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The effect of alkali reactivity on the mechanical properties of concrete

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Abstract

The effects of highly reactive aggregate, fused silica, and slowly reactive aggregate, Thames Valley sand, on the mechanical properties of concrete were investigated in this paper. The mechanical properties studied over a period of 12 months were the compressive strength, direct tensile strength, tensile splitting strength, flexural tensile strength (modulus of rupture), static modulus of elasticity and water absorption. The effects of both reactive aggregates on the mechanical properties of concrete were compared with that of sound concrete mix. The results presented in this investigation show that the effect of the reactive aggregates on the mechanical properties varies, depending on the type of reactive aggregate. From this study it appears that the direct tensile and static modulus of elasticity were the best indicators of reactivity.

Keywords: Alkali silica; Mechanical properties; Expansion; Cracks; Absorption

1. Introduction

Alkali–silica reaction (ASR) occurs in concrete when alkali from the cement, or from an external source, reacts with free silica presents in certain aggregates to form an alkali–silica gel. The latter has the property of taking in water and expanding. This expansion can cause the aggregate particles and the concrete to crack, and ultimately can damage the concrete.

When concrete has become damaged by the alkali–silica reaction, the characteristic feature it displays is a network of cracks, which on the surface of the concrete produces a pattern referred to as 'map cracking'. Leaching of the gel from the cracks may also be observed in concrete damaged by ASR.

The BRE/SERC ASR concrete mix [1] was proposed by the Building Research Establishment as a structural concrete suitable for use in research into the appraisal of ASR-affected structures. The engineering properties of the BRE mix have not been fully investigated by other researchers (Table 2) and for this reason the mechanical properties of the mix were monitored for a period of 12 months.

1.1. Research significance

This paper describes and compares the effect of highly reactive material, i.e. fused silica, and slowly reactive aggregate, Thames Valley sand, on the compressive strength, direct tensile strength, tensile splitting strength, flexural strength (modulus of rupture), static modulus of elasticity and water absorption. Measurements of the ultrasonic pulse velocity (UPV) and surface expansion were also used to monitor the deterioration of concrete due to ASR over a period of 12 months.

2. Test details

To establish the mechanical properties of both concrete mixes, the following test were carried out. Three samples were tested to obtain each result, except that for surface expansion and UPV measurements, two specimens were used.

1. Compressive strength on $100\times100\times100\text{-mm}^3$ cubes [2];

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Table 1
Mix proportions of the ASR mixes (Mix A, B) and the control mix C

Mix type	Cement (OPC)	Water/cement ratio	Aggregate			
			Limestone		Reactive	Non-reactive limestone 2 mm (dust)
			10 mm	20 mm		
Mix A (ASR)	1.00	0.50	1.06	2.14	1.39[a]	–
Mix B (ASR)	1.00	0.50	1.06	2.14	0.48[b]	0.91[c]
Mix C (sound)	1.00	0.50	1.06	2.14	–	1.39

[a] Thames Valley sand.
[b] Fused silica, i.e. 15% of total aggregate.
[c] (1.39–0.48) of total aggregate.

2. Direct tensile strength on dumb-bell briquette test specimens [3];
3. Tensile splitting strength (indirect tensile strength, ITS) on 100×100-mm^2 cylinders [4];
4. Flexural strength (modulus of rupture, MOR) on $100\times100\times500$-mm^3 prisms [5];
5. Static modulus of elasticity on 150×300-mm^2 cylinders [6];
6. Water absorption on $100\times100\times100$-mm^3 cubes; and
7. Surface expansion and UPV [7] on $100\times100\times500$-mm^3 prisms and 150×300-mm^2 cylinders.

The majority of the measurements were carried out according to the relevant British Standard.

3. Concrete mix

Three different mixes were used throughout the research, namely A, B and C; these are shown in Table 1. The mix proportions, by weight, were 1.0:1.39:1.06:2.14 cement/fine reactive aggregate/10-mm limestone aggregate/20-mm limestone aggregate, with a cement content of 400 kg/m^3 and water/cement ratio of 0.5. Mixes A and B were ASR mixes, with mix A (BRE mix) containing Thames Valley sand as a reactive aggregate, whereas in mix B the Thames Valley sand was partially replaced by fused silica to accelerate the alkali–silica reaction, and 2-mm crushed limestone (dust). The amount of fused silica is equal to 15% by weight of the total aggregate. The fused silica contained 99.7% silica and had a particle size distribution of 150–600 μm. Mix C (control mix) was similar to mixes A and B, except that the reactive aggregate was replaced by 2-mm crushed limestone (dust).

An ordinary Portland cement having a high alkali content of 1.225% Na_2O equivalent (i.e. 4.9 kg/m^3) was used for all three mixes. The total alkali content required is 7 kg/m^3, and therefore 1.21 kg/m^3 of Na_2SO_4 and 4.417 kg/m^3 of K_2SO_4 were added in solution to the mixing water to raise the total alkali content to the value required.

The Thames Valley Sand (0–5 mm) contained 50% chert as the reactive fine aggregate. The coarse aggregate was (0–20 mm) limestone, which is known to be non-reactive. The proportion of reactive silica in the combined sand–limestone aggregate was the 'Pessimum' proportion [1] so that the reaction was maximised.

4. Conditioning

The specimens using both the reactive mixes and the control mix were cast and cured according to BS 1881 Part 122 [6]. After casting, the specimens were stored under polythene sheets. All the specimens were unmoulded after 1 day and then cured for 28 days in water at 20 °C. They were then transferred to water at 38 °C in order to accelerate the reaction. The specimens remained in the hot water tank until the day of testing. The tests were carried out within 1 h of removal of the samples from the conditioning tank.

5. Monitoring of ultrasonic pulse velocity (UPV) and surface expansion

An ultrasonic pulse method was used to monitor the deterioration of the concrete due to ASR. A portable ultrasonic non-destructive digital indicating tester (PUNDIT) was used to monitor pulse velocity.

The pulse velocity was measured prior to the curing period at 20 °C and on the first day at 38 °C, the latter reading being used as a data point. Measurements were made every 2 weeks for the first 4 months at 38 °C, and then every month for the next 8 months.

A digital Vernier scale was used to measure the surface expansion on $100\times100\times500$-mm^3 prisms and 150×300-mm^2 cylinders. Longitudinal and lateral expansion were measured on the prisms, whereas only longitudinal expansion was measured on the cylinders. Expansion and ultrasonic pulse velocity were measured at the same time.

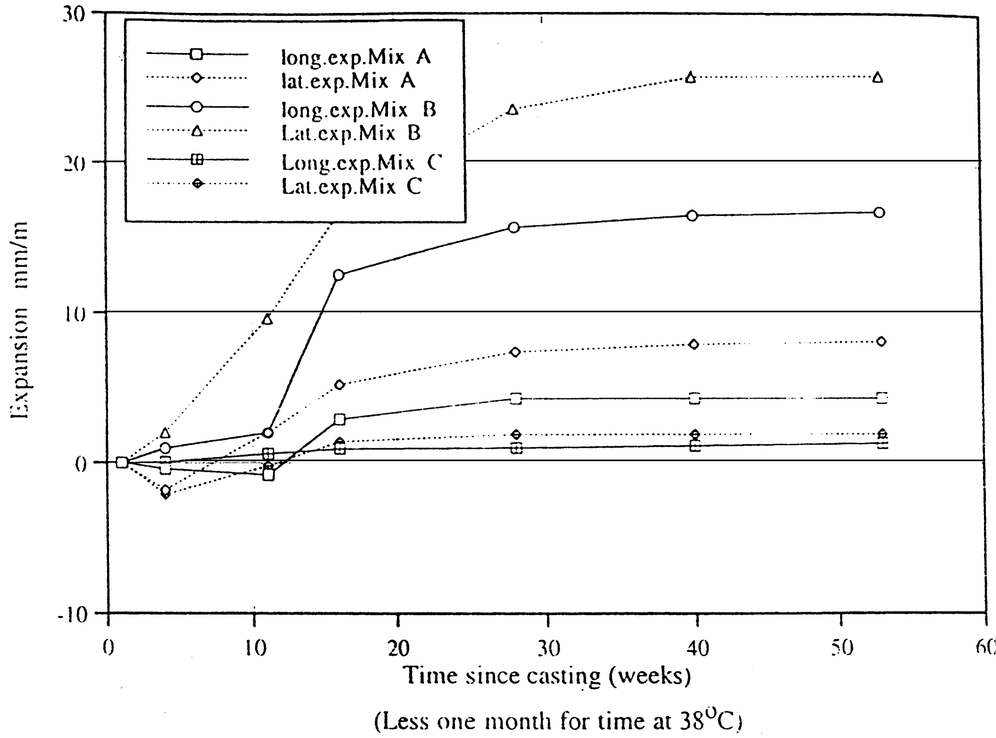

Fig. 1. Longitudinal and lateral expansion of prism ($100\times100\times500$ mm^3) with time.

6. Test results and discussion

The effect of ASR on the properties of hardened concrete containing Thames Valley sand as reactive sand, mix A, will be discussed in conjunction with mix B, in which fused silica was used instead of the reactive sand. All the results are shown in Table 2.

The expansion of the prisms and cylinders of the control and ASR mixes in relation to time is shown in Figs. 1 and 2, respectively, to enable the changes in concrete properties to be related to ASR expansion. The changes in mechanical properties, expansion, water absorption and ultrasonic pulse velocity of mixes A and B are compared with the control mix (Mix C), as well as with data published by other researchers.

6.1. Expansion of concrete samples due to ASR

Measurement of expansion is a principal method for monitoring the physical progress of the reaction. As described earlier, two different types of specimens, vertically cast cylinders and horizontally cast prisms, were used and two specimens of each type were cast to measure the free expansion caused by ASR to unrestrained concrete. All had demec points glued on, as shown in Figs. 21 and 22.

After standard curing at 20 °C, the specimens were transferred to water at 38 °C. On the first day of transference, demec measurements were made on the prisms and cylinders. This initial set of specimen readings was used as the data for all subsequent sets of measurements. Measurements were made every 2 weeks until the expansion rates slowed down. After this, they were made every month until the reactions were exhausted (i.e. 12 months after casting).

The overall expansion in mm/m is plotted against time in weeks for $100\times100\times500$-mm^3 prisms in Fig. 1. The overall expansion is the mean set of demec readings for two specimens cast from the same batch. Initially, mixes A and C showed negative expansion, i.e. contraction, for the first 4 weeks in hot water, i.e. shrinkage, whereas mix B expanded from the first week in hot water. Then, at approximately 49 days, mix A and B specimens began to rapidly expand. As the reaction progresses, the curves begin to diverge. The fused silica concrete, mix B, achieved a higher expansion rate and higher final expansion value than the Thames Valley sand concrete, mix A. It is evident from Fig. 1 that the lateral expansion of mix B (25.93 mm/m) is 1.5-fold greater than the longitudinal expansion (16.86 mm/m), and three-fold greater than the lateral expansion (8.1 mm/m) of mix A. The lateral expansion of mix B was also greater than the longitudinal expansion of mix A. The final lateral expansion of mixes B and A was 25.93 and 8.1 mm/m, respectively.

The expansion in the longitudinal direction of the prisms and cylinders plotted against time is shown in Fig. 2. Cylinders which were vertically cast show a

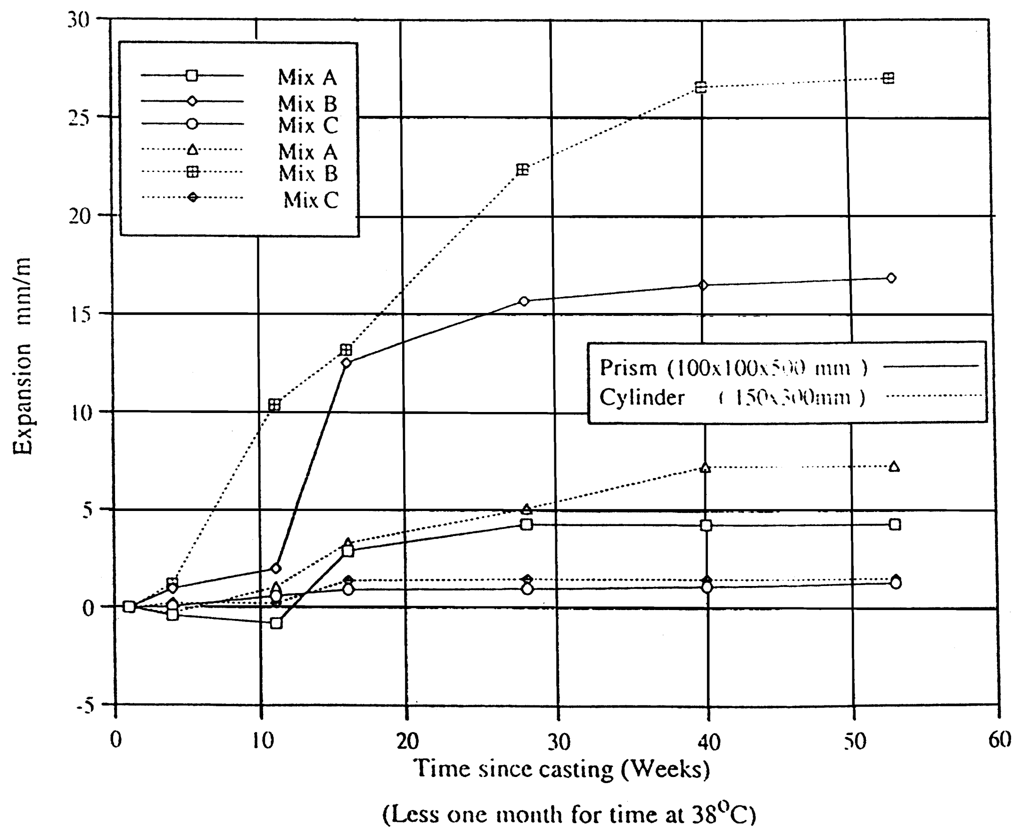

Fig. 2. Longitudinal expansion of prism and cylinder with time.

greater expansion than the horizontally cast prisms. The fused silica concrete, mix B, showed greater expansion than the Thames Valley concrete, mix A. The final longitudinal expansion achieved by mixes B and A was 16.86 and 4.3 mm/m, respectively. The expansion of the prisms was 37.56% and 41.09% of the corresponding cylinder expansion for mixes B and A, respectively. Therefore, the direction of casting and/or the geometry of the specimens (square or circular) could be considered to be one of the most important factors in accounting for the considerable range of expansion results.

Prisms made from the Thames Valley sand concrete, mix A, show a few transverse cracks branching from the dominant longitudinal crack, whereas many more cracks are evident in the prisms cast from the fused silica concrete, mix B. Figs. 21 and 22 show that the crack patterns are very different for the two types of specimen.

The typical ASR map-like cracking patterns are distributed over the cylinders shown in Fig. 22. These are axi-symmetrical, and are therefore stressed more uniformly on their surface due to ASR. The reaction forms a more uniform system of cracks, and greater expansion is expected in both the direction of casting and opposite to it. The prisms, however, have a concentration of stress along the centre line of each side, and hence a crack first appears parallel to the prism axis due to the edge effect; this then widens and, at higher expansion, fine transverse cracks appear. This is why the lateral expansion is greater than the longitudinal expansion of the prisms. Mix B cylinder showed a more intensive crack pattern than the corresponding sample prepared from mix A. The product of the alkali–silica reaction, the alkali–silica gel, can be clearly observed leaching out of the cracks of the mix B cylinder in Fig. 22.

6.2. Weight gain in sound and ASR concrete specimens

6.2.1. Variation of water absorption with time

One of the important properties of the ASR product, i.e. the alkali–silica gel, is that it is known to absorb water, expand and develop pressure that forces the concrete particles apart, which ultimately leads to extensive cracking in some structures.

The results from the water absorption tests are summarised in Table 2. The variation of water absorption with time is plotted in Fig. 3. These results show that water absorption increased with time, but at different rates throughout the period investigated. The water absorption for concretes of reactive mixes, such as mixes A and B, depends on the type and quantity of reactive aggregate present in the concrete.

Table 2
Engineering properties of the two ASR concrete mixes and the control

Test	Mix	Time at 20 °C		Time elapsed in hot water at 38 °C				
		7 days	28 days	7 weeks	3 months	6 months	9 months	12 months
Prism expansion (mm/m)	Long, A	–	−0.4	−0.8	2.9	4.3	4.3	4.3
	Lat, A	–	−1.8	2.0	5.2	7.4	7.9	8.1
	Long, B	–	0.96	2.0	12.53	15.73	16.56	16.86
	Lat, B	–	2.01	9.6	16.59	23.61	25.8	25.93
	Long, C	–	0.05	0.6	0.93	1.0	1.13	1.27
	Lat, C	–	−2.1	−0.2	1.4	1.9	1.9	1.9
Cylinder expansion (mm/m)	Side, A	–	−0.29	1.05	3.3	5.1	7.3	7.3
	Face, A	–	0.6	1.65	3.3	4.1	3.9	3.7
	Side, B	–	1.2	10.4	13.2	22.4	26.6	27
	Face, B	–	3.2	6.8	11.8	15.5	15.1	14.6
	Side, C	–	0.23	0.23	1.4	1.5	1.5	1.5
	Face, C	–	−0.02	0.7	0.8	1.2	2.4	2.5
Compression strength (N/mm^2)	A	48.7	50.3	50.3	42.25	54.9	55.9	57
	B	45.1	41	38.1	27.5	26.2	26.4	26.5
	C	45.8	46.8	51.15	51.15	57.25	63.45	65.3
Tensile splitting strength (N/mm^2)	A	3.91	4.16	5.67	5.35	3.37	3.25	3.57
	B	3.5	3.5	2.54	2.42	1.85	1.97	2.2
	C	4.28	4.64	4.59	5.22	5.16	5.28	5.54
Flexural strength (N/mm^2)	A	6.58	6.89	6.59	2.73	1.81	2.68	3.5
	B	5.3	5.81	1.65	1.1	0.59	0.66	0.96
	C	5.11	5.26	5.74	6.06	6.37	6.53	6.84
Direct tensile strength (N/mm^2)	A	1.87	2.35	2.78	3.63	2.55	2.31	2.45
	B	1.31	1.44	1.71	1.74	1.13	1.1	0.88
	C	4.8	4.98	4.8	4.8	4.98	4.9	4.92
Static modulus of elasticity (kN/mm^2)	A	34.43	38.6	34.69	33.38	27.11	15.33	12.65
	B	20.23	21.13	8.85	2.93	2.89	2.17	1.72
	C	28.33	31.38	32.45	33.7	33.95	35.25	36.36
Ultrasonic pulse velocity (km/s)[a]	A	–	4.81	4.89	4.60	4.58	4.69	4.73
	B	–	4.72	3.60	3.24	3.10	3.29	3.64
	C	–	4.88	4.99	5.05	5.09	5.09	5.07
Ultrasonic pulse velocity (km/s)[b]	A	–	4.88	4.89	4.65	4.64	4.73	4.75
	B	–	4.63	3.72	3.61	3.22	3.32	3.39
	C	–	4.76	4.78	4.83	4.95	4.89	4.90
Water absorption (g)	A	8	9.56	15.4	21.25	29.3	29.1	29.6
	B	14.83	28.02	43.85	71.55	73.2	75.15	75.19
	C	8.9	9.67	10.43	10.43	10.3	10.7	10.2

Values are the mean of three samples. Mix A, alkali–silica reacted concrete (BRE/SERC) with Thames Valley sand as the reactive aggregate. Mix B (BRE/SERC), the reactive sand was replaced by 15% fused silica as the reactive aggregate. Mix C, control mix; the reactive aggregate was replaced by 2-mm crushed limestone. Long, longitudinal expansion of the prism; Lat, lateral expansion of the prism; Side, side of the cylinder; and Face, top surface of a cylinder.

[a] Ultrasonic pulse velocity of $100\times100\times500$-mm^3 prisms.

[b] Ultrasonic pulse velocity of 150×300-mm^2 cylinders.

The ASR concretes, mixes A and B, unlike the control concrete, showed different demand for water at a very early stage. The fused silica concrete, mix B, showed a sharp increase in water absorption up to the 4th week in the hot water tank. The rate dropped slightly between weeks 4 and 11, followed by another high rate up to week 16. A very small increase was recorded up to 10 months, and then stabilised from then up to an age of 1 year. The Thames Valley sand concrete (mix A), on other hand, showed similar behaviour, but with lower water absorption. An increase in rate was recorded up to week 27, and then the rate of water absorption stabilised up to the end of the investigation, at week 52. The control concrete, mix C, showed a slight increase in rate in the first couple of weeks, and then remained constant up to 1 year. It seems that the water absorption of all the concrete mixes was nearly stabilised when they had spent 12 months in hot water at 38 °C.

The ASR concretes showed different rates of water absorption at different ages, and this could be attributed

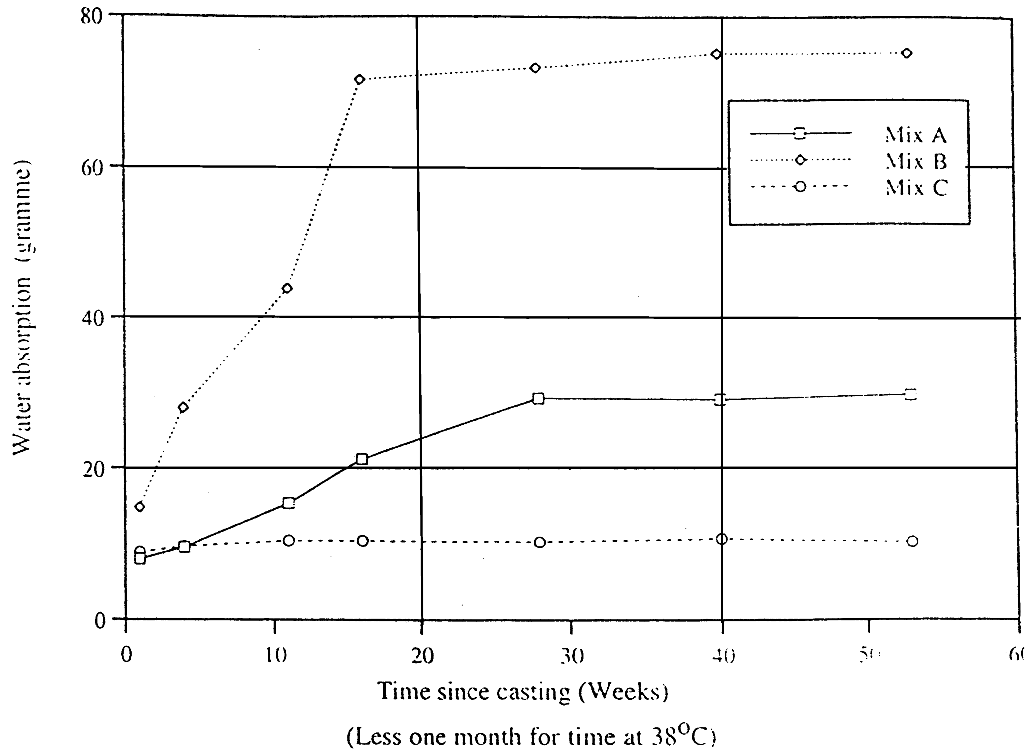

Fig. 3. Variation of water absorption with time.

to the development of cracks at different ages. The increase in the water absorption rate could be due to new cracks having opened up or the existing channels having been extended, which would enable water to reach new reaction sites.

The water absorption of mixes B and A after 12 months in hot water was 637% and 190% compared to that of the control, mix C. Therefore, the water absorbed by mix B samples is three-fold that absorbed by mix A samples. The product of the fused silica and the alkali showed a greater capability to absorb water than the gel produced by the Thames Valley sand and alkali reaction.

6.2.2. Variation of water absorption with expansion

The correlation between water absorption and expansion is plotted in Fig. 4. This shows that expansion of the Thames Valley sand concrete, mix A, is almost linear with water absorption, whereas the fused silica concrete, mix B, absorbed a significant amount of water during the first 12 weeks in hot water, when the expansion was 2 mm/m. The demand for water by mix B then increased. It absorbed 27.7 g of water and the expansion increased from 2 to 12.5 mm/m. The absorption of water almost stopped as the reaction reached completion.

It is clearly evident that the fused silica concrete, mix B, absorbed more water than the Thames Valley sand concrete, mix A, to achieve the same level of expansion. This indicates that the water requirement varies for some reactive aggregates, and that it also varies depending on the level of expansion.

It is clear from Table 2 that the rate of water absorption does not steadily increase with expansion, and it decreased significantly as the expansion stopped. The water absorption of the mixes B, A and C after 1 year in hot water was 75.2, 29.6 and 10.2 g, respectively.

6.2.3. Cracking due to ASR

As the alkali–silica reaction takes place, the rate of growth of the alkali–silicate gel rapidly increases and the internal stresses build up to a high level that the concrete can no longer support, thus leading to expansion and cracking of the concrete.

The first crack visible to the naked eye was observed, after 3 weeks, on the surface of the concrete prisms containing 15% fused silica (mix B), whereas for the concrete prisms containing Thames Valley sand, (mix A), the first crack was observed after 6 weeks in hot water. In both concretes, the cracks due to ASR formed individual three-armed star shapes, which joined up over time to produce a pattern of cracks as illustrated in Figs. 21 and 22. The cracks developed in three stages. In the first stage, a few hair cracks are evident, but more microcracks can be detected with a magnifying glass. In the second stage, the hair cracks mostly spread over the entire concrete surface. As the ASR ceased, the crack pattern reached its final shape and the cracks

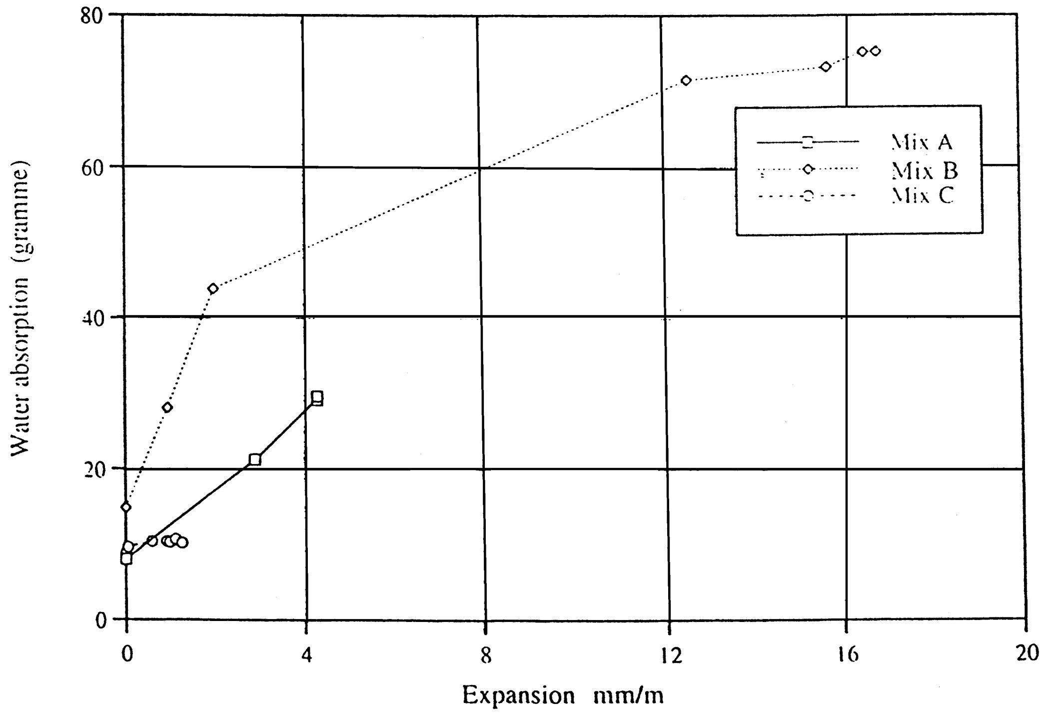

Fig. 4. Variation of water absorption with expansion.

opened to contain both the reaction products and absorbed water.

The cracks have many functions in the ASR process. They take the volumetric pressure exerted by the ASR; they also act as a transport network, distributing the moisture received from the surface of the concrete to the ASR site. They also assist in dispersion of the reaction product from the reaction site to the voids and enable them to be leached to the surface.

The leaching of the ASR products is clearly evident on the surface of the fused silica concrete samples, mix B, in Fig. 22. This also shows that the ASR of mix B has a greater reactivity than the Thames Valley sand concrete (mix A).

The development of cracks in the concrete is clearly evident in Fig. 5. The fused silica concrete, mix B, developed wider cracks than the Thames Valley sand concrete, mix A. After 11 weeks in hot water, the maximum crack width was 0.008 and 0.016 mm for mixes A and B, respectively. The cracks for both mixes increased with time until week 28, when a sharp increase in the maximum crack width was recorded for both mixes up to week 52. A linear relationship between crack width and time was not observed. It can be reported that the fused silica, mix B, causes severe damage to the concrete by creating high expansion and wider cracks than the Thames Valley Sand, mix A.

A non-linear relation was also observed between expansion and crack width, as shown in Fig. 6. As the expansion increases, the crack width increases for both mixes A and B.

6.3. The effect of ASR on the compressive strength of concrete cubes

The cube compressive strength is plotted against time and expansion in Figs. 7 and 8, respectively. Mix B showed a greater decrease between weeks 11 and 16 than in the first few weeks. After 24 weeks in the hot water, the compressive strength stabilised. Mix A, on the other hand, showed increases in compressive strength for the first 8 weeks in hot water, followed by a decrease up to week 16. Another sharp increase in the compressive strength was recorded from then up to the end of this investigation, i.e. at 1 year. This recovery in strength may, however, be largely due to continued hydration of the cement and/or the cracks being filled by the gel itself. The control concrete, mix C, showed a steady increase in strength throughout the 12 months.

Even though mix A concrete shows an increase in compressive strength with time, it still has a lower compressive strength than mix C.

The drop in compressive strength for mix A is approximately −7.5% and 12.7% compared with the control, mix C, at 28 days and 1 year, respectively. The compressive strength for mix A was higher than the control (mix C) after 28 days in cold water. For the

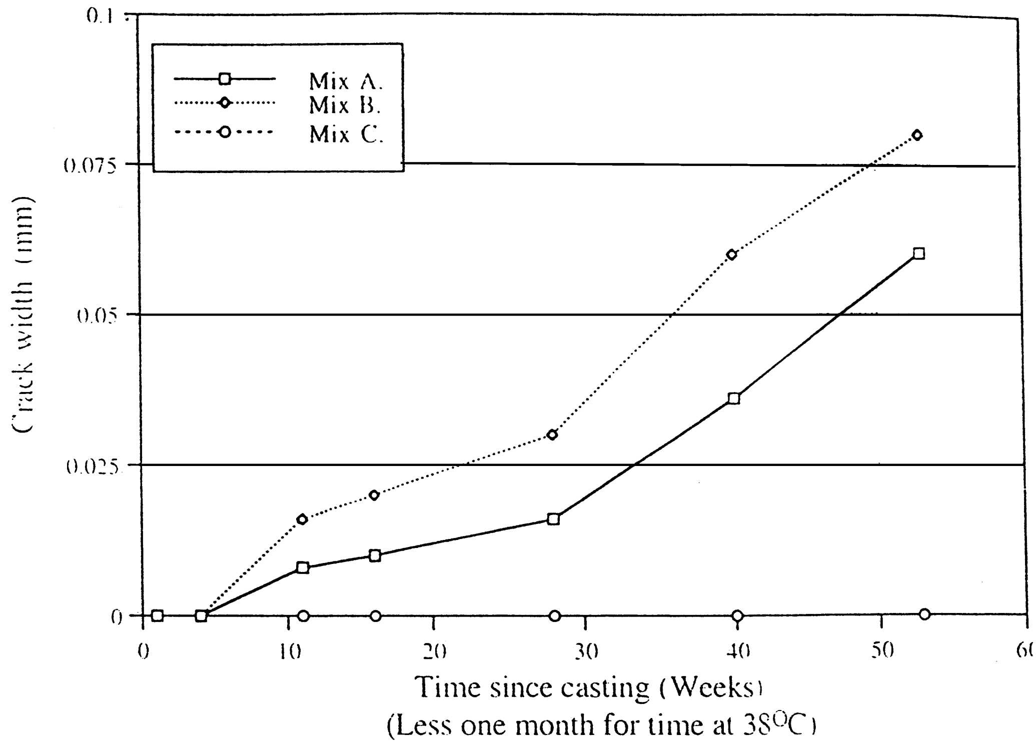

Fig. 5. Variation of crack width with time.

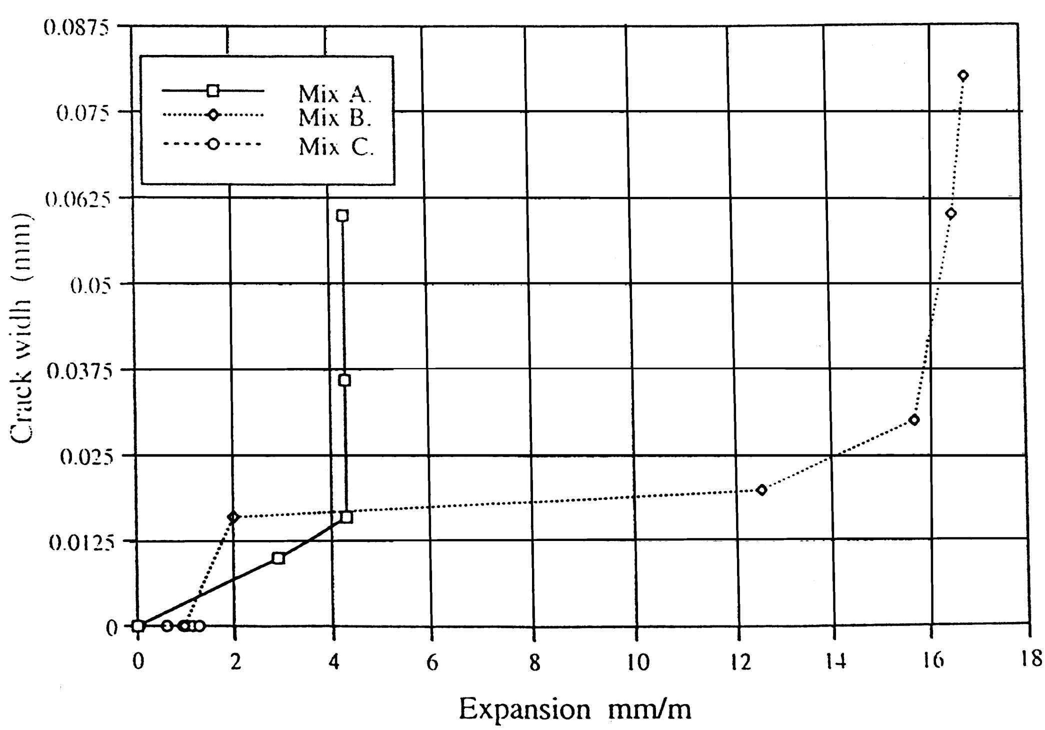

Fig. 6. Variation of crack width with expansion.

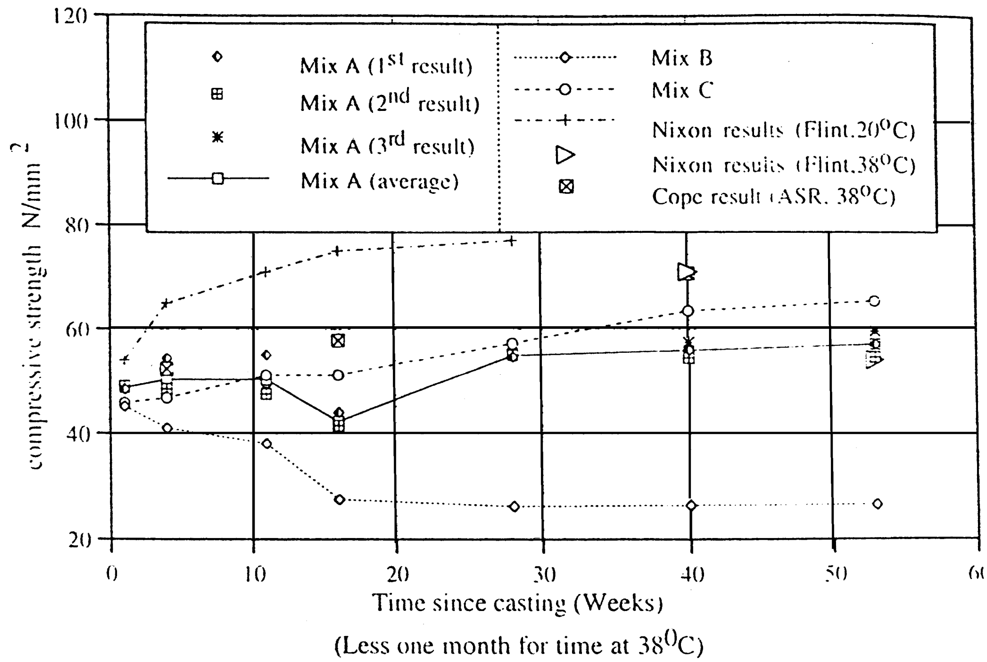

Fig. 7. Compressive strength of control and ASR-affected concrete vs. time.

specimen with fused silica (mix B), the drop in strength was 12.39% at 28 days in cold water and 59.42% after 1 year in hot water. Therefore, the strengths of mixes A and B at 38 °C both show a considerable drop at 1 year, by which time cracking and expansion were reported to be severe.

Cope and Slade [8]reported an increase in the compressive strength of the same mix, mix A, and stated that:

> The mix itself provided a surprise, in that the cube strengths at the times of testing were up to about 50% higher than the 28-day values.

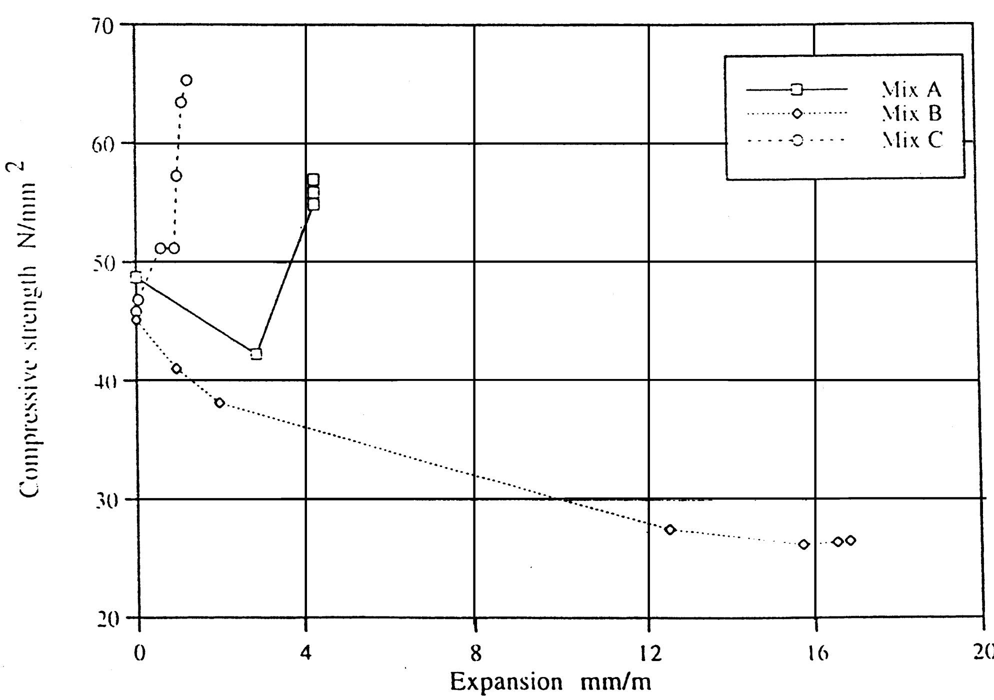

Fig. 8. Compressive strength of control and ASR-affected concrete vs. time.

Table 3
Comparison of concrete properties affected by ASR

Concrete property	Fused silica at 1 year [14,18][a]			Fused silica at 14 years [17]			Present results at 1 year					BRE/SRC			
							Mix C	Mix A		Mix B		[11][b]		[10][c]	
	Sound concrete	Result	Loss (%)	Uncracked	Cracked	Loss (%)		Result	Loss (%)	Result	Loss (%)	Result	Loss (%)	Result	Loss (%)
Water absorption (g)	63	302	−379	–	–	–	10.2	29.6	−190.19	75.19	−637.16	–	–	–	–
Compressive strength (N/mm²)	73.5	44.50	39.5	103.0	84.0	18.4	65.3	57	12.71	26.5	59.42	–	25	56	23.81
Direct tensile strength (N/mm²)	–	–	–	–	–	–	4.92	2.45	50.2	0.88	82.11	–	75[d]	–	–
Tensile splitting strength (N/mm²)	4.29	1.83	57.3	6.0	4.9	20.4	5.54	3.57	35.56	2.2	60.29	–	55	3.0	30.07
Flexural strength (N/mm²)	5.58	1.3	76.7	–	–	–	6.84	3.5	48.83	0.96	85.96	–	65	2.60	53.41
Modulus of elasticity (kN/mm²)	45.40	18.88	58.4	46.0	27.0	41.3	36.36	12.65	65.21	1.72	95.27	–	65	–	–
Pulse velocity (km/s)	4.78	3.64	23.8	5.05	4.75	5.9	5.07	4.73	6.71	3.64	28.21	–	–	–	–

A negative sign indicates a gain.
[a] Expansion at 0.623%.
[b] Clark and Ng reported a percentage loss for expansion of 5.0 mm/m and the concrete mix used (BRE/SERC) contained 9 kg of alkali.
[c] Clayton used 7 kg of alkali in the BRE/SERC concrete mix. The samples showed an expansion of 4 mm/m after 4 months in hot water.
[d] Data for mortar.

Thus, the increase in the compressive strength of mix A at 38 °C could be due to the fact that the curing of concrete containing slowly reactive aggregates, such as flint, at high temperature has little effect on this particular property at an early age, or even after a considerable amount of time.

Table 3 shows a comparison between the present results and those of other researchers. This shows that the reduction reported by Clark [9] and Clayton et al. [10] is 25% and 23.81%, respectively, which is close to the current result of 22.45%, but the former researchers did not specify whether this reduction is related to the strength obtained at 28 days or the strength of control concrete that was cured and tested in the same way as the reactive mix.

Fig. 8 shows that, at any level of expansion, mix B showed a greater loss in compressive strength than mix A. This is due to the difference in reaction rates of both reactive aggregates, fused silica and Thames Valley sand, which allows the hydration of cement to develop the strength of the concrete at different rates. The effect of cracks due to ASR was also greater than the effect of hydration for the fused silica concrete, mix B. Examining Fig. 8 shows that once the concrete ceased to expand, the hydration effect seems to exceed the cracking effect and a significant recovery in strength was gained by the Thames Valley sand concrete, mix A, whereas mix B showed a very small recovery.

6.4. The effect of ASR on the tensile strength of concrete

6.4.1. Flexural strength (i.e. modulus of rupture) and tensile splitting strength

The flexural strength (i.e. modulus of rupture; MOR) and tensile splitting strength (i.e. indirect tensile strength; ITS) of ASR and control concrete are plotted against time in Figs. 9 and 11, respectively. The flexural strength of the Thames Valley sand concrete, mix A, showed a very small decrease in strength after 6 weeks in hot water, at which time expansion and microcracking were not recorded. A marked drop in strength then occurred after 3 months in hot water, when expansion was 2.9 mm/m. A sharp decrease in strength was recorded between 6 weeks and 6 months in hot water, when the expansion was 4.3 mm/m. The fused silica concrete, mix B, showed a dramatic decrease in strength after 6 weeks in hot water, when the expansion reached 15.73 mm/m. The decrease in strength continued, at varying rates, up to 6 months in hot water. The reduction in strength of mix B after 6 weeks in hot water was

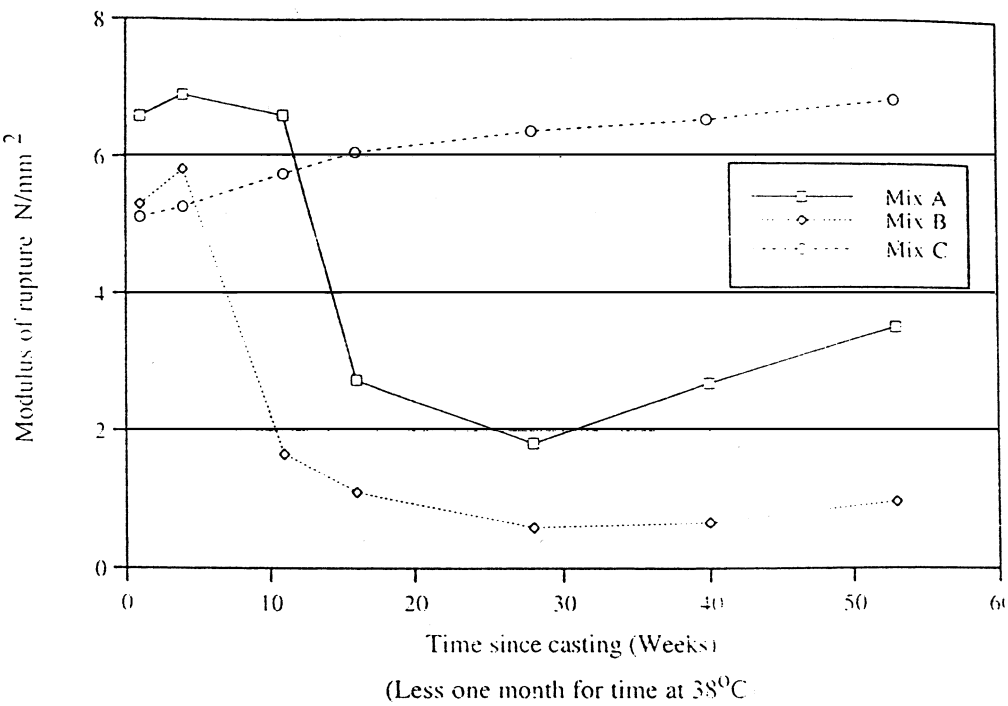

Fig. 9. Variation of flexural strength (i.e. modulus of rupture) of control and ASR concrete with time.

achieved by mix A after 6 months. A modest recovery was shown by both ASR mixes after 6 months in hot water. Thames Valley sand, mix A, showed greater recovery in strength than the fused silica concrete, mix B, This could be attributed to the fact that the effect of hydration of the cement exceeded the detrimental effect of cracking to a greater extent for mix A than for mix B.

The tensile splitting strength of mix A showed a similar behaviour to that of the flexural strength of the same concrete, but different to the tensile splitting strength of mix B. Both ASR mixes showed different behaviour in the first 6 week in hot water. The tensile splitting strength of mix A sharply increased in the first 6 weeks in hot water, whereas a decrease in strength was shown by mix B. Between 6 weeks and 6 months, both ASR mixes showed a decrease in tensile splitting strength, at which time the expansion of mix A and mix B was 4.3 and 15.73 mm/m, respectively.

After 6 months in hot water, both concretes showed a recovery when tested for flexural strength and tensile splitting strength, with a further slow increase in these strengths being recorded up to the end of this investigation at 1 year. This is clearly evident in Table 4, which shows the percentage loss in flexural strength and tensile splitting strength.

The percentage loss in flexural strength and tensile splitting strength for mix A and mix B after 1 year was 48.83, 33.56, 85.96 and 60.03%, respectively. The percentage is related to the corresponding value for the

Table 4
Tensile/compressive ratio and percentage loss in the mechanical properties of ASR-affected concrete

Age in hot water	Expansion (mm/m)			Tensile/compressive ratio			Loss (%)											
							Compressive strength		*Direct* tensile strength		Tensile splitting strength		Flexural strength (MOR)		Elasticity modulus		Pulse velocity	
	A	B	C	A	B	C	A	B	A	B	A	B	A	B	A	B	A	B
7 weeks	−0.8	2.0	0.6	0.113	0.067	0.089	1.66	25.51	42.08	64.38	−23.53	44.66	−14.81	71.25	−6.9	72.73	2.00	27.86
3 months	2.9	12.53	0.93	0.127	0.088	0.102	1.74	46.24	24.38	63.75	−2.49	53.64	54.95	81.85	0.95	91.31	8.90	35.84
6 months	4.3	15.73	1.0	0.061	0.071	0.09	4.1	54.42	48.79	77.31	34.69	64.15	71.59	90.73	20.15	91.49	10.02	39.09
9 months	4.3	16.56	1.13	0.058	0.075	0.083	11.89	58.39	52.86	77.55	38.45	62.69	58.96	89.89	56.51	93.84	7.86	35.36
12 months	4.3	16.86	1.27	0.063	0.083	0.085	12.71	59.42	50.20	82.11	33.56	60.03	48.83	85.96	65.21	95.27	6.71	28.21

A negative sign indicates a gain.

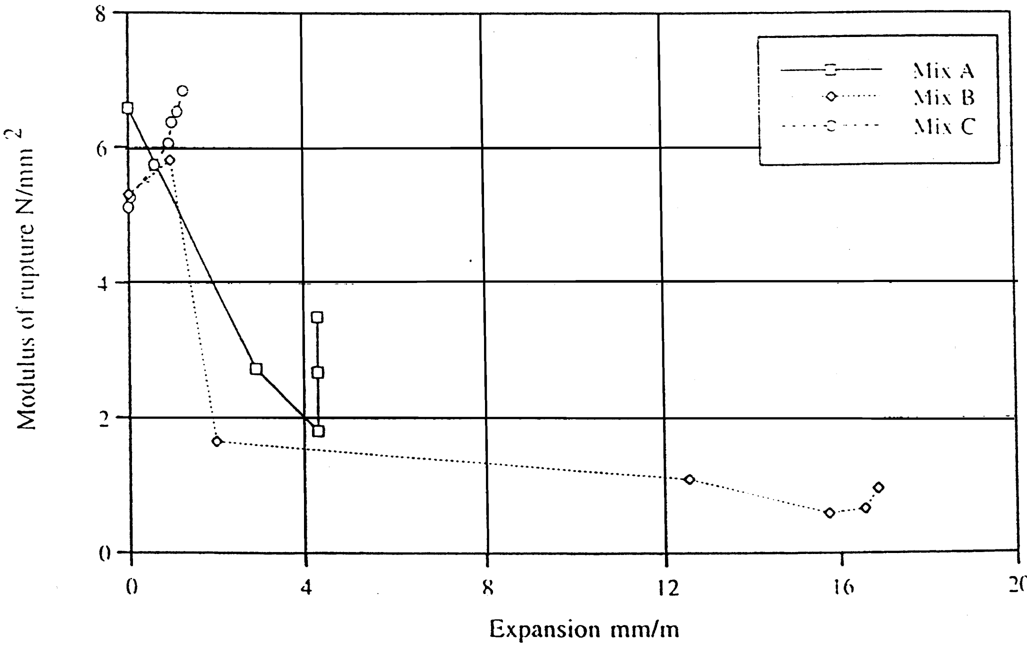

Fig. 10. Variation of flexural strength (i.e. modulus of rupture of control and ASR concrete) with expansion.

sound concrete, mix C, which was cast, cured and tested in the same way as the ASR concrete.

The control mix showed steady increases in flexural strength and tensile splitting strength throughout the investigation.

To clarify the change in tensile strength with expansion, Figs. 10–12 were plotted. It is evident from Fig. 10 that flexural strength is very sensitive to ASR, unlike compressive strength, as the flexural strength for both concretes decreased sharply at a very low expansion.

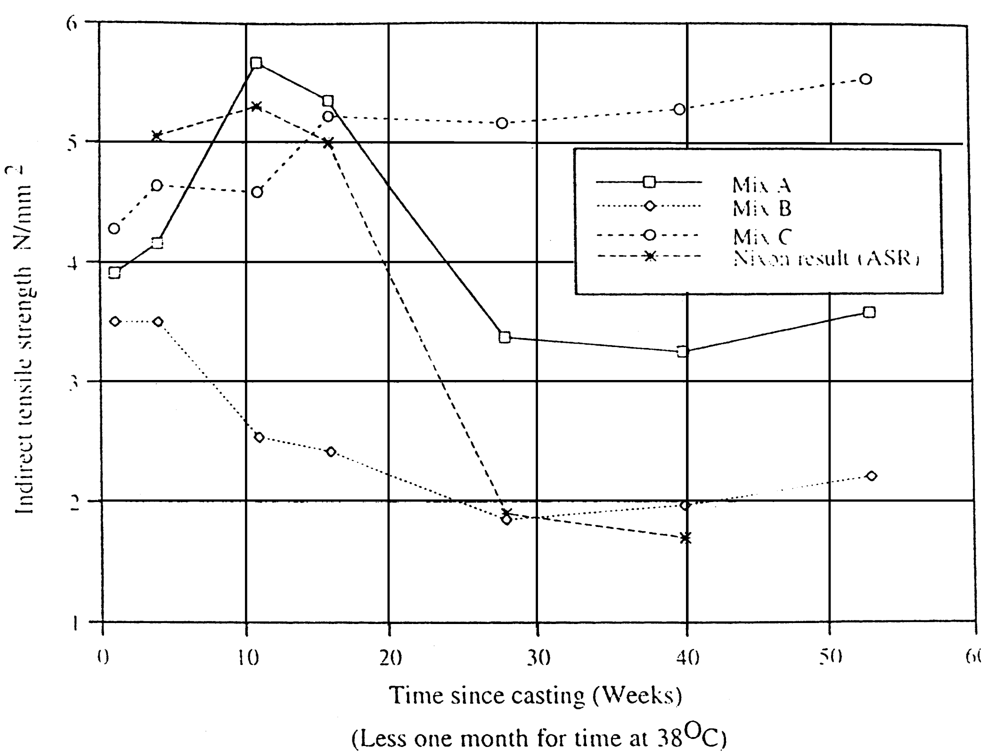

Fig. 11. Tensile splitting strength of control and ASR concrete vs. time.

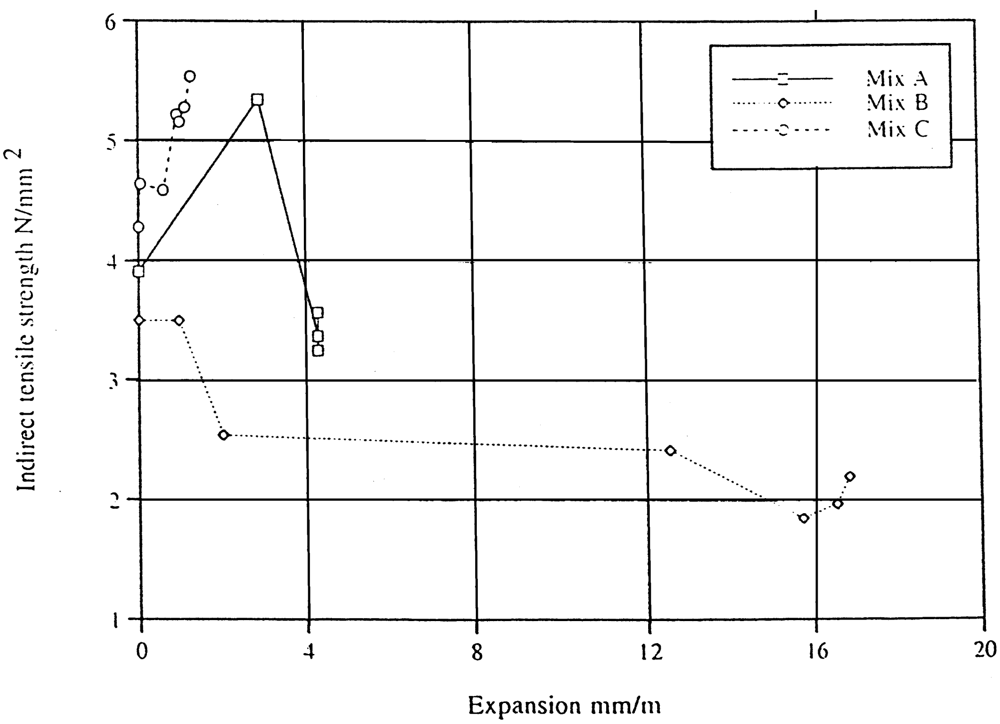

Fig. 12. Tensile splitting strength of control and ASR concrete vs. expansion.

The Thames Valley sand concrete, mix A, showed a dramatic decrease in strength at an early age, even before any visible cracking or abnormal expansion was observed. The fused silica concrete, mix B, showed a very sharp drop in flexural strength for a small increase in expansion. The drop then continued at a low rate as the expansion increased. The final percentage loss in flexural strength for mixes A and B was 71.59 and 89.89%, respectively.

The effects of expansion on the tensile splitting strength of both ASR mixes are shown in Fig. 12. Mix A gained strength in the first few weeks in the hot water tank, then suddenly lost strength between expansion of 2.9 and 4.3 mm/m. In contrast, mix B showed a dramatic decrease in strength, even before any expansion was recorded. When the expansion reached 2.0 mm/m the strength continued to drop, but at a slower rate, and at an expansion of 16.86 mm/m a modest recovery was noted. The percentage loss in tensile splitting strength for mixes A and B (Table 2) after all expansion was complete was 33.56 and 60.03%, respectively. The Thames Valley sand concrete, mix A, showed a gain in strength in the first few weeks in hot water compared to the fused silica concrete, mix B. This could be attributed to the fact that the flint in the Thames Valley sand is only slowly reactive, or that a greater percentage of the reactive aggregate is not involved in the chemical reaction, i.e. is inert.

The flexural strength and tensile splitting strength are plotted together against time and expansion in Figs. 13 and 14, respectively. It is clearly evident that the flexural strength is more sensitive to ASR than the tensile splitting strength, especially at very low expansion.

6.4.2. Direct tensile strength

Clark, in his critical review of ASR [9]and in his paper with Ng [11], showed that all the data on direct strength have been obtained from tests on mortars. There is therefore a lack of data on the direct tensile strength of ASR concrete.

We adopted the method described in BS 6319 Part 7 [3] using dumb-bell-shaped briquette specimens to obtain the direct tensile strength of ASR concrete. The results were satisfactory and showed that the test can be used for any future research to measure the direct tensile strength of concrete.

The samples were cast, cured and tested in the same way as the samples used to measure other properties. The tensile strength of the three mixes is plotted against time and expansion in Figs. 15 and 16, respectively. The tensile strength used in this section is the maximum tensile stress that the test specimen is capable of supporting. It is defined as the tensile force carried by the test specimen per unit area of the original cross-sectional area, at the central portion of the specimen.

From Fig. 15 it is evident that a reduction in direct tensile strength occurred almost as soon as the alkali–silica reaction started; when the samples were placed in hot water the strength increased significantly up to the first 3 months, and then a sudden decrease in strength

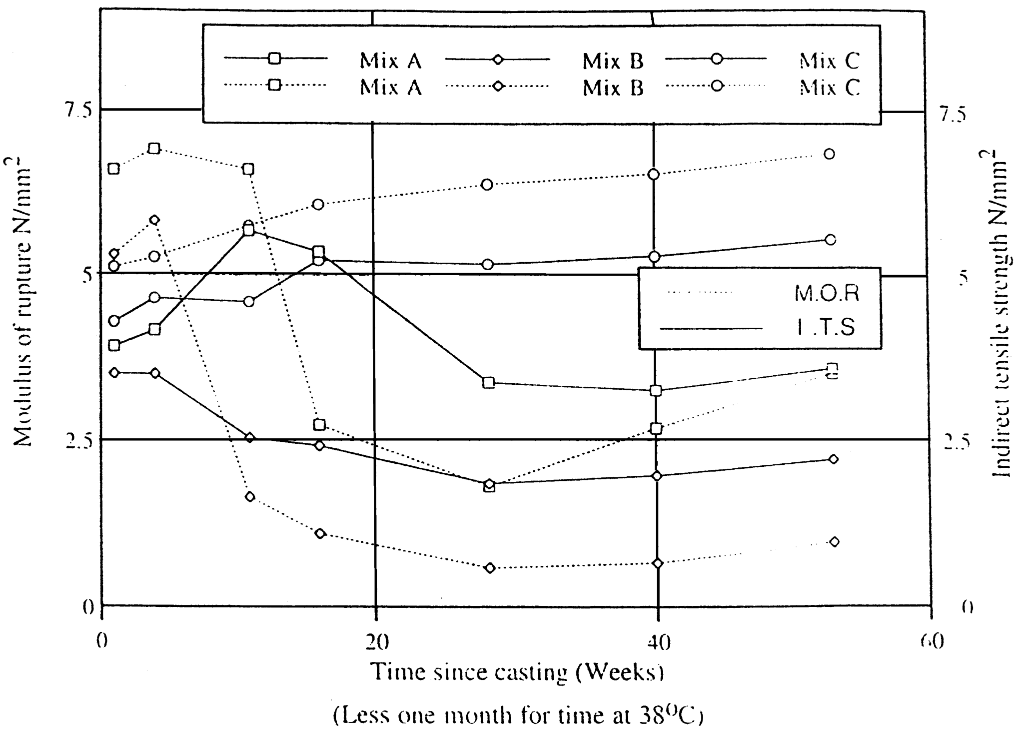

Fig. 13. Variation of flexural strength [i.e. modulus of rupture (MOR)] and tensile splitting strength (TTS) of control and ASR concrete with time.

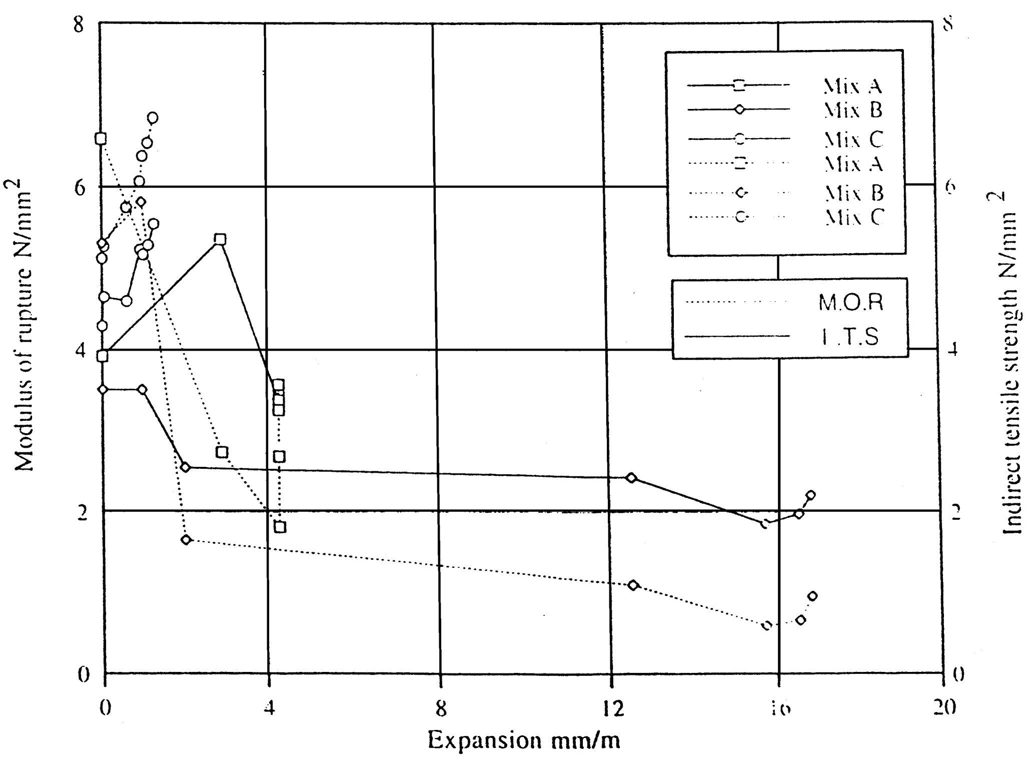

Fig. 14. Variation of flexural strength [i.e.modulus of rupture (MOR)] and tensile splitting strength (TTS) of control and ASR concrete with expansion.

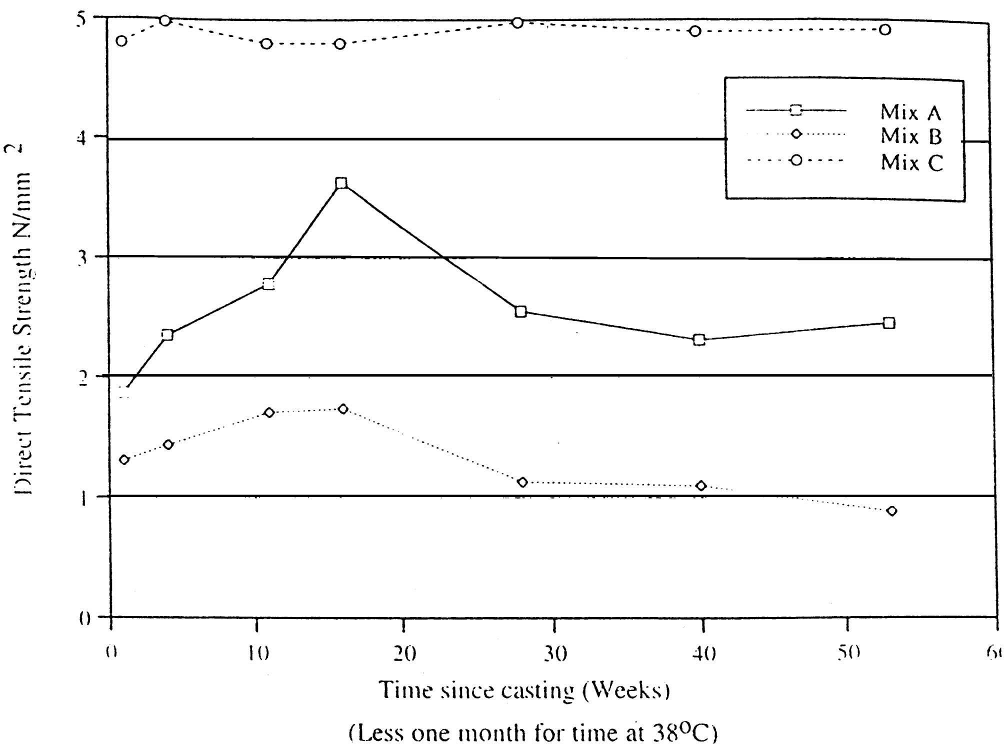

Fig. 15. Direct tensile strength of control and ASR-affected concrete vs. time.

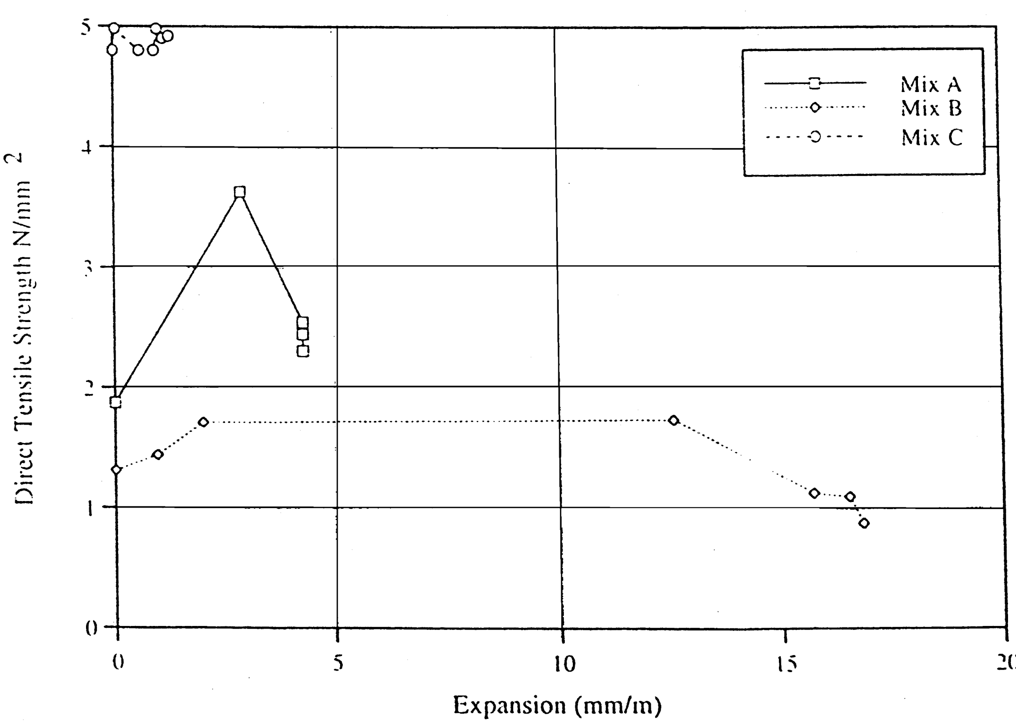

Fig. 16. Variation of direct tensile strength of control and ASR-affected concrete with expansion.

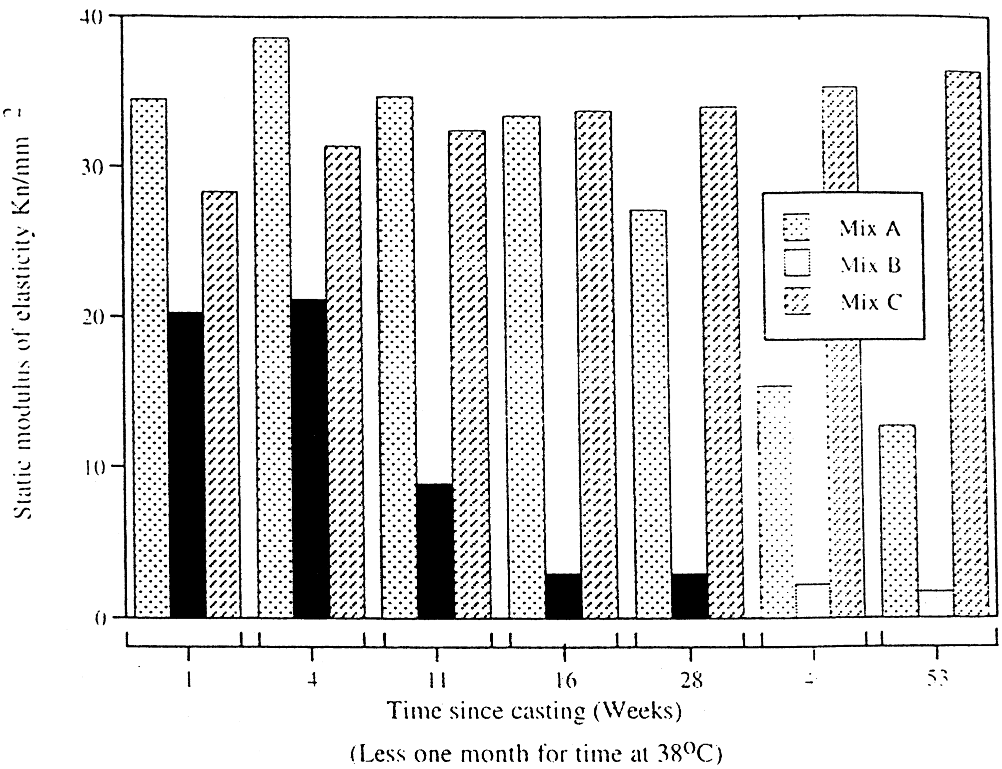

Fig. 17. Variation of modulus of elasticity with time.

was recorded for both ASR mixes. At high expansion, after 1 year, the reduction tends to be approximately 50.2% and 82.11% for the Thames Valley sand concrete, mix A, and the fused silica concrete, mix B, respectively. Mix B showed a sharper fall in strength than the slowly reactive mix A. The control, mix C, showed a steady increase in strength.

The variation of the direct tensile strength as the expansion progresses is shown in Fig. 16. The direct tensile strength of the Thames Valley sand, mix A, increases as the expansion progress, but once the expansion reached 2.9 mm/m a decrease in strength was noted. The fused silica, on the other hand, showed a small increase in strength as the expansion starts to take place. The strength remained constant until the expansion reached 12.53 mm/m, and then started to decrease until the end of this investigation at 1 year. The decrease in the direct tensile strength occurred at a late stage in the expansion. This could be due to the combined effect of shrinkage and hydration of the cement exceeding the effects of cracking at an early stage.

Therefore, it can be concluded that the expansion due to ASR has less effect, at early age, on the direct tensile strength than on the tensile splitting strength and the flexural strength. The direct tensile strength of the Thames Valley sand concrete, mix A, showed a higher percentage loss than the tensile splitting strength and flexural strength, as shown in Table 2. In contrast, the direct tensile strength of the fused silica concrete, mix B, has a higher percentage loss than the tensile splitting strength, but less than the flexural strength.

6.5. The influence of ASR on the static modulus of elasticity

The variation of static modulus of elasticity (SME) with time is shown in Fig. 17. The trend of the curve of the Thames Valley sand concrete, mix A, changes, after an initial increase, from ascending to descending, indicating a drop in the static modulus of elasticity. The fused silica concrete, mix B, did not show any increase in the modulus of elasticity, with a continuous decrease recorded. The SME of both ASR concretes showed a similar pattern to the previous properties reported above. A drop in the static modulus of elasticity also occurred with mix B immediately after the reaction took place and before any expansion or microcracks were noted. The failure to detect the expansion due to ASR when the mechanical properties start to drop could be due to the fact that the apparatus used to measure the expansion was not sensitive enough to detect expansion or internal changes in the concrete due to ASR before any change in the physical properties has taken place. The control mix, mix C, showed a continuous increase in static modulus of elasticity at varying rates up to 1 year.

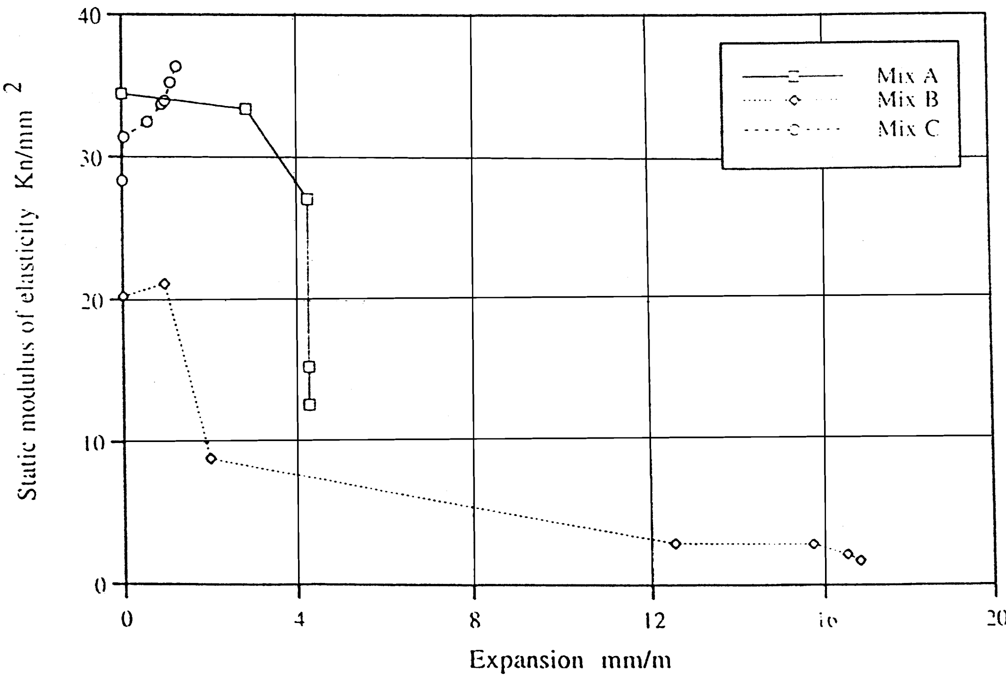

Fig. 18. Static modulus of elasticity vs. expansion.

From Fig. 17 and Table 2 it is evident that the loss in elasticity continued to increase with time, and that the speed and extent of loss depend on the type of reactive aggregate used in the concrete. This is clearly evident in the difference between mix A and mix B.

Fig. 18 was plotted to clarify the influence of expansion due to ASR on the static modulus of elasticity. Both concrete mixes showed a significant decrease in elasticity as the expansion due to ASR took place. The fused silica concrete, mix B, showed a significant drop in elasticity before the expansion reached 2 mm/m, and the elasticity then continued to decrease at varying rates until the end of investigation. The Thames Valley sand, mix A, on the other hand showed little change in the first 3 months in the hot water tank, followed by a sharp decrease in elasticity up to the age of 6 months. The expansion did not increase thereafter but, surprisingly, a significant drop in elasticity was recorded. There is a difference in elasticity between the two different concretes at any given expansion, and this is due to the difference in the rate of reaction of both aggregates and hydration of the cement, which plays an important part in developing the concrete strength.

6.6. The detection of ASR by the ultrasonic pulse velocity method

UPV was used to detect the internal deterioration of concrete due to alkali–silica reaction. The UPV of the horizontally cast $100\times100\times500$-mm^3 prisms and the vertically cast 150×300-mm^2 cylinders are plotted against time and expansion in Figs. 19 and 20, respectively. A sharp drop in UPV was shown in the fused silica specimens, mix B, in the early stages of the reaction, even before any expansion or microcracks were noted. Therefore, it can be noted that the PUNDIT detected the effect of ASR inside the concrete before the less sensitive expansion-measurement apparatus. The decrease in UPV continued at various rates and then showed a modest recovery. The UPV of prisms and cylinders dropped from 4.72 to 3.64 km/s and from 4.63 to 3.39 km/s, respectively. The Thames Valley sand, mix A, showed an increase in UPV in the first few weeks, as hydration of cement and/or the gel partially filling the cracks dominated the negative effect of the reaction, After 6 weeks in hot water, when visible microcracks appeared on the surface of the concrete specimens, a decrease in UPV was noted up to 6 months in hot water, after which a modest recovery started to take place. The drop in UPV of mix A was lower compared to that of mix B. The former showed a drop from 4.81 to 4.73 km/s and from 4.85 to 4.75 km/s for prisms and cylinders, respectively.

The final percentage loss in UPV of prisms made from mixes A and B, shown in Table 3, are 6.71 and 28.21%, respectively.

The sound concrete, mix C, showed a steady increase in UPV throughout the investigation.

The horizontally cast prisms showed a greater decrease in UPV than the corresponding vertically cast cylinders. This is due to the reduced expansion in the longitudinal direction of the vertically cast cylinders as,

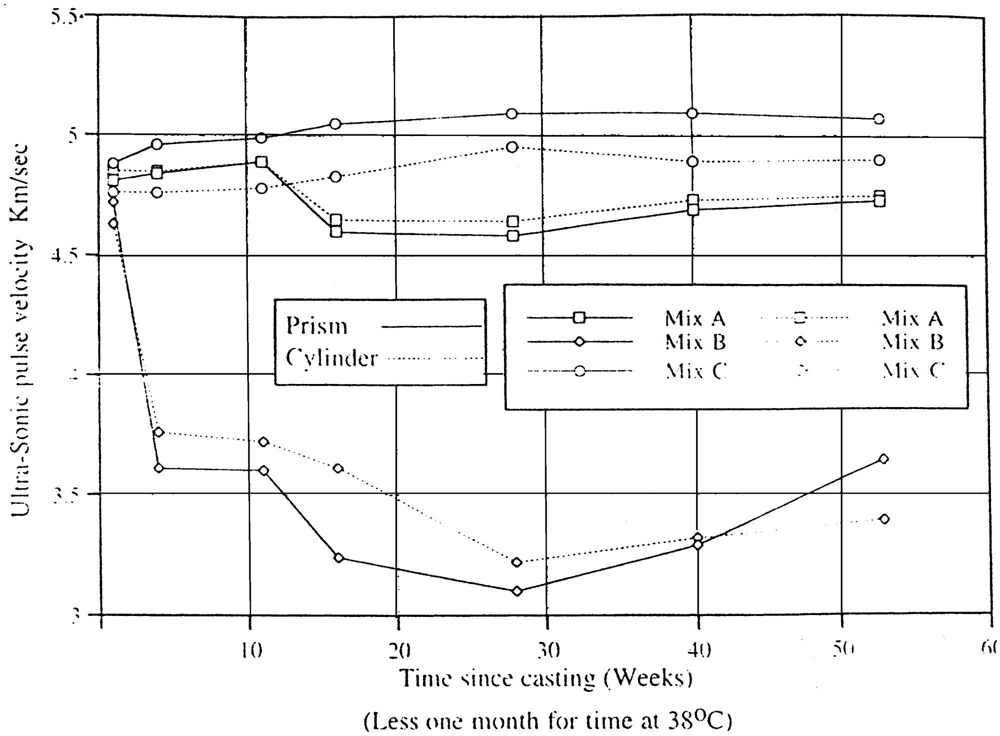

Fig. 19. Variation of ultrasonic pulse velocity of prism ($100 \times 100 \times 500$ mm^3) and cylinder (150×300 mm^2) with time.

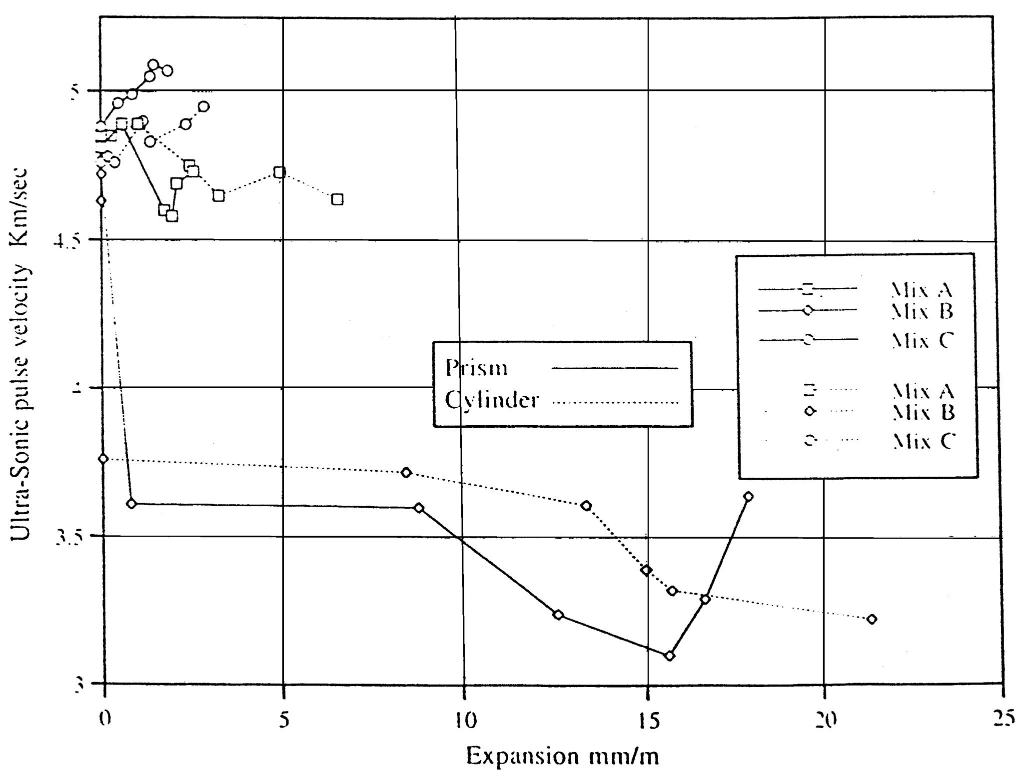

Fig. 20. Variation of ultrasonic pulse velocity of prism ($100 \times 100 \times 500$ mm^3) and cylinder (150×300 mm^2) with expansion.

cracks are formed in the weaker transverse plane, which is perpendicular to the vertical cast direction, whereas in the horizontally cast prisms, greater expansion occurs in the longitudinal direction, which is parallel to the horizontal cast direction; this in turn leads to a greater length of time for the pulses to travel through the concrete.

The formation of weaker planes in concrete is due to the water gain phenomenon, as reported by Hughes and Ash [12]. As concrete is vibrated during casting, the mix water and air voids migrate upward, opposite to the direction of casting. The coarse crushed aggregate traps the air and mix water at its underside. During cement hydration, the water is used up and hence forms a weaker plane perpendicular to the direction of casting. Hughes and Ash also reported that the concrete strength is weaker in the direction of casting when tested in tension. Hence, the ASR gels form at the weak planes where mix water is more abundant, and, as the gels expand, cracks are formed parallel to the weaker plane and perpendicular to the direction of casting.

6.7. The effect of ASR on the tensile/compressive strength ratio

In normal concrete, the compressive strength increases and the tensile strength also increases, but at a decreasing rate, with time. In the case of ASR, most of the previous research revealed that the compressive strength decreased with time. This is not the case for Thames Valley sand concrete, mix A. As reported earlier, this showed an increase with time in hot water. Cope and Slade [8]also reported an increase in compressive strength when they used the same mix, BRE mix A. It can thus be concluded that there is no direct proportionality between the strength in normal or ASR concretes. The fused silica concrete, mix B, on the other hand, showed a drop in tensile and compressive strength with time in hot water.

Table 4 shows the ratio of tensile to compressive strength of mixes A and B, as well as that of sound concrete, mix C. Swamy and Al-Asali [13]found that the ratio of tensile to compressive strength for both control and a fused silica ASR mix (their mix constituent were different to those used here) decreased with age. The same conclusion was reported by Nixon and Bollinghaus [14]. The conclusions reported in [13,14] were not found in this investigation, as can be observed in Table 4 for all three mixes. Mixes A, B and C showed an increase in the tensile to compressive strength ratio up to the age of 3 months in hot water, then the ratio decreased up to the age of 9 months, but increased again up to the end of the investigation at 1 year.

At 3 months in hot water, the ratio of tensile to compressive strength of mix A, when expansion was 2.9 mm/m, was 0.127, which is 24.51% greater than the control ratio. The fused silica at the same age, when the expansion was 12.53 mm/m, showed a ratio of 0.088, which is 13.73% less than the control. At 9 months, mixes A and B showed expansion of 4.3 and 16.56 mm/m and a ratio of tensile to compressive strength of 0.058 and 0.075, respectively. The latter values are 30.12% and 9.64% less than the corresponding control ratio, respectively.

At the end of the investigation, both ASR mixes A and B showed an increase in the tensile to compressive strength ratio of 0.063 and 0.083, which is 34.92% and 2.35% less than the control ratio, respectively. The expansion of mix A was 4.3 mm/m, whereas Mix B specimen expanded to 16.86 mm/m. Therefore, it is clear that different reactive aggregates influence the expansion and mechanical properties of concrete in different ways.

Neville [15]reported that the ratio of tensile to compressive strength of sound concrete is 0.11–0.07. The values obtained in Table 4 clearly show that this limit is valid for mix C, the control mix. The ASR mixes, A and B, show a ratio which lies between 0.05 and 0.13. This range is also valid for the recommendation made in the report of the Cement and Concrete Association working party on the diagnosis of ASR [16]. This report stated that any ratio of less than 0.06 can be regarded as evidence of internal deterioration in the concrete, which may have been caused by ASR (Figs. 21 and 22).

7. Comparison of test results with other published data

The mechanical properties of ASR concrete are greatly influenced by the type of reactive aggregate that is used. The type of reactive aggregate also dictates the expansion of concrete specimens, as observed in the case of the Thames Valley sand, mix A, and the fused silica, mix B. With 7 kg/m^3 of alkali in the mix, mix B achieved much higher expansion than observed for mix A. The engineering properties of ASR concrete do not decrease in proportion to expansion. The use of two different reactive aggregates enabled us to compare the properties of a slowly reactive aggregate, Thames Valley sand, and a faster reactive aggregate, fused silica, when comparing the decrease in compressive strength of the latter to the surprising increase in the same property of the former. This demonstrates that the compressive strength is not a sensitive indication of ASR expansion compared to the tensile strength or static modulus of elasticity.

Alkali–silica reaction ceases immediately once any one, or both of the reactants, or water is used up in the reaction, and the expansion then ceases. Recovery of lost structural properties may take place.

Fig. 21. Crack pattern of horizontally cast concrete prism containing Thames Valley sand (mix A) and 15% fused silica (mix B).

Table 3 shows a comparison of concrete properties affected by ASR as measured in this study compared to those determined by Swamy and Al-Asali [13], Hobbs [17], Clark [9] and Clayton et al. [10].

Examination of the data shows a close agreement between the present results for mix A and these obtained by Clark and Ng [11]and Clayton et al. [10], who both used the BRE mix. The percentage loss for the fused silica concrete, mix B, is close to the values obtained by Swamy and Al-Asali [18], who also used a fused silica mix. The percentage loss in Hobbs' results [17] is low compared to the present results and those of Swamy and Al-Asali [18]. This is due to the fact that Hobbs [17] carried out tests at a late age, with hydration of cement continuing after the end of expansion, which helped to recover most of the lost physical properties. The previous publications agree that ASR influences the engineering properties at different rates; the tensile strength was most affected, whereas the compressive strength is less affected. Therefore, the latter is not a good indicator of ASR.

With regard to the expansion of concrete, ASTM C227 [19] states that cement–aggregate combinations that show expansion greater than 0.05% at 3 months or

Fig. 22. Crack pattern of vertically cast concrete cylinder containing Thames Valley sand (mix A) and 15% fused silica (mix B).

0.1% at 6 months should be considered capable of harmful reactivity. This statement is explained below and compared to the test results.

ASTM C227 [19] recommends 0.05% (i.e. 0.5 mm/m) and 0.17% (i.e. 1.0 mm/m) expansion limits at 3 and 6 months, respectively, for non-reactive aggregate. Above these limits, the aggregate should be considered capable of harmful reactivity. The results obtained by the authors are shown in Table 2. The expansion limits stated by ASTM C227 (0.05%) was achieved by both mixes well before 3 months in hot water. At that particular time, the Thames Valley sand concrete, mix A, showed a reduction in compressive strength of 1.74%, while the loss in flexural strength was approximately 54.95% compared with the gain of 2.4% in indirect tensile strength and loss of approximately 0.95% in static modulus. The reduction in compressive strength, flexural strength, tensile splitting strength and static modulus was 46.24, 81.85, 53.64 and 91.31%, respectively.

8. Conclusions

1. The crack patterns and the amount of expansion of specimens are affected by the concrete geometry and the direction of casting. More expansion occurs parallel to the direction of casting.
2. The cracking patterns on prisms are concentrated at the middle line of the prism surfaces and are predominantly longitudinal, with transverse cracks branching from them.
3. The expansive strain in horizontally cast prisms is generally less than in vertically cast cylinder specimens.
4. Thames Valley sand, which contains flint, is a slowly reactive aggregate and, at a high temperature, caused only a small reduction in compressive strength. This small reduction was progressive throughout the investigation.
5. No significant loss of compressive strength was observed in the Thames Valley sand concrete, mix A. Sharp reductions in tensile strength for both mixes A and B were noted, even at an early stage in the reaction. We thus conclude that compressive strength is not a good indicator of ASR.
6. The dumb-bell-shaped briquette test, which is normally used for measuring the direct tensile strength of resin-based mortars, was successfully used to measure the direct tensile strength of sound and ASR concrete. It can be concluded from the test results that the expansion due to ASR has less effect, at an early age, on the direct tensile strength than on the tensile splitting strength and the flexural strength.
7. The ASR reduces the direct tensile strength by approximately 50% and 80% for Thames Valley sand concrete, mix A, and fused silica, mix B, respectively.
8. The static modulus of elasticity is a sensitive and reliable indicator of the deterioration of concrete due to ASR.
9. The horizontally cast prisms showed a greater drop in UPV than the vertically cast cylinders. This is due to the greater expansion that occurs in the longitudinal direction, which is parallel to the horizontal cast direction, and this in turn leads to a higher UPV.
10. Cracks due to the reaction may also lead to corrosion of steel reinforcements in a hostile environment.

Acknowledgments

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Appendix A: Conversion factors

1 lbf: 4.448 N
1 kN: 0.228 kips
1 in.: 25.4 mm
1 lbf/in.^{2}: 6895 Pa
1 lbf/ft^3: 16.02 kg/m^3
1 ft/s: 0.3046 m/s

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