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Engineering Properties of Concrete Affected by Alkali-Silica Reaction

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A detailed study of the effects of alkali-silica reaction (ASR) on the engineering properties of concrete such as compressive and tensile strength, elastic modulus, and pulse velocity is presented. Two types of reactive aggregate — a naturally occurring Beltane opal and a synthetic fused silica — were used. The tests were carried out at 20 C and 96 percent relative humidity (RH). The results showed that losses in engineering properties do not all occur at the same rate or in proportion to the expansion undergone by the ASR-affected concrete. The two major properties affected by ASR were flexural strength and dynamic modulus of elasticity. Compressive strength was not a good indicator of ASR, but the flexural strength proved to be a reliable and sensitive test for monitoring ASR. Nondestructive tests like dynamic modulus and pulse velocity were also able to identify deterioration of concrete by ASR. The data indicate that critical expansion limits due to ASR would vary depending on the type and use of a concrete structure.

Keywords: absorption; **alkali-aggregate reactions**; compressive strength; concrete durability; concretes; **dynamic modulus of elasticity; expansion; flexural strength**; mechanical properties; tensile strength; tests.

Although the phenomenon of alkali aggregate reaction has been known and researched since it was first identified by Stanton[1] more than 45 years ago, most of the research has been directed at understanding the mechanism of the reaction and devising ways of controlling or preventing the expansion arising from the reaction. There is, however, only limited data on the physical effects caused by the deterioration process due to alkali-silica reaction (ASR); even then, most of the available information may not be directly useful to the engineer who wishes to understand the influence of the development of such reaction on the behavior of concrete and concrete members. Further, much of the published data relate to mortar rather than concrete.

This paper presents a detailed study of the effects of ASR on the engineering properties of concrete such as compressive and tensile strength, modulus of elasticity, and ultrasonic pulse velocity. Tests were carried out on concrete specimens containing two reactive aggregates — a naturally occurring Beltane opal and a synthetic amorphous form of fused silica, which the authors have identified as suitable artificial reactive aggregate to produce ASR expansion in the laboratory.[2,3] The tests were carried out for at least 12 months to establish the effects of expansion and time on the engineering properties of concrete.

RESEARCH SIGNIFICANCE

The research significance of the paper is identifying the major properties of concrete that are affected by ASR expansion and determining the extent and magnitude of the loss in these properties. Emphasis is also given to the use of nondestructive testing techniques, such as dynamic modulus of elasticity and ultrasonic pulse velocity, to examine whether these methods could be used to identify the initiation of expansion and the internal structural damage caused by ASR.

TEST PROGRAM AND DETAILS

Concrete mix and materials

Only one concrete mix was used for all the tests reported here — a 1:1.125:2 (cement:sand:coarse aggregate) mix, by weight, having a cement content of 520 kg/m^3 and a water-cement ratio of 0.44. The cement used was an ordinary portland cement (ASTM Type 1) having a high alkali content of 1 percent expressed as percentage equivalent sodium oxide, i.e., 5.2 kg alkali content per m^3 of concrete. The fine aggregate was a washed and dried natural sand, and the coarse aggregate consisted of a mixture of rounded and crushed gravel with 10 mm maximum size.

Two types of reactive aggregate were used to create expansion. In Series A, Beltane opal, ground to a size of 150 to 300 μm, was used as partial replacement of fine aggregate by an amount equal to 4½ percent by

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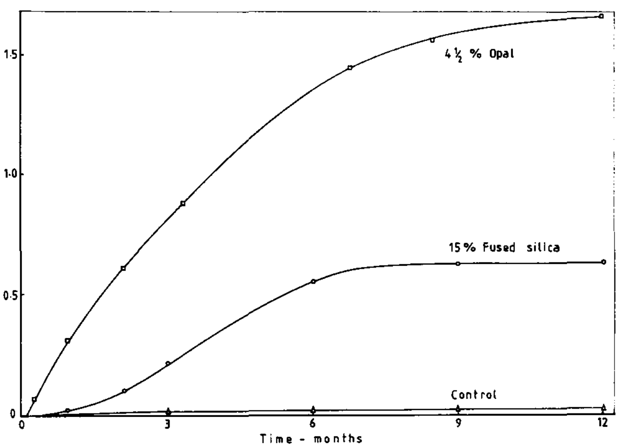

Fig. 1 — Expansion of control and ASR-affected concrete at 20 C and 96 percent RH

weight of the total aggregate. In Series B, an amorphous fused silica reported earlier[2,3] was used, which contained 99.7 percent silica and had a particle size distribution of 150 to 600 μm. This was also used to replace fine aggregate by an amount equal to 15 percent by weight of the total aggregate.

Test details

To relate the engineering properties of ASR-affected concrete to expansion arising from ASR, tests on expansion were first carried out on 75 x 75 x 300-mm prisms. These measurements were taken on a special rig with an attached micrometer.[4]

To establish engineering properties, the following tests were carried out: compressive strength (on 100 mm cubes), tensile splitting strength (on 100 x 200 mm cylinders), water absorption, modulus of rupture, dynamic modulus of elasticity, and pulse velocity (all on 100 x 100 x 500 mm prisms), all according to the relevant British Standards.[5,6] The dynamic modulus test was conducted by excitation in the longitudinal mode of vibration.[7] Commercially available portable equipment (PUNDIT), calibrated at regular intervals, was used to monitor pulse velocity. Transducers of 50-mm diameter were used, and measurements were taken at the top, middle, and bottom of the 100 x 100 mm end faces over a path length of 500 mm. All appropriate precautions were taken to obtain consistent data.[8]

All the test specimens were demolded at one day and then cured under constant temperature and humidity conditions of 20 ± 1 C and 96 ± 2 percent RH.

TEST RESULTS AND DISCUSSION

In the study reported here, two tests were carried out for a given property at any age. The results are thus the average of two tests.

Expansion due to ASR

To relate the change in concrete properties to expansion, the expansion of both sound control concrete and concrete affected by ASR was first established. This expansion is shown in Fig. 1. These results confirm earlier findings that expansion due to ASR, for a given environment, is influenced by a number of factors related to the reactive aggregate.[2,3] Both the rate of expansion and final expansion are dependent on the type of reactive aggregate, the amount present, and its particle size distribution.

Water absorption

The alkali-silicate gel arising from ASR is known to imbibe water, expand, and develop pressure resulting in the initiation of cracking, which then progresses with the reactivity. To establish these relationships, the water absorption measurements are plotted against time and expansion in Fig. 2 and 3, respectively. The data in Fig. 2 show that both the rate of absorption and the total absorption are dependent upon the type of reactive aggregate and the gel produced by its reaction with alkalis. For a given reactive aggregate, the differences in the rate of absorption at different ages can be attributed partly to the nature of the gel and partly to the development of cracks at various stages. It appears that the rate of absorption increases when moisture becomes available to new reaction sites, which produces more gel; on the other hand, the rate also increases when new cracks have formed or existing cracks have extended to form continuous channels. Note that at the end of one year, the water absorption of concretes containing opal and fused silica had increased by about 600 and 400 percent, respectively, compared to that of the control concrete.

The relation between water absorption and expansion shown in Fig. 3 is, however, very different from the variation of absorption with time, and it reveals some interesting phenomena. The gel resulting from fused silica had initially absorbed a significant quantity of water before any sign of expansion was observed, but with opal concrete, some expansion took place without measurable water absorption. To some extent, this is due to the very disordered structure of opal, which creates rapid expansion at very early ages, as shown in Fig. 1. It also indicates that with some reactive aggregates like fused silica, abundant moisture is essential to trigger the detrimental expansion, whereas with opal, the expansion may be initiated with the minimal moisture that is inherently present in all concretes soon after making them.

Fig. 3 also shows that at any expansion level, there is a higher water demand for fused silica concrete than for opal concrete to achieve the same level of expan-

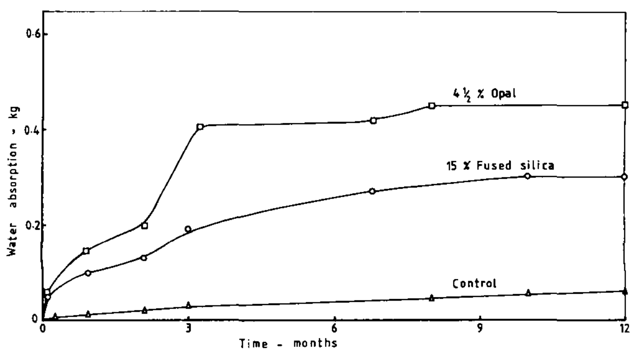

Fig. 2 — Water absorption of control and ASR-affected concrete

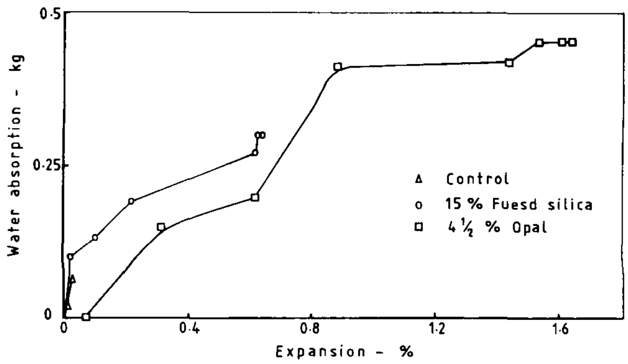

Fig. 3 — Relation between expansion and water absorption

sion. The water demand also varies with the level of expansion, and the rate of water absorption does not increase steadily with expansion, since it is also influenced by the degree of cracking. With time, the water absorption may decrease significantly when the rate of expansion declines, or it may even cease almost entirely when expansion is completed or all the reactive aggregate present has been consumed.

The data in Fig. 2 and 3 seem to indicate that there is probably no unique mechanism of ASR expansion, and that the physical structure of the silicate gel is dependent upon the type of reaction.

Compressive strength

The effect of ASR expansion and cracking on compressive strength of concrete containing opal or fused silica in relation to the unaffected control concrete is shown in Table 1. Both ASR-affected concretes initially show an increase in strength; but, consistent with the differences in their rate of expansion shown in Fig. 1, the two concretes commenced to show a gradual loss in strength — opal concrete at about 10 to 20 days; fused silica concrete at about 2 months. With time, both of these concretes showed a modest recovery or a cessation of loss of strength — opal concrete at about 8 months; fused silica concrete at about 7 months, largely due to the continued hydration of the cement. The data in Table 1 show that at one year, opal concrete suffered a loss of strength of about 54 and 63 percent, respectively, compared to the control strength at 28 days and 1 year, whereas fused silica resulted in loss of strength of about 26 and 39 percent of the control 28-day and 1-year strengths, respectively.

Note that concrete made with flint aggregate and cured at 38 C also showed considerable loss in strength at 1 year by which time both expansion and cracking of the concrete were reported to be severe; specimens stored at 20 C, however, showed little evidence of deterioration and continuous increase in compressive strength.[9] This behavior of concrete with flint aggregate at 20 C is in contrast to what happens to concrete in the presence of opal and fused silica. On the other hand, the data on flint aggregates,[9] although limited, also emphasize the problems that could be faced in practice with slow reactive aggregates. At ambient temperatures, such aggregates may show little expansion and loss of compressive strength at early ages or even after considerable time, whereas higher temperatures can cause harmful expansions and loss in strength.[2,3,9]

The loss in compressive strength related to expansion is shown in Fig. 4 and Table 2. The differences in the rate of development of early strengths of control and ASR-affected concretes indicate that the initial level of reactivity and the time required to trigger the deleterious reaction are of importance in enabling the concrete to develop its early hydration largely uninterrupted and to mature before the effects of expansion take place. The rate of reaction of the reactive aggregate is thus an

Table 1 — Effects of ASR expansion on concrete properties

Test	Mix	Age in days							
		1	2	3	7	10	28	100	365
1. Expansion, percent	Control	0.0	0.0	0.0	0.0	0.001	0.003	0.017	0.021
	4½% opal	0.0	0.0	0.004	0.071	0.097	0.316	0.883	1.644
	15% fused silica	0.0	0.0	0.0	0.0	0.005	0.023	0.259	0.623
2. Compressive strength, N/mm²	Control	26.7	—	44.2	48.6	—	60.1	61.9	73.5
	4½% opal	31.1	—	39.9	44.4	—	44.5	39.9	27.5
	15% fused silica	—	38.5	—	—	50.2	52.45	50.5	44.5
3. Indirect tensile strength, N/mm²	Control	2.61	—	3.23	3.58	—	3.90	4.26	4.29
	15% fused silica	—	2.81	—	—	3.67	3.29	—	1.83
4. Modulus of rupture, N/mm²	Control	3.52	—	4.24	4.88	—	5.25	5.37	5.58
	15% fused silica	—	3.84	—	—	5.3	4.58	1.83	1.30
5. Dynamic modulus of elasticity, kN/mm²	Control	35.593	38.054	38.818	41.034	41.119	42.510	44.193	45.400
	4½% opal	33.846	36.301	37.486	32.720	23.720	20.801	19.550	10.415
	15% fused silica	—	37.032	—	39.479	40.171	40.809	24.013	18.883
6. Ultra-sonic pulse velocity, km/sec	Control	4.28	4.48	4.55	4.60	4.64	4.67	4.71	4.78
	4½% opal	4.12	4.27	4.32	4.02	3.70	3.48	3.29	2.70
	15% fused silica	—	4.45	—	4.57	4.59	4.61	3.80	3.64

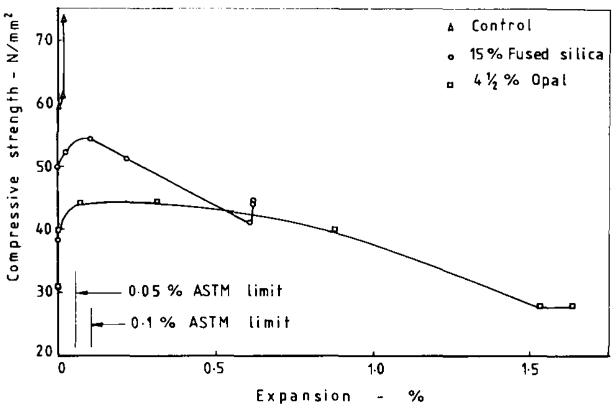

Fig. 4 — Variation of compressive strength with ASR expansion

important factor in controlling and counteracting the effects of hydration of cement, and different rates of reaction allow the development of the strength of ASR-affected concretes at different rates (Table 2). Once the concrete has reached a steady state in its expansion, the continued hydration of cement appears to have some beneficial affects in enabling modest recoveries of strength.

It is clear from the preceding data that loss in compressive strength increases with expansion and is controlled by the rate and extent of deleterious reactivity.

Tensile strength

Due to lack of availability of opal, both the modulus of rupture (MOR) and tensile splitting tests only were carried out on concrete containing fused silica. The results of these tests and those of control specimens are shown in Table 1. Following an initial increase due to early hydration, both the strengths recorded a sudden and a very marked drop, which continued at a decreasing rate until about 7 months when both registered, like compressive strength, a modest recovery of strength.

The loss in tensile strength with expansion is shown in Fig. 5 and Table 3. It can be seen that the drop in strength commenced at about 10 days when the expansion was about 0.005 percent, i.e., when no significant expansion or visible cracking had occurred. At 28 days, when the expansion was about 0.023 percent, the drop in MOR was about 13 percent, whereas the loss in splitting strength was about 16 percent. At one year, the loss in these two strengths was about 77 and 57 percent, respectively, compared to control specimens.

Comparing Fig. 4 and 5, it is seen that tensile tests are very sensitive (much more so than compressive strength tests), particularly at very early ages when values of expansion due to ASR are low; and the modulus of rupture is more sensitive to ASR than the splitting strength test in identifying the early effects of ASR. In most concretes undergoing ASR in this study, visual (i.e., unaided by eye) cracking was observed when expansion reached a value of about 0.05 percent. It is very clear from Fig. 5 that the drop in tensile strength occurs long before any visible cracking can be detected or even abnormal expansion has been observed.

The data in Tables 2 and 3 confirm that tensile strength is far more sensitive to the effects of internal stresses and microcracking caused by the expansive reaction of ASR than compressive strength. The results show that the reaction can be identified through tensile tests before it becomes large enough to produce visible microcracking and expansive disruption of concrete. The results of the tensile strength obtained by the fluid pressure method also confirm the data obtained by the conventional modulus of rupture tests reported here.[9]

Table 2 — Percentage loss in compressive strength of ASR-affected concrete

	4½ percent opal		15 percent fused silica	
Expansion, percent	Age, days	Loss, percent	Age, days	Loss, percent
0.05	6	9	40	12
0.10	8	11	60	11
0.20	17	20	87	15
0.40	36	27	140	30
0.60	60	30	200	40
1.00	117	38	—	—
1.60	270	62	—	—

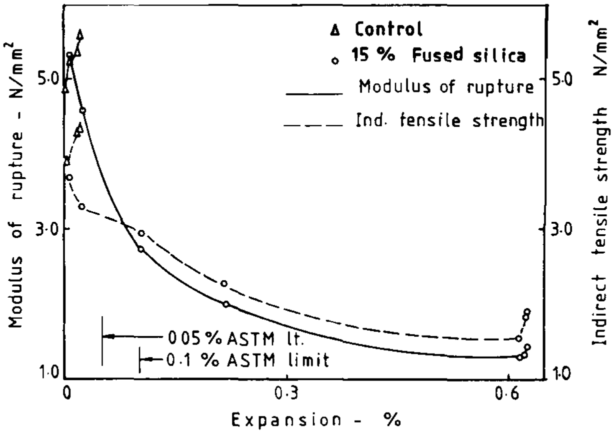

Fig. 5 — Loss in tensile strength with expansion

Table 3 — Percentage loss in tensile strength of ASR-affected concrete

Expansion, percent	Age, days	Loss of tensile strengths, percent	
		Modulus of rupture	Indirect tensile
0.02	27	11	11
0.04	36	20	19
0.05	40	30	27
0.06	45	29	23
0.08	54	40	26
0.10	60	48	29
0.15	75	56	38
0.30	110	67	55
0.60	200	78	64

Dynamic modulus of elasticity

The dynamic modulus measurements were taken with both reactive aggregates, and the results are shown in Table 1. The fall in dynamic modulus with expansion is shown in Fig. 6 and Table 4. These data show a pattern of behavior similar to tensile strength — a dramatic fall with age and expansion, and a modest recovery in time when the reactivity has more or less stabilized.

These results also confirm that dynamic modulus exhibits a very high sensitivity in reflecting the changes in the structure of the deteriorating concrete. Table 4 shows that this loss was noticed at a very early age, i.e., at 2 days when both reactive aggregates indicated no expansion. Bearing in mind that the dynamic modulus is the result of longitudinal excitation, a drop in this modulus at zero expansion is a clear indication that longitudinal resonance is sensitive enough to pick up changes in the internal structure of the concrete due to ASR long before any change in the physical properties or visible cracking has taken place.

Like other properties, the speed and extent of loss in dynamic modulus depend largely on the type of reactive aggregate and its reactivity (Fig. 1). The rate at which changes in the structure and physical properties of the ASR-affected concrete occurs is the result of the direct interaction of two conflicting phenomena — the damaging effect of the expansive reactivity and the continuing hydration of the cement paste. This is reflected in the data presented in Table 4 with both ASR-affected concretes. This can be illustrated by examining changes in the dynamic modulus, for example, of opal concrete between the ages of 28 and 100 days. During this period, although expansion had increased from 0.316 percent to 0.883 percent, the loss in dynamic modulus was only modest — from about 51 to about 56 percent. The reason for this small change in dynamic modulus is that, during the same period, the water absorption increased from 0.147 kg (at 28 days) to 0.410 kg [at 100 days (see Fig. 2)]. This large increase in water absorption has also obviously accelerated the cement hydration and possibly sealed many of the ASR microcracks with hydration products. This was evidenced by the small loss of compressive strength from 44.5 N/mm^2 at 28 days to 39.9 N/mm^2 at 100 days. Thus it is the large water absorption and the consequent hydration of the cement that kept the loss in strength and dynamic modulus to a minimum.

Ultrasonic pulse velocity

As noted earlier, ultrasonic pulse velocity measurements were taken at the top, middle, and bottom of the 100 x 100 mm cross section and represented as a mean value. Because of some overlap in the areas across which the velocity was measured, there was no significant differences in the three readings. Since both the dynamic modulus and pulse velocity are theoretically interrelated, Fig. 7 is presented to illustrate the changes in both these properties with time. The results confirm that both show generally similar behavior, although the magnitudes of their changes are different.

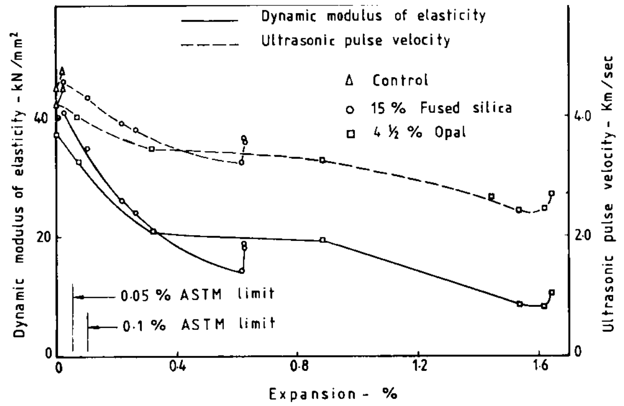

Fig. 6 — Variation of dynamic modulus and pulse velocity with expansion

Table 4 — Percentage loss in dynamic modulus of ASR-affected concrete

	4½ percent opal		15 percent fused silica	
Age, days	Expansion, percent	Loss, percent	Expansion, percent	Loss, percent
2	0.0	4.6	0.0	2.7
7	0.071	20.3	0.0	3.8
10	0.097	42.3	0.005	2.3
28	0.316	51.1	0.023	4.00
100	0.883	55.8	0.259	45.7
204	1.442	74.7	0.615	68.0
300	1.618	81.9	0.625	59.8
365	1.644	77.1	0.623	58.40

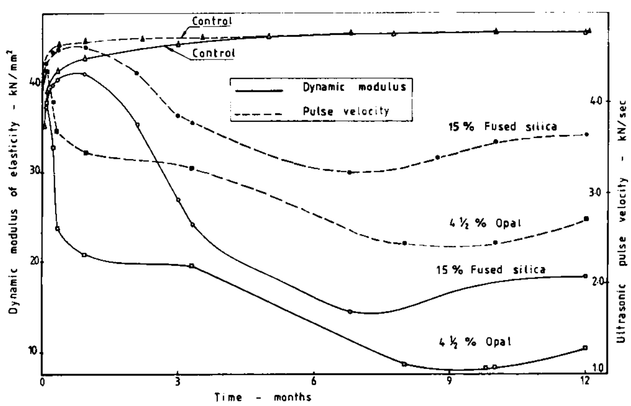

Fig. 7 — Variation of dynamic modulus and pulse velocity with time

The loss in pulse velocity with expansion at different ages is summarized in Table 5. A comparison of loss in pulse velocity with loss in dynamic modulus in Table 4 shows that both are highly sensitive to changes occurring in the internal structure of the concrete due to ASR, and both these properties registered measurable losses even before any expansion could be measured. It thus appears that both these techniques offer potentially useful nondestructive test methods to identify the physical condition of concrete due to internal chemical reactions arising from ASR.

Table 5 — Percentage loss in pulse velocity of ASR-affected concrete

Age, days	4½ percent opal		1.5 percent fused silica	
	Expansion, percent	Loss, percent	Expansion, percent	Loss, percent
2	0.0	1.1	0.0	< 1.0
7	0.071	9.5	0.0	< 1.0
10	0.097	17.0	0.005	1.0
28	0.316	23.0	0.023	1.3
100	0.883	30.1	0.259	19.3
204	1.442	44.0	0.615	32.0
300	1.618	48.9	0.625	25.3
365	1.644	43.5	0.623	23.8

Table 6 — Ratio of tensile to compressive strength for control and ASR-affected concrete

Age, days	Rate of tensile to compressive strength for control concrete	15 percent fused silica	
		Expansion, percent	Ratio of tensile to compressive strength
28	0.087	0.023	0.087
63	0.087	0.102	0.049
100	0.086	0.259	0.036
365	0.076	0.623	0.029

Ratio of flexural to compressive strength

The data presented earlier show that with concrete affected by ASR, the decrease in flexural strength takes place before visible cracking develops. Compressive strength, on the other hand, is little affected during the early stages of reaction, and does not decrease significantly until cracking is severe.[2,9] The ratio of tensile to compressive strength should therefore offer another means of identifying the deteriorating effect of ASR.

The ratio of tensile to compressive strength of ASR-affected concrete containing 15 percent fused silica as well as that of sound concrete is summarized in Table 6. The effect of expansion and cracking is clearly demonstrated in these results. For sound concrete, the ratio of tensile to compressive strength generally varies from about 0.11 to 0.07; the ratio decreases with increase in compressive strength and age. For ASR-affected concrete, significant reductions in this value occur. At 0.1 percent expansion, the ratio decreased to 0.049; at an expansion of 0.259 percent, this ratio was only about 40 percent of the original value, while it was still further reduced to about a third of the original ratio at an expansion of 0.623 percent.

Ratios of tensile to compressive strength of 0.03 for laboratory specimens and 0.03 to 0.050 for ASR-affected concrete from actual structures have been reported in the literature.[9] In the Cement and Concrete Society report issued in February 1987[10] for the diagnosis of alkali silica reaction, a ratio of less than 0.06 is recommended as evidence of internal deterioration in ASR-affected concrete. In light of the results for fused silica reported here, this ratio of tensile to compressive strength would correspond to an expansion of about 0.075 percent. It should be possible to identify ASR reaction at a much earlier stage than this. In any case, in practice, this particular criterion is unlikely to be helpful because it is not often that control specimens are available for completed concrete structures.

Comparison with published data

There is little published data in literature on the losses in engineering properties at maximum expansion or maximum losses in properties suffered by concrete undergoing ASR. However, in Table 7, a comparison of these values obtained in this study and reported by Hobbs[11] are presented. In the data on the 14-year-old high strength concrete cubes, some of which had cracked from alkali silica reaction after less than 56 days, no details are given of the mix proportions, type of reactive aggregate, or curing regime used in the tests.[11] Nevertheless, the data clearly show that there is a wide difference in losses in the concrete properties and that ASR influences different properties at different rates. The maximum effect appears to be on flexural strength, with significant losses in the elastic modulus, both of which can have major effects on the flexural rigidity of reinforced concrete members. The compressive strength test is clearly not a good indicator of ASR.

ASTM C 227 limits

ASTM C 227 recommends 0.05 and 0.1 percent expansion limits at 3 and 6 months, respectively, for nonreactive aggregates.[12] Above these limits, aggregates should be considered capable of harmful reactivity. Table 8 summarizes, for opal and fused silica, the number of days required to reach these limits as well as the strength and elastic properties of the deteriorating concrete, and the percentage losses in these properties compared to the control specimens at the same age.

The results show that different reactive aggregates affect the engineering properties at different rates, and that the properties most affected by ASR are flexural/tensile strength and elastic modulus. These are also two of the important parameters in engineering design and are significant in relation to cracking and deflection of flexural members, as well as cracking and durability of all concrete members.

It is doubtful, therefore, if the same values of critical harmful expansive limits can be specified for all types of structures without regard to either their effect on engineering properties or the type of reactive aggregate (i.e., the rate of reactivity) that gives rise to the rate of loss in these properties. At 0.1 percent expansion, concrete with fused silica lost nearly 50 percent flexural strength and about 20 percent elastic stiffness. Concrete with opaline aggregates, on the other hand, lost nearly 40 percent elastic modulus, and the loss in its flexural strength is likely to be greater than 50 percent because of its greater severity of cracking than fused silica. Since losses in engineering properties do not occur at the same rate or in proportion to expansion undergone by the concrete, and since expansions can be excessive or deleterious without evidence of cracking, depending on the function of the concrete element, it is difficult to see how single values of critical limits can be applicable to all situations.

Table 7 — Comparison of concrete properties affected by ASR

Properties of concrete	Authors — at 1 year					Hobbs[11] at 14 years		
	Sound concrete	Opal at expansion of 1.644 percent		Fused silica at expansion of 0.623 percent				
		Result	Loss, percent	Result	Loss, percent	Uncracked	Cracked	Loss, percent
Water absorption, kg*	0.063	0.454	−620.0	0.302	−379.0	—	—	—
Compressive strength, N/m^2	73.50	27.50	63.0	44.50	39.5	103.0	84.0	18.4
Modulus of rupture, N/mm^2	5.58	—	—	1.30	76.7	—	—	—
Indirect tensile strength, N/mm^2	4.29	—	—	1.83	57.3	6.0	4.9	20.4
Modulus of elasticity, kN/mm^2	45.40	10.41	77.0	18.88	58.4	46.0	27.0	41.3
Pulse velocity, km/sec	4.78	2.70	43.5	3.64	23.8	5.05	4.75	5.9

*Negative sign indicates gain.

CONCLUSIONS

From the results presented here, and for the type of reactive aggregates, particular mixes, and test conditions used in these tests, the following conclusions can be drawn.

1. Both the rate of water absorption and total absorption as well as the rate of losses and total losses in engineering properties of concrete affected by ASR depend on the physical and chemical characteristics of the reactive aggregate present in concrete.

2. Losses in engineering properties do not all occur at the same rate or in proportion to the expansion undergone by the ASR-affected concrete.

3. Compressive strength is not a good indicator of the initiation or progress of ASR, particularly at early ages. Tensile strength tests, particularly the modulus of rupture test, are a sensitive and reliable method to pick up the changes in the internal state of concrete undergoing ASR. For example, at expansions of 0.05 to 0.1 percent, loss in compressive strength remained low and static at about 10 percent, but loss in flexural strength could be monitored at expansions as low as 0.005 percent when no significant expansion or visible cracking had occurred.

4. Both dynamic modulus of elasticity and pulse velocity give good indications of the extent of deterioration of concrete affected by ASR. Both properties showed measurable losses at a very early age when no expansion was indicated, i.e., long before any change in the physical properties or visible cracking had taken place.

5. ASR causes substantial reductions in the engineering properties of concrete. At 0.1 percent expansion, for example, loss in flexural strength amounted to nearly 50 percent, whereas loss in dynamic modulus was about 20 percent. At one year, at an expansion of about 0.6 percent, loss in compressive strength was about 40 percent, whereas losses in flexural strength and dynamic modulus were about 75 and 60 percent, respectively.

6. Slow reactive aggregates such as flint may show little expansion and loss of compressive strength at ambient temperatures; however, at higher temperatures such aggregates can exhibit harmful expansions and considerable loss in strength with time.

7. ASR influences different properties at different rates. The level of losses in engineering properties with any reactive aggregate is primarily influenced by the rate and extent of deleterious expansion. The damaging effect of the expansive reactivity is countered to some extent by the continuing hydration of the cement paste. When expansion has reached a stable state, the continuing hydration of the cement paste can result in a cessation of losses or even a modest recovery in engineering properties.

8. Since losses in engineering properties do not occur at the same rate or in proportion to expansion, it is doubtful if the same values of expansion limits can be specified for all types of structures. Critical limits of deleterious expansion need to be defined according to the type and use of a concrete structure.

9. ASTM C 227 limits may not be applicable to

Table 8 — Concrete properties at ASTM C 227 limits

Property of concrete	Expansion limits							
	0.05 percent				0.1 percent			
	Opal		Fused silica		Opal		Fused silica	
	Property at 0.05 percent expansion	Percent loss compared to to control at the same age	Property at 0.05 percent expansion	Percent loss compared to control at the same age	Property at 0.1 percent expansion	Percent loss compared to control at the same age	Property at 0.1 percent expansion	Percent loss compared to control at the same age
Number of days	6	—	40	—	8	—	60	—
Compressive strength, N/mm^3	43.6	9.2	53.5	12.3	44.5	11	54.5	11.4
Modulus of rupture, N/mm^2	—	—	3.7	29.9	—	—	2.75	48.3
Split tensile strength, N/mm^2	—	—	3.2	27.1	—	—	2.95	28.9
Dynamic modulus, kN/mm^2	34.0	15.5	38.0	11.1	26.0	36.7	34.5	20.3
Pulse velocity, km/sec	4.08	7.2	4.5	2.1	3.95	11.2	4.35	5.8

slowly reacting aggregates. With such aggregates, the ASTM limits may need modification if excessive damage in a field structure is to be avoided.

CONVERSION FACTORS

1 lb	=	0.4536 kg
1 in.	=	25.4 mm
1 lbf/in.^{2}	=	6895 Pa
1 lb/ft^3	=	16.02 kg/m^3

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