replacement of aggregates than 0% replacement. The research also pointed out that compressive strength for both 7- and 28-day cured samples reduced and was prominent for replacement levels higher than 50%. Based on the observations the authors concluded that sulfate attack was less aggressive in recycled aggregate concrete. In another research study, Sheoran [32] used 0 to 40% with an increment of 10% replacement of conventional aggregates with recycled aggregates to produce high-strength concrete specimens. To lower the water demand the author used 0.6% (by weight of cement) dosage of superplasticizer. Test results for sulfate resistance of the concrete showed similar and even improved results with recycled aggregates than with conventional aggregates.

The analysis of concrete against sulfate attack has also been studied by Arafa et. al. [33] using 108 cube specimens prepared by replacing conventional aggregates with recycled aggregates in dosages of 0, 30%, 60%, and 100%. The authors observed that the effect of sulfate becomes prominent after 90 days. They also concluded that a reduction in compressive strength is more sensitive against sulfate attack. Al-Ansary and Iyengar [34] in their research articles argue that the soil in Qatar is rich in sulfur, therefore, evaluation of the physio-chemical properties of recycled aggregates is essential to ensure their better performance. They used the XRF technique to achieve the target. Although the authors observed inferior water absorption and porosity of the aggregates their performance against sulfate attack was good. Xie et. al. [35] also observed excellent sulfate resistance of recycled aggregate concrete prepared with GGBS and fly-ash-based geopolymer. Al-Baghdadi [36] based on experimental observations also concluded excellent resistance of recycled aggregate concrete against sulfate attack, but the author used modified recycled aggregates. The modification was achieved by soaking the aggregates in water with polyvinyl alcohol (0.5% of the total volume of water). Different replacement of levels of the aggregates and the water-cement ratio was used to prepare the specimens and kept in a Sulfate solution for 150 days. The authors also observed better compressive strength of samples prepared with soaked aggregates.

It may be observed from the above discussion that a good number of publications are available in the literature for alkali-silica reactions and sulfate resistance of concrete. Different alternative or modified techniques for the evaluation of the parameters have also been developed. Yet more work is required to reach a good confidence level and to reduce the testing time of the parameters. Also, either no or least work is devoted to checking the parameter in recycled aggregate concrete. Recycled aggregate concrete made by using demolishing waste on other hand is a need of the day not only to conserve the environment and natural sources of aggregates but also to reduce waste management issues[6]. Therefore, in this research work, sulfate resistance and alkali-silica reaction of recycled aggregate concrete are aimed to investigate. Recycled aggregate concrete will be prepared using demolishing waste collected from Nawabshah, Pakistan. It is hoped that the outcome of the research will not only enrich the literature on the topic but also will give a good insight into the parameter for the proposed concrete.

3 Materials and Testing

The demolishing waste used in this research work was obtained in the form of large blocks from demolishing of a reinforced concrete building in Nawabshah, Sindh, Pakistan. These blocks were first hammered down to a maximum size approximately equal to 25 mm, followed by screening and washing. After drying the aggregates were ground to a size of fine aggregates. Conventional coarse aggregates of Noori Abad hills and conventional sand (Hill sand) were obtained from a local market (Figure 1). Like recycled aggregates, conventional aggregates were also washed and dried followed by grinding to the size of fine aggregates. Both aggregates are first sieved with a 4.75 size sieve to remove the oversized particles. Sieve analysis of both fine aggregates from recycled aggregates and conventional aggregates was performed. The percentage passing of the particles on different sieves is shown in Figure 2. It may be observed that with very minor variations the percentage passing is the same for both types of aggregates and is in the specified range of ASTM C33 standards [23].

The chemical composition of both conventional and recycled aggregates was evaluated using an XRD D-8 advance analyzer followed by qualitative technique at third-party commercial laboratories. Indeed, it is due to the un-availability of the requisite equipment at the place of the present research. The obtained results are listed in Table 1. It may be observed that the results of recycled aggregates are in good agreement with conventional aggregates and both aggregates and the results reported by Emiliano et. al [37] and Edgar et. al. [38].

3.1 Compressive strength test

The compressive strength using the proposed and conventional material is carried out to ensure the minimum strength of the concrete mix used. This correlates

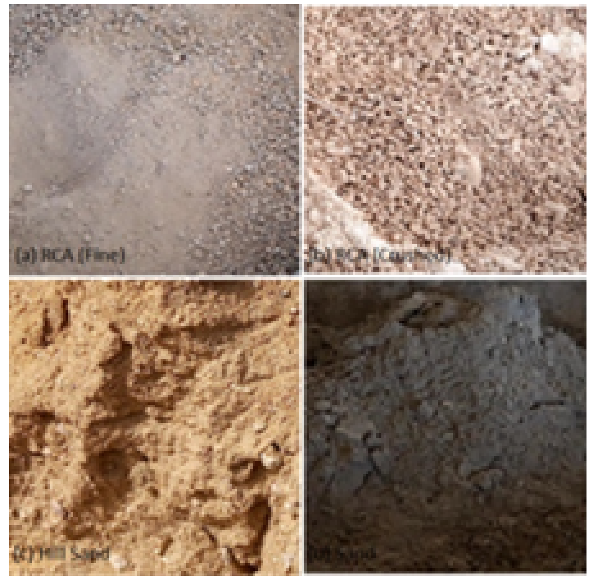

Fig. 1: Aggregates

with the concrete used in the field. For this purpose standard size cubes (6”x6”x6”) were cast using an arbitrary 1:2:4 mix and 0.4 water-cement ratios; which is commonly used in the field. Two batches of cubes (one with recycled aggregates and the other with conventional aggregates) with three samples in each were cast and cured in a standard way followed by testing in UTM under gradually increasing load (0.5 kN/min) till failure. The load recorded was then used to evaluate the compressive strength. Obtained results are listed in Table 2. It may be observed that the sample cast with conventional aggregates attained an average compressive strength equal to 24.8 MPa, whereas the samples containing recycled aggregates attained the same equal to 20.9 MPa. Although the average strength of the recycled aggregate concrete samples is 15.73% less than those of conventional concrete, both qualify for the minimum strength requirement of commonly used concrete in the field (21 MPa / 3000 psi).

3.2 Sample preparation and testing

To evaluate the sulfate resistance and alkali-silica reaction total of eighteen prisms of standard size (25mm x 25mm x 286mm) as specified by ASTM C1260 are prepared in three batches. In these batches, conventional aggregates, recycled aggregates, and sand are used. In the first batch conventional hill sand was used with cement in a 1:3 ratio; viz. one part of cement with three parts of fine aggregates in accordance with the requirement of the test procedure given by ASTM C1260. Similarly, in the second batch demolishing waste was reduced to fine aggregates and used with

TABLE 1: Chemical Analysis of the aggregates

#	Oxide	Conventional Aggregates	Recycled Aggregates
1	Sodium oxide	0.13	0.07
2	Calcium oxide	12.18	12.52
3	Silicon oxide	58.9	68.61
4	Aluminum oxide	0.61	0.91
5	Magnesium oxide	10.12	5.93
6	Potassium oxide	0.07	0.84
7	Phosphorus oxide	0.01	0.01

TABLE 2: Compressive strength

#	Concrete	Compressive Strength (MPa)	Average	Deviation (%)
1	Conventional	24.5	24.8	–
		25.3		
		24.6		
2	Recycled Aggregate	20.1	20.9	15.73

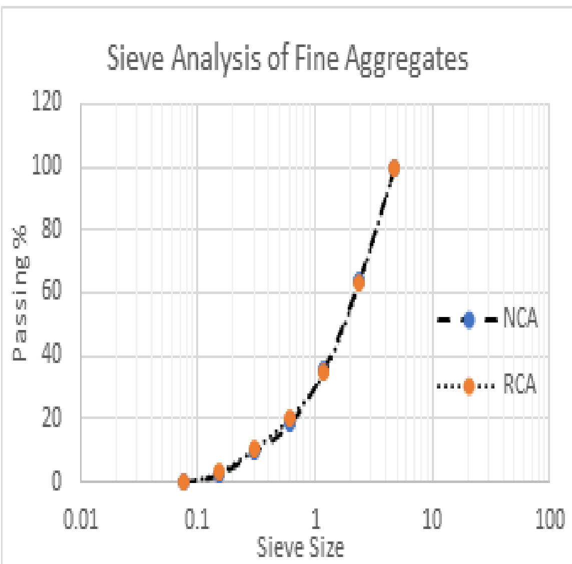

Fig. 2: Gradation of fine aggregates

Fig. 3: Prism Specimen

cement in a 1:3 proportion. The specimens of the third batch are prepared by using conventional river sand in a similar way to the first two batches. For all specimens, a 0.4 water-binder ratio is used. The mixed ingredients are quantified by weight method. The water used in mixing the ingredients is potable water with a pH value equal to 7.1. Wooden molds of the required dimension (ASTM C1260) are prepared and filled in standard fashion (Figure 3).

To prepare the specimens for evaluation of sulfate resistance, samples were arranged in a pan and loosely covered with towels in the oven at 35C for 24 hours. The samples were then de-molded and placed in lime water for another 48 hours. After that time, the initial length of the specimens was recorded. The sulfate solution was prepared by adding 50 grams of Na2SO4 per liter of deionized water and samples were immersed in it and kept at room temperature in line with recommendations of ASTM C1012[5]. The length change of the samples was recorded regularly for up to 28 days using a digital length comparator. In the instrument, the specimen is mounted manually between the base clamp and probe of the digital dial gauge (Figure 4). The reading of the dial gauge is then compared with the initial reading of the specimen and a change in length is computed. At each reading, the solution was replaced with a fresh solution. Length change recordings are listed in Table 3.

To prepare the specimens for studying alkali-silica reaction specimens were cast similarly as explained earlier. The curing of specimens was done in the moist cabinet for 1 day, followed by 1 day of curing in

TABLE 3: Change in length of specimens for sulfate resistance

#	Reading on	RCA-1	RCA-2	RCA-3	NCA-1	NCA-2	NCA-3	Sand -1	Sand -2	Sand -3
1	Day-1	0.08	-0.01	0.03	0.05	0.52	0.39	-0.04	0.01	0.04
2	Day-3	0.02	0.01	0.05	0.02	0.01	-0.10	0.01	-0.03	0.05
3	Day-5	0.01	0.00	-0.04	0.02	0.00	-0.20	0.01	0.01	-0.01
4	Day-7	-0.10	-0.03	-0.07	0.00	0.00	-0.30	0.05	0.03	0.02
5	Day-14	-0.07	0.10	0.13	0.04	0.06	0.14	0.06	0.03	0.02
6	Day-21	-0.17	0.11	0.18	0.03	0.06	0.19	0.16	-0.02	0.03
7	Day-28	-0.12	0.12	0.23	0.06	0.17	0.21	0.18	0.08	0.13

Fig. 4: Measuring change in Length

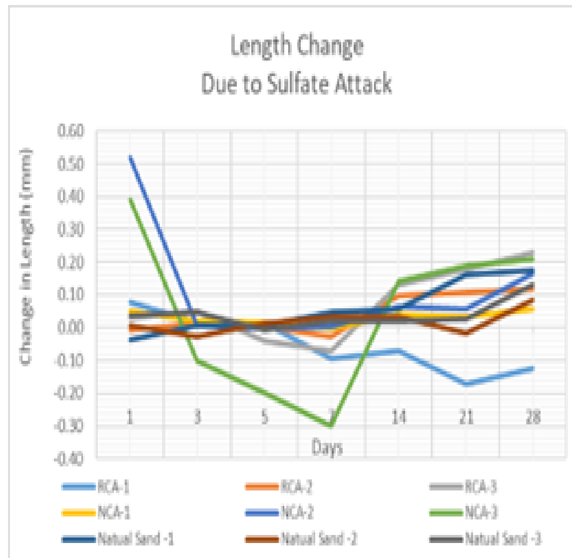

Fig. 5: Change in length due to sulfate attack

deionized water at 80°C as per the recommendations of ASTM C1260[1]. Then the specimens were kept in 1N sodium hydroxide solution prepared in deionized water at 80°C and length change was recorded regularly up to 28 days. At each reading, the solution was changed with a fresh solution. The recorded values of change in length are listed in Table 4.

4 Result and Discussion

4.1 Sulfate resistance:

The change in length of prism specimens due to the sulfate attack tabulated earlier is compared in Figure 5. It may be observed that almost all specimens observed both expansion and contraction during the measurements. A similar phenomenon is also reported in the literature [27][36-38]. Maximum expansion equal to 0.5 mm is observed on the 14th day in specimens with conventional aggregates. Also, the maximum contraction is recorded in the same type of specimen. These extreme values are recorded in a few samples only whereas the results of other samples of different batches are observed close to each other. The average values computed for each batch are plotted in Figure 6. It may be observed that the performance of recycled aggregates is better compared to conventional aggregates and sand. The percentile change in length is listed in Table 5. It may be observed from this table that the percentile change of length in all three types of samples is less than the specified limit (0.1%) of ASTM C1012. At 14 days performance of sand remained better compared to its other two counterparts. It is attributed to the washing of the sand with water, as the material was obtained from the riverbed, whereas at 28 days, the performance of the recycled aggregates is evident. Indeed, it may be attributed to the previous use of the aggregate where the reactive ingredients might have been released. Hence the performance of the aggregates is better compared to the other two types of aggregates.

4.2 Alkali-Silica reaction:

The change in length tabulated earlier is plotted in Figure 7 to compare the results of individual specimens of all three batches. Analogous to sulfate resistance, the samples in all three batches observed both

TABLE 4: Change in length of specimens for alkali-silica reaction

#	Reading on	Sand - 1	Sand - 2	Sand - 3	NCA-1	NCA-2	NCA-3	RCA-1	RCA-2	RCA-3
1	Day-1	0.07	-0.07	-0.16	-0.05	0.07	0.03	0.04	0.02	-0.07
2	Day-3	0.06	-0.03	0.24	-0.06	0.10	0.02	-0.03	-0.07	-0.08
3	Day-5	0.08	-0.07	-0.11	-0.05	0.12	0.08	-0.09	-0.14	-0.03
4	Day-7	0.07	-0.08	-0.16	-0.05	0.09	0.12	-0.03	-0.14	0.01
5	Day-14	0.07	-0.05	-0.11	0.00	0.06	0.08	0.01	0.00	-0.07
6	Day-21	0.12	-0.03	-0.13	0.04	0.04	0.15	-0.03	-0.11	-0.06
7	Day-28	0.13	0.03	-0.13	0.08	0.16	0.17	-0.01	-0.12	0.01

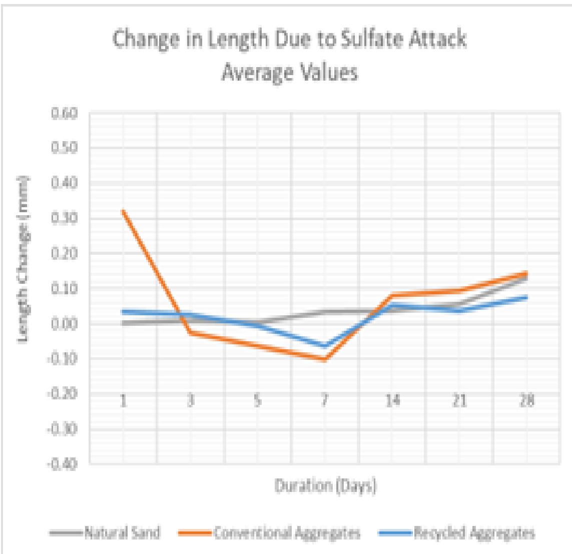

Fig. 6: Average values of change in length

contraction and expansion. Both extreme values are observed in the sample cast with sand. The upper and lower peak in a sample cast with sand is also shown in Figure 7. Except for these peaks, the rest of the results are in the close band. The upper peak is due to the swelling of the gel formed due to the alkali silica reaction in concrete voids. The same with time is when released, results in contraction of the specimen resulting in a lower peak. Both actions result in excessive stresses in the body of concrete giving rise to inside cracks [36]. The average values of all samples in all three batches plotted in Figure 8 also show a similar trend. From the tables and graphs, the performance of recycled aggregate samples for this aspect is observed better compared to the other two types of aggregates. The percentile length changes for all specimens at all reading times are listed in Table 6. It may be observed that both at 14- and 28-day the readings remained less than the specified limit of the parameter by ASTM C1260 (0.1%). Readings for recycled aggregate samples remained less compared to both sand and conventional aggregate. The positive behavior of the aggregates is the same as explained

TABLE 5: Percentile length change due to sulfate attack

#	Change in Length on	RCA	NCA	Sand
1	Day-1	0.0117	0.1119	0.0007
2	Day-3	0.0093	-0.0086	0.0033
3	Day-5	-0.0026	-0.0219	0.0016
4	Day-7	-0.0224	-0.0352	0.0117
5	Day-14	0.0182	0.0284	0.0128
6	Day-21	0.0133	0.0324	0.0198
7	Day-28	0.0261	0.0503	0.0455

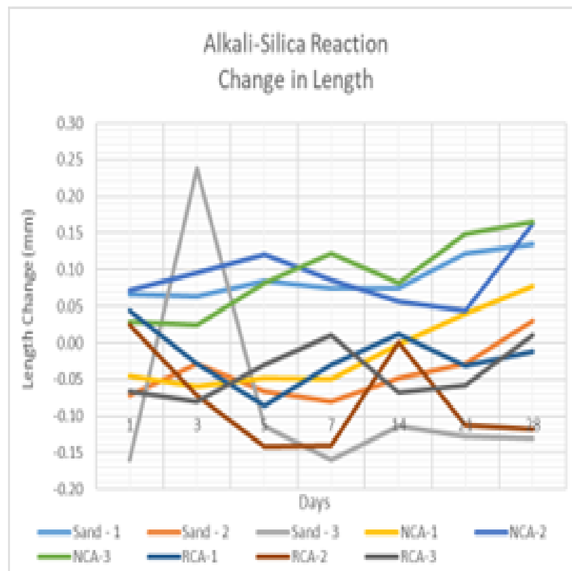

Fig. 7: Change in length due to ASR

earlier.

The outcome of this investigation shows that the performance of recycled aggregates for both sulfate attack and alkali-silica reaction is better compared to conventional coarse aggregates and sand. Thus, it has good potential to provide good resistance to concrete against alkali-silica reactions and sulfate attacks during service life. Indeed, both phenomena are material degrading due to chemical action inside the body of the concrete, resulting in early deterioration or failure of the structural member. The information on reactive materials in constituents of concrete particularly the

TABLE 6: Percentile length change due to alkali-silica reaction

#	Description	Sand	NCA	RCA
1	Day-1	-0.0193	0.0063	0.0002
2	Day-3	0.0319	0.0070	-0.0210
3	Day-5	-0.0112	0.0179	-0.0301
4	Day-7	-0.0193	0.0184	-0.0186
5	Day-14	-0.0103	0.0159	-0.0065
6	Day-21	-0.0040	0.0270	-0.0235
7	Day-28	0.0040	0.0473	-0.0140

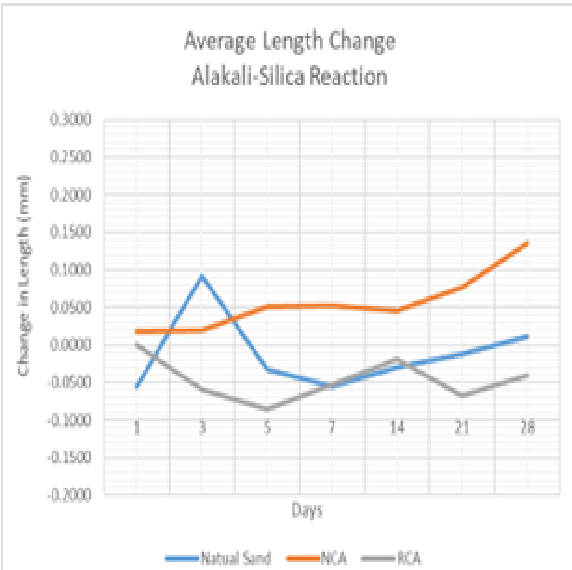

Fig. 8: Average length change due to ASR

recycled coarse aggregates ensures that the degradation of the concrete due to this action will be in control during the service life of the structure except in special/sudden situations due to environmental changes or any other hazardous activities. This, in turn, helps improve confidence in the use of recycled aggregate construction. However, the strength of the product is one of the key parameters and thus should be considered before the final decision. Also, these investigations are done for up to 28 days only, prolonged investigation should be undertaken to check the performance for a longer duration and thus improve confidence in the use of the aggregates.

5 Conclusion and Future Work

In this experimental program laboratory investigations on sulfate resistance and the alkali-silica reaction of recycled aggregate concrete are presented. Samples are cast in three batches using recycled, conventional aggregates and sand. Chemical analysis of the aggregates shows a good correlation between the oxide's contents. Obtained results of change in length of specimens show better performance of recycled aggregates than conventional aggregates and sand up to 28 days. The maximum change in length for both sulfate resistance and alkali-silica reaction at 14- and 28-days is observed less than the specified limit by the standards. Therefore, it is concluded that the recycled aggregate from demolishing waste has good potential to provide better resistance to concrete against sulfate attack and alkali-silica reactions.

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