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Effects of aggregate size and angularity on alkali–silica reaction

K. Ramyar[a,*], A. Topal[b], Ö. Andiç[a]

[a]Department of Civil Engineering, Faculty of Engineering, Ege University, 35100, Bornova, Izmir, Turkey
[b]Department of Civil Engineering, Faculty of Engineering, Dokuz Eylul University, 35160, Izmir, Turkey

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Abstract

The effects of reactive aggregate size and aggregate angularity on alkali–silica reaction (ASR) were studied. An all-in natural reactive aggregate was used. The coarse aggregate particles were crushed to obtain crushed fine particles. The angularity of the aggregate was determined using ASTM C1252 and EN 933-6 methods. ASTM C1260 accelerated mortar bar test was conducted to compare the ASR expansion caused by various aggregate size fractions. The effect of the size of the particles on ASR expansion was studied by replacing each size fraction of the non-reactive aggregate with the reactive aggregate of the same size. In spite of similarity of the chemical and mineralogical compositions, the crushed aggregate caused higher ASR expansion than the natural aggregate in all size fractions. The summation of the expansions of individual reactive size fractions of both aggregates was found to be higher than that of corresponding control mixtures.

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1. Introduction

The utilization of crushed fine aggregate by the concrete industry is increasing substantially in coastal parts of Turkey due to lack of natural fine aggregate sources. It is known that ASR expansion is related to aggregate size. At least for particle sizes greater than a definite value, it is expected that round and angular aggregates may behave in a different way because of the fact that angular aggregates have larger surface area than round particles when same size fraction is considered. Many studies have been conducted on the effect of aggregate size on ASR [1–6]; however, angularity effect has not been widely researched.

Early research of Vivian [7], as cited by Woods [1], has shown that for opalline aggregate, ASR expansion is maximum in the particle range of 0.07 mm–0.85 mm; larger or smaller reactive silica particles considerably reduce the expansion. Other researchers, using opalline silica, have shown that the mortar expansions increased as the reactive particle size was reduced to 0.05 mm or 0.02 mm, but below a particle size of 0.02 mm no abnormal expansion was observed [2–4]. Similar results have been obtained on siliceous magnesium limestone aggregate composed of calcite and dolerite containing chalcedony and opal as cited by Hobbs [6].

Kawamura et al. [8] measured expansions of mortar bars containing seven different size fractions of opalline rock at 10% of total aggregate with aggregate/cement ratio of 0.75, and kept in a fog box at 38 °C for 50 days as cited by Helmuth and Stark [9]. Total alkali content of mortar was 1.56% by mass of cement. Mortar bars made with the finest fraction (less than 0.074 mm) did not expand significantly. The 30-day expansions of mortar bars made with intermediate size fractions were about 0.3%. Mortar bars made with the two coarsest fractions, 2.5–5 mm and 1.2–2.5 mm, showed reduced expansions because the particles were not affected by the reaction to the same extent as the finer fractions.

Kodama and Nishino [10] prepared two mortar mixtures containing reactive andesite in two different size fractions

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[*] Corresponding author. Tel.: +90 232 3886026; fax: +90 232 3425629.
E-mail address: kramyar@bornova.ege.edu.tr (K. Ramyar).

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Table 1
Chemical composition of N, C and L aggregates

Material	Composition (%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
N	78.9	8.0	2.4	4.1	0.8	0.1	1.5
C	79.9	6.7	1.9	5.6	0.9	0.1	1.8
L	0.9	0.6	0.4	54.4	0.4	0.1	0.2

(<0.15 mm and 0.15–5 mm). An ordinary portland cement of 0.85% Na_2O equivalent was used. The cement content of the mortar mixtures was 612 kg/m^3. The 56-day expansion of 0.15–5 mm andesite-containing mixture was greater than 0.2%, whereas that of <0.15 mm andesite-containing mixture was approximately 0.02%. Kawamura's and Kodama's work appear to contradict that of Vivian's. This could have arisen from the differences between the alkali reactivity of the aggregates used in these investigations, as well as different cement/aggregate ratios and alkali contents.

Zhang et al. [11] stated that for siliceous aggregate, the smaller the particle size, the greater the ASR expansion when the aggregate size is within the range of 0.15–10 mm.

In short, it seems that two distinct effects should be considered: (1) the rate of reaction which would be faster for smaller particle size, and (2) the overall long-term expansion which may be larger for coarser aggregate.

In this study, the effects of reactive aggregate size and aggregate angularity on ASR were studied. In addition to a natural reactive aggregate a crushed aggregate obtained from coarse particles of the natural aggregate was used. The alkali reactivity of various size fractions of both of the aggregates was investigated using ASTM C1260 mortar bar test method.

2. Materials and test methods

2.1. Materials

One type of natural all-in reactive aggregate provided from Gediz riverbed was used. Coarse reactive particles were crushed to obtain particle sizes as specified in ASTM C1260. The natural sand was also screened and regraded to fulfill ASTM C1260 grading requirements. The chemical compositions of the natural fine aggregate (N) and the crushed fine aggregate (C) are given in Table 1. There is a close similarity between the chemical compositions of the two aggregates. A non-reactive crushed limestone aggregate (L) was used to evaluate the aggregate size effect on ASR expansion.

Both natural and crushed aggregates showed very close mineralogical compositions. Quartz+quartzite (~75%), mica-schist and muscovite minerals (~25%) were found in both aggregates. Besides, small amounts of basalt, onyx and travertine minerals were detected in crushed fine aggregate (less than 1%).

An ordinary portland cement conforming to relevant Turkish standard and having an equivalent Na_2O content of 0.95% was used for the manufacture of mortar bars.

2.2. Test methods and mixture characteristics

ASTM C1252 was used to determine the uncompacted unit weights of the three types of fine aggregates having the same standard grading. This method estimates the angularity, sphericity and surface texture of the aggregate having a given grading. EN 933-6 test method [12] was used to determine the flow coefficient of both N and C, flow coefficient is a measure of particle shape, texture and grading. The grading of the aggregates was kept constant according to Fuller curve to diminish the effect of grading, so that the test results indicate the shape and texture of particles only.

ASTM C1260 accelerated mortar bar test method was used to determine the expansions of the mortar bars. The proportions of the sands used in mortar mixtures are given in Table 2. The grading of the aggregate was kept constant while each size fraction of the non-reactive aggregate (L) was replaced with the corresponding size fraction of the reactive aggregate. The mixtures prepared by replacement of each size fraction of non-reactive aggregate with natural aggregate are designated N1, N2, N3, N4 and N5, while those prepared by replacement of each size fraction of non-reactive aggregate with crushed reactive aggregate are designated C1, C2, C3, C4 and C5 as shown in Table 2.

3. Results and discussion

The results of ASTM C1252 and the results of EN 933-6 test are given in Table 3. The uncompacted void content of

Table 2
Proportions of the sands used in mortar mixtures

Particle size fraction (mm)	(%) Used in ASTM C1260	N mixtures						C mixtures					
		N control	N1	N2	N3	N4	N5	C control	C1	C2	C3	C4	C5
2–4	10	N	N	L	L	L	L	C	C	L	L	L	L
1–2	25	N	L	N	L	L	L	C	L	C	L	L	L
0.5–1	25	N	L	L	N	L	L	C	L	L	C	L	L
0.25–0.5	25	N	L	L	L	N	L	C	L	L	L	C	L
0.125–0.25	15	N	L	L	L	L	N	C	L	L	L	L	C

Table 3
Uncompacted void content and flow coefficient of aggregates

Aggregate	Uncompacted void content on standard graded sample, % (ASTM C1252)	Flow coefficient, s (EN 933-6[a])	
		0.063–2 mm	0.063–4 mm[b]
N	40.0	25	13
C	45.5	31	16
L	42.4	34	16

[a] The test measures the time of flow of aggregate (in seconds) through standard funnels.

[b] The size fractions of the tested samples.

natural aggregate is lower than that of the other two aggregates, indicating that the N sample has a smooth and round surface. The flow coefficients of C and L samples (two crushed aggregate samples) are close to each other and higher than that of the N sample, indicating that these two aggregates are more angular than N aggregate. UNPG (Union Nationale des Producteurs de Granulats) recommends the following flow coefficients for 0/2 mm sea-dredged concrete aggregates used in concrete roads: for low traffic loads a flow coefficient of at most 30 s, for medium traffic loads a flow coefficient of 35 s and for high traffic loads a flow coefficient of at least 38 s [13]. On the other hand, Superpave (Superior Performing Asphalt Pavements), depending on the traffic load and depth from the surface for asphalt concrete aggregate, limits the uncompacted void content to 40% up to 45% [14].

All of the expansion tests were repeated twice on the different portions of the same aggregate samples, by the same operator (in the same laboratory) using the same equipment within 2 months time interval (repeatability r_1 conditions as specified by EN 932-6) [15]. The 14-day expansion results presented in Table 4 indicate that the differences between two test results (X1 − X2) are less than r_1 values, where r_1 is $2.8\sigma_{r1}$ and σ_{r1} is the standard deviation of two test results. Thus, according to EN 932-6 test results are compatible and can be averaged. The expansion values presented in Figs. 1–3 are the averages of the two tests.

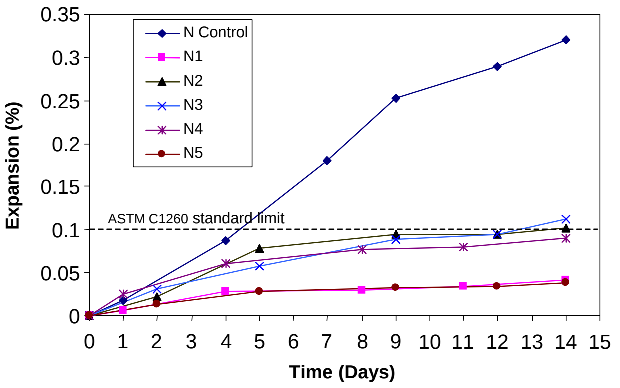

Fig. 1. Expansion–time relationship of N-bearing mixtures; the amounts of reactive aggregate for N1 and N5 are 10% and 15%, respectively, and for N2, N3, N4 are 25%.

Table 4
Statistical evaluation and repeatability of two test results

Mixtures	X1	X2	σ_{r1}	r_1	$\lvert X1-X2 \rvert$	Average (X1,X2)
N control	0.3	0.327	0.019	0.053	0.027	0.314
4–2 N	0.022	0.06	0.027	0.075	0.038	0.041
2–1 N	0.095	0.108	0.009	0.026	0.013	0.102
1–0.5 N	0.13	0.095	0.025	0.069	0.035	0.113
0.5–0.25 N	0.084	0.096	0.008	0.024	0.012	0.090
0.25–0.125 N	0.025	0.053	0.020	0.055	0.028	0.039
C control	0.276	0.335	0.042	0.117	0.059	0.306
4–2 C	0.052	0.062	0.007	0.020	0.01	0.057
2–1 C	0.14	0.11	0.021	0.059	0.03	0.125
1–0.5 C	0.199	0.15	0.035	0.097	0.049	0.175
0.5–0.25 C	0.18	0.2	0.014	0.040	0.02	0.190
0.25–0.125 C	0.047	0.047	0.000	0.000	0	0.047

The 14-day expansion of mortar bars containing aggregate L is 0.001%, indicating that aggregate L is non-reactive. The time–expansion relationship of N-bearing mortar bars is given in Fig. 1. It is seen that the natural aggregate is highly reactive and the control sample without any non-reactive aggregate gives the highest expansion value (0.31% in 14 days). Obviously, compared to the sample containing non-reactive aggregate, replacement of each non-reactive size fraction with natural reactive aggregate increases the expansions in all mixtures used. N2, N3 and N4 mixtures showed very close and higher expansions than N1 and N5 mixtures.

As it can be seen from Fig. 2, the expansions caused by C1 and C5 mixtures are close to each other and considerably lower than that of C2, C3 and C4 mixtures. The effect of size of the particles on ASR expansion is more pronounced in the crushed aggregate. The expansion–time relationship of mixtures containing natural aggregate of various size

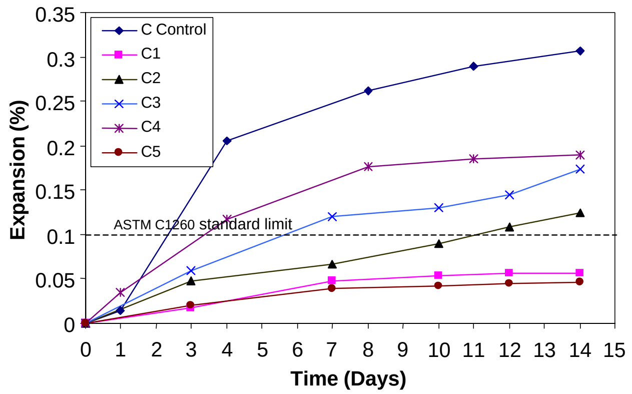

Fig. 2. Expansion–time relationship of C-bearing mixtures; the amounts of reactive aggregate for C1 and C5 are 10% and 15%, respectively, and for C2, C3, C4 are 25%.

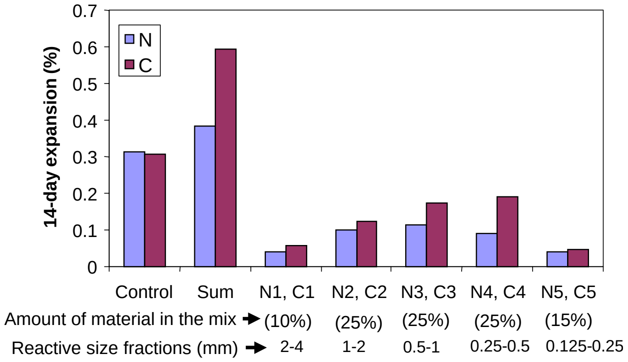

Fig. 3. The 14-day expansions of individual size fractions and control mixtures.

fractions are very close to each other. However, those of crushed aggregate show larger scatter.

The 14-day expansions of samples containing individual size fractions of natural aggregate are below 0.1%. However, the 14-day expansions of C2, C3, C4 mixtures are higher than 0.1% standard limit specified by ASTM C1260 for non-reactive aggregate.

The lower expansions observed in very coarse (N1 and C1) and very fine (N5 and C5) reactive particle-bearing mixtures may be, in part, due to the higher expansion potential of the intermediate size fractions and, in part, due to the amount of reactive material, found in the mixture. It should be noted that the amount of intermediate size fractions is 2.5 times and 1.6 times that of the largest and the smallest size fractions, respectively, as specified by the ASTM C1260.

In Fig. 3, the 14-day expansion of N- and C-bearing mixtures are shown. The angularity of particles has negligible effect on ASR expansion for very small and very large size fractions. However, for intermediate size fractions, the angularity effect is more pronounced. For an individual size fraction, the surface area of crushed particles may be larger than that of natural particles due to higher angularity as well as higher aspect ratio. Crushing operation may also create unsatisfied weaker bonds on the surface of the aggregate. This, in part, may lead to a greater reactivity and higher expansion values.

In Fig. 3, the summation of the expansion of the individual size fractions is also compared to that of the corresponding control mixtures containing all of the reactive size fractions, simultaneously. It can be seen that the summation of expansions caused by individual reactive size fractions is larger than that of corresponding control mixtures. This difference may be due to the interaction between the reactive size particles. Too many reaction sites may create a barrier effect when all the size fractions are very reactive, as shown by Shayan [16], for very reactive opal aggregate.

Interestingly, while no pop-outs were observed in control mixtures, pop-outs were noted in C1 and N1 mixtures containing 2–4 mm reactive material.

4. Conclusion

For the materials used and test methods applied the following conclusions can be drawn.

- No considerable difference was observed in the 14-day expansions of control specimens containing either natural reactive aggregate or crushed reactive aggregate.
- Larger differences were observed between mixtures containing crushed and uncrushed aggregate of specific size fractions of intermediate grain size, at 25% reactive aggregate content. This may be due to higher expansion potential of intermediate size fractions of crushed aggregate compared to the uncrushed aggregate.
- The effect of size of the reactive particles is more pronounced in crushed aggregate.
- The angularity of particles has negligible effect on ASR expansion for very large and very small particles. However, for intermediate size fractions, the angularity effect on ASR expansion is more evident.
- The summation of expansions caused by individual reactive size fractions is larger than that of the corresponding control mixtures. This may be due to the interaction between the reactive size particles: when all the size fractions are very reactive, too many reaction sites may create a barrier effect, as shown for very reactive opal aggregate by Shayan [16].

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