Characteristics of Lightweight Concrete and Their Application in Structures

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Abstract□The research significance of the paper is to identify the major properties of synthetic lightweight concrete that are affected by ASR expansion and to determine the extent and magnitude of the loss in these properties. Emphasis is also given to the use of non-destructive 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.

Keywords□Lightweight concrete, Alkali-silica reaction, Fused silica, Synthetic lightweight aggregate, Dynamic modulus of elasticity, Ultrasonic pulse velocity, Expansion, Non-destructive test.

I. Introduction

Lightweight aggregates are well known for their porous and cellular structure. The porosity of aggregate has a significant influence on the properties of the aggregate and mix design, and on the properties of the fresh and hardened concrete made with such aggregate.

The most notable characteristics is probably the porosity which affects all other properties, and which may vary from about 25 to 75% of the aggregate volume.

Lightweight aggregates suitable for structural concrete are generally made artificially by expanding, foaming, sintering clays, shales and slate, or industrial by-products such as pulverized fuel ash and blast furnace slag.[4,6,10]

Pulverized fuel ash(PFA) is the principal waste product obtained from coal burning power stations in generation of electricity. Vast volumes of such PFA create serious disposal and environmental problem in many countries. One effective method of utilizing PFA is to manufacture aggregates for plain and structural concrete.[11]

Also, alkali-silica reaction(ASR) is a chemical reaction between the hydroxylions in the pore water in concrete and certain forms of silica that occasionally occur as part of aggregate resulting in the formation of alkali-silica solutions. This type of reaction is known to cause abnormal expansion in concrete, and as a result, extensive cracking occurs.[13]

On the other hand, an amorphous-fused silica is a synthetic aggregate used extensively in the steel, foundry, aluminum, and refractory industries, particularly for its properties of high thermal-shock resistance, low thermal expansion, and resistance to molten metals.[14)]

The purpose of this study 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, such as dynamic modulus of elasticity and ultrasonic pulse velocity.

II. Literature Review

Recently, worldwide annual production of PFA is estimated at about 180~200 million tons. Less than 20% of these were used in concrete related materials such as cement manufacture, concrete and concrete products, and lightweight aggregate. It is estimated that by the turn of this century approximately 750 million tons of PFA will be produced annually worldwide. Current annual productions of coarse and fine aggregates from PFA are 600,000 m^3 in UK and 300,000 m^3 in USA ; this represents the utilization of only a fraction of the total ash collected in the world.[11)]

On the other hand, although the phenomenon of alkali aggregate reaction has been known and researched since it was first identified by Stanton [7)] more than 50 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 reaction. However, only limited data on the physical effects caused by the deterioration process due to alkali silica reaction.

Swamy et al.[13)] reported that temperature is a major factor influencing ASR, and even aggregates such as flint, that is generally considered to be unreactive, can create deleterious expansions under warm (35~40℃) and humid condition.

Swamy[18)] also reported the followings : Alkali-silica reaction is recognized to be able to cause disruptive deformations and structural distress in reinforced and pre-stressed concrete members. High alumina cement is a typical example where the type of cement is the basic cause of concrete deterioration. With ASR, it is the cement matrix-concrete aggregate interaction that is primarily responsible for the cracking and disruption of concrete. The most dramatic visual evidence of ASR is extensive cracking. The reaction is essentially an expansive one, resulting from the formation of a gel which can imbibe water, swell and exert pressure which can crack the concrete.

Since water, alkalies and reactive silica are necessary for ASR damage to occur, the following factors influence the reaction :

a. The nature, size and amount of reactive siliceous particles.

b. The alkali content of the cement, and the cement content of the concrete.

c. The amount of alkali that could be leached out of aggregates.

d. Sources of external alkali, and

e. Ambient environmental conditions, i. e. moisture and temperature.

The gel may form in dry conditions but needs water to expand and cause damage. So moist concrete inside a dry building is probably safe from ASR(relative humidity : RH<75%). On the other hand, concrete exposed to rain, sea water or ground water is susceptible to ASR.

The avaliable methods to control the deleterious expansion caused by ASR are as follows :

a. Use of non-reactive aggregate.

b. Use of low-alkali cement, and

c. Incorporation of pozzolanic or mineral admixtures.

ASTM C 227[1] recommends 0.05 and 0.1% expansion limits at 3 and 6 months, respectively, for non-reactive aggregates. Above these limits, aggregates should be considered capable of harmful reactivity.

Swamy et al.[15] reported that both the rate of expansion and final expansion are dependent on the type of reactive aggregate, the amount present, and its particle size distribution.

Swamy et al.[14] reported that for a given type of cement and given type and amount of reactive aggregate, the final expansion increases as the cement content increases, but not in proportion to the cement content. Also he reported that disruptive expansions can occur even with as low an alkalinity as 2.5kg/m^3 when amorphous silica is used as reactive aggregate and the ambient temperature is 38℃. But, since expansions can be excessive or deleterious without evidence of cracking, depending on the function of the concrete element, it is difficult to apply single value of critical limits to all situations. So, critical limits of deleterious expansion need to be defined according to the type and use of a concrete structure.

Ⅲ. Materials

1. Cement

The cement used was a normal portland cement (ASTM Type-1) having alkali content of 1 percent. The chemical compositions of cement used are summarized in the Table 1.

Table 1. Chemical composition of normal portland cement(%)

SiO_2	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Fe_2O_3
21.09	4.84	63.85	3.32	3.09	1.13	0.29	2.39

2. Fine Aggregate

The fine aggregates used were washed and dried natural sand, and the fused silica with 0.6 mm maximum size. The physical properties of natural sand and chemical compositions of fused silica are summarized in the Table 2 and 3, respectively.

3. Coarse Aggregate

The coarse aggregates consisted of rounded and curshed natural gravel with 13.2mm maximum size, and synthetic lightweight coarse aggregate made from sintered pulverized fuel ash. The physical properties and chemical compositions of synthetic lightweight coarse aggregate are summari-

Table 2. Physical properties of natural sand

Specific gravity	Maximum size(mm)	Absorption rate(%)	Fineness modulus	Unit weight (t/m^3)	Organic content
2.50	4.75	5.00	2.74	1.56	Nil

Table 3. Chemical composition of fused silica(%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MnO	TiO_2	MgO	Na_2O	P_2O_3	SO_3	Loss on ignition
99.71	0.15	0.35	0.04	0.03	<0.01	0.03	<0.05	<0.1	<0.01	<0.02	0.1

Table 4. Physical properties of synthetic lightweight coarse aggregate

Fineness modulus	Unit weight(t/m^3)	Water absorption(%)	Type	Color	Pore size(mm)	Thickness (mm)	Maximum size(mm)
5.98	0.83	13.1	Honeycomb	Gray – brown	0.001 – 0.15	0.15 – 0.50	13.2

Table 5. Main chemical composition of synthetic lightweight coarse aggregate(%)

SiO_2 (silica)	Al_2O_3 (alumina)	CaO (lime)	Carbon in the form of unburnt fuel
30~60	15~30	1~7	<8

zed in the Table 4 and 5, respectively.

4. Concrete Mix

Based on the initial trial mix results, concrete mixes, having a slump of 75~100mm and 28 day target compressive strength(dry cured) of 460 kg/cm^2 were designed(Table 6).[11] In type B and C concrete, an amorphous fused silica reported earlier was used,[13,14] which contained 99.7 percent silica and a particle size distribution of 0.15~0.6 mm. This was also used to replace the fine aggregate by an amount equal to 15 percent by weight of the total aggregate.[14]

Table 6. Mix design of concrete(kg/m^3)

Item	Cement	Sand	Lightweight coarse aggregate	Normal coarse aggregate	Fused silica	Free water	Remark
Normal concrete	335	645	–	715	–	175	Type A
Synthetic lightweight aggregate concrete	335	441	715	–	204	217	Type B
	335	441	715	–	204	217	Type C

Table 7. Curing methods of concrete specimen

Item	Curing age(days)			
	1	2~14	15~28	29~180
Type A	Humidity curing (20±1℃, 96±2% RH)	Humidity curing	Humidity curing	Humidity curing
Type B	Humidity curing (20±1℃, 96±2% RH)	Water curing (20±1℃)	Air curing	Air curing
Type C	Humidity curing (20±1℃, 96±2% RH)	Water curing (20±1℃)	Air curing	Water curing (38±1℃)

5. Manufacture and Curing of Test Specimens

Test for dynamic modules of elasticity and ultrasonic pulse velocity of specimens were carried out on 100×100×500mm prisms, and test for expansion was carried out on 75×75×300mm prisms. All the test specimens were demolded after cured at 20± 1℃ and 95± 2 percent relative humidity(RH) for one day, and then exposed to various curing environments, as Table 7, Especially, the curing temperature of type C concrete was carried out on 38± 1℃, which showed the highest expansion.[13,14,16]

IV. Methodology

1. Dynamic Modulus of Elasticity

The dynamic modulus test was conducted by excitation in the longitudinal mode of vibration.[9] The equation is as follows :

$$D.\ M.=40.81632652\ n^2 I^2 \rho \times 10^{-12}$$

where, D. M.=Dynamic modulus of elasticity (kg/cm^2)

n =Hz

I =Length of test specimen(mm)

ρ =Bulk density of test specimen (kg/cm^3)

2. Ultrasonic Pulse Velocity

Transducers of 50mm diameter were used, and measurements were taken at the top and bottom of the 100×100mm end faces over a path length of 500mm.[12] The equation is as follows :

$$P.\ V=\frac{L}{10^{-6}\sec \times D}$$

where, P. V=Ultrasonic pulse velocity(m/sec)

D =Number of digital

L =Length of test specimen(m)

3. Expansion

The measurements of expansion were taken on a special rig with an attached micrometer.[3] The equation is as follows :

$$E.\ P=\frac{I}{L}\times 100$$

where, E. P=Expansion(%)

L =Length of test specimen(mm)

I =Incresed or decreased length of test specimen(mm)

V. Results and Discussion

In this study, three tests were carried out for a given property at many curing ages. The results are the average of three test specimens and summarized in the Table 8.

1. Dynamic Modulus of Elasticity

The dynamic moulus were measured and the results are shown in Table 8 and Fig. 1. The percentage loss in dynamic modulus of ASR-affected concrete is shown in Table 9. The reduction rates means the difference between the values of dynamic modulus of type A concrete, these results confirm that dynamic modulus exhibits a very high sensitivity in reflecting the change in the structure of the deteriorating concrete. This shows a similar trend to Swamy's report.[15]

Table 9 shows that this loss was noticed at a very early age, i. e., at 1 days when two type concretes showed 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 prope-

Table 8. Effects of ASR expansion on concrete properties

Test	Mix	Curing age(days)									
		1	3	7	14	21	28	60	90	180	365
Dynamic moulus of elasticity (kg/cm^2)	Type A	352,989	385,897	408,510	413,874	419,252	423,571	427,752	430,540	436,998	439,150
	Type B	216,836	226,142	239,826	259,255	273,969	283,724	249,677	221,397	204,510	181,887
	Type C	216,836	226,142	239,826	259,255	273,969	283,724	197,914	167,724	145,683	125,287
Ultrasonic pulse velocity (m/sec)	Type A	4,066	4,277	4,347	4,399	4,438	4,483	4,508	4,527	4,572	4,608
	Type B	3,644	3,711	3,843	3,927	4,042	4,159	3,992	3,894	3,770	3,707
	Type C	3,644	3,711	3,843	3,927	4,042	4,159	3,826	3,720	3,679	3,657
Expansion (%)	Type A	0.0000	0.0003	0.0008	0.0012	0.0021	0.0032	0.0105	0.0174	0.0191	0.0198
	Type B	0.0000	0.0059	0.0194	0.0228	0.0016	−0.0050	−0.0160	−0.0245	−0.0313	−0.0406
	Type C	0.0000	0.0059	0.0194	0.0228	0.0016	−0.0050	+0.2861	+0.4546	+0.7162	+0.7189

Table 9. Percentage loss in dynamic modulus of ASR-affected concrete

Curing age, days	Type B		Type C	
	Expansion, percent	Loss, percent	Expansion, percent	Loss, percent
1	0.0000	38.6	0.0000	38.6
3	0.0059	41.4	0.0059	41.4
7	0.0194	41.3	0.0194	41.3
14	0.0228	37.4	0.0228	37.4
21	0.0016	34.7	0.0016	34.7
28	−0.0050	33.1	−0.0050	33.1
60	−0.0160	41.7	+0.2861	53.8
90	−0.0245	48.6	+0.4546	61.1
180	−0.0313	53.3	+0.7162	66.7

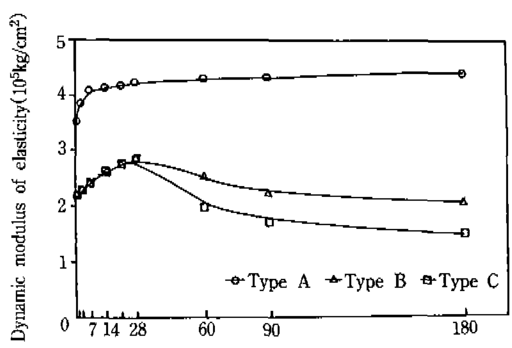

Fig. 1. Relationship between curing age and dynamic modulus of elasticity

rties or visible cracking has taken place.

Like other properties, the speed and extent of reduction in dynamic modulus depend largely on the type of reactive aggregate and its reactivity. This results showed that different reactive aggregates affect the engineering propertities at different rates. This shows a similar trend to British standard,[2)] and Sung's report.[8)] 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.

Consequently, the dynamic modulus of elasticity of type A concreet was increased with increase of curing age. The type B and C concretes showed the highest dynamic modulus of elasticity at the 28 days curing age.(Fig. 1). It was gradually decreased with increase of curing age at those concrete. Especially, the dynamic modulus of curing age 180 days was decreased up to 53.3% in type B and 66.7% in type C concrete than the type A concrete, respectively.

2. Ultrasonic Pulse Velocity

The results of the ultrasonic pulse velocity are shown in Table 8 and Fig. 2. Also, the loss in pulse velocity of ASR-affected concrete at different

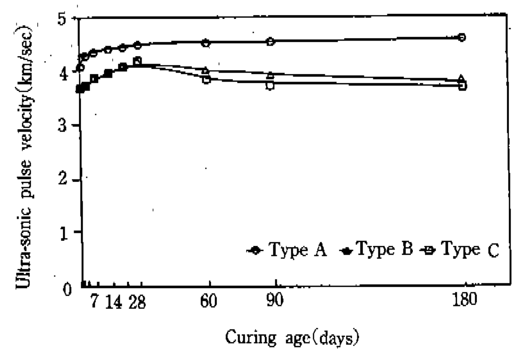

Fig. 2. Relationship between curing age and ultrasonic pulse velocity

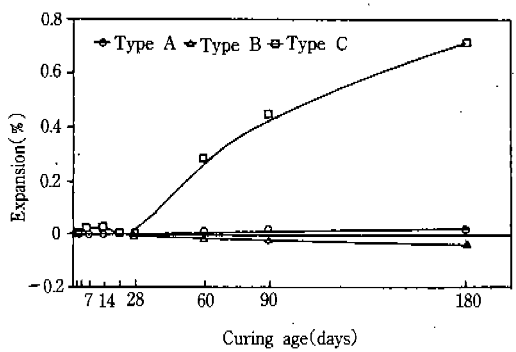

Fig. 3. Relationship between curing age and expansion

Table 10. Percentage loss in pulse velocity of ASR-affected concrete

Curing age, days	Type B		Type C	
	Expansion, percent	Loss, percent	Expansion, percent	Loss, percent
1	0.0000	10.4	0.0000	10.4
3	0.0059	13.3	0.0059	13.3
7	0.0194	11.6	0.0194	11.6
14	0.0228	10.8	0.0228	10.8
2¹	0.0016	9.0	0.0016	9.0
28	−0.0050	7.3	−0.0050	7.3
60	−0.0160	11.5	+0.2861	15.2
90	−0.0245	14.0	+0.4546	17.9
180	−0.0313	17.6	+0.7162	19.6

age is summarized in Table 10. In these results, the ultrasonic pulse velocity of type A concrete was increased with increase of curing age. The type B and C concretes showed the highest ultrasonic pulse velocity at the 28 days curing age(Fig. 2). It was gradually decreased with increase of curing age at those concrete. This is a similar trend to Swamy's report.[15)] Especially, at the curing age 180 days, the ultrasonic pulse velocity was decreased up to 17.6% in type B and 19.6% in type C concrete than the type A concrete, respectively.

3. Expansion

The results of the expansion are shown in Table 8 and Fig. 3. After 28 days curing age, the expansion of the type A and C concrete was increased with increase of curing age, respectively. But, the type B concrete was decreased with increase of curing age. Also, at the curing age 180 days, the rate of expansion of the type A and C concrete was increased 0.0191% and 0.7162%, respectively. But, type B concrete was decreased 0.0313%, Especially, the rate of expansion of the type C concrete was 37 times higher than the type A concrete.

This results confirm earlier findings that expansion due to ASR, for a given environment, was influenced by many factors related to the reactive aggregate. This is a similar trend to Swamy et al.[13,14]

Fig. 4.(38℃ water curing, age=90 days) shows that, Cracking due to ASR in concrete was very irregular because of the nature of the expansive reaction and the internal stresses it creats. In lightweight aggregate concrete, ASR cracks appeared horizontal and vertical direction, and its was readily seen. Visible cracking due to ASR can be further complicated by the fact that the reaction needs both moisture and favourable temperature

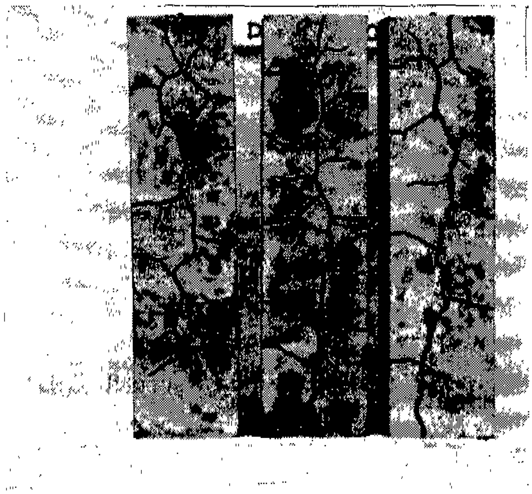

Fig. 4. Typical ASR cracking in unrestrained concrete

for it both to start and continue. Thus, the interior structures of an exposed bridge, sheltered from direct sunshine and rain, may show no cracking whilst the exterior structures may develop extensive cracking. On the other hand, a structural member, partly sheltered and exposed by the nature of the structure, may show different crack patterns, with extensive cracking on the exposed faces and little or no cracking on the sheltered regions.

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. In moist conditions, both the rate of reaction and the final expansion occurred much more rapidly at higher than ambient temperature.

4. Relationship between Dynamic Modulus of Elasticity and Ultrasonic Pulse Velocity

Since both the dynamic modulus and pulse velocity are theoretically interrelated, Fig. 5 is presented to illustrate the changes in both properties. The results confirm that both show generally similar behavior, although the magnitudes of their changes are different. This is a similar trend to Swamy's report.[15]

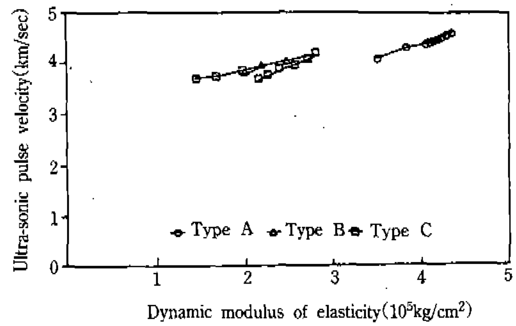

Fig. 5. Relationship between dynamic modulus of elasticity and ultrasonic pulse velocity

A comparison of loss in pulse velocity and dynamic modulus in Tables 9 and 10 shows that both are highly sensitive to change of internal structure of the concrete due to ASR, and both properties registered measurable losses even before any expansion could be measured. Both Dynamic modulus and pulse velocity gave good indications of deterioration of concrete affected by ASR, and both properties showed measurable losses at a very early age when no expansion was indicated. It thus appears that these two techniques offer potentially useful for nondestructive test methods to identify the physical condition of concrete for nondestructive test methods to identify the physical condition of concrete due to internal chemical reactions arising from ASR. Also, the pulse velocity was increased with increase and was decreased with decrease of the dynamic modulus. The decreasing rate of the dynamic modulus was 3 times higher than the pulse velocity at all curing age, respectively.

5. Relationship between Dynamic Modulus of Elasticity and Expansion

The rate at which changes occur in the structure and physical properties of the ASR-affected concrete 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 9 with both ASR-affected concretes. Also, this can be illustrated by examining changes in the dynamic modulus, of type C concrete between the curing ages of 90 and 180 days. During this period, although expansion had increased from 0.4546 percent to 0.7162 percent, the loss in dynamic modulus was modest(from about 61.1 percent to about 66.7 percent). This is a similar trend to Sung's report,[8] That is, this was evidenced by the small loss of compressive strength from 348 kg/cm^2 at the curing age 90 days to 319 kg/cm^2 at the curing age 180 days.

In addition, relationship between ultrasonic pulse velocity and expansion showed a similar trend to results of dynamic modulus.

VI. Summary and Conclusion

This paper presents a detailed study of the effects of ASR on the engineering properties of synthetic lightweight concrete, such as modulus of elasticity and ultrasonic pulse velocity. The tests were carried out for 6 months to establish the effects of expansion and time on the engineering properties of synthetic lighweight concrete.

1. The dynamic modulus of elasticity of type A concrete was increased with increase of curing age. The Type B and C concretes showed the highest dynamic modulus of elasticity at the 28 days curing age. But, it was gradually decreased with increase of curing age at those concrete, respectively. Especially, the dynamic modulus of curing age 180 days was decreased up to 53.3% in type B and 66.7% in type C concrete than the type A concrete, respectively.

2. The ultrasonic pulse velocity of type A concrete was increased with increase of curing age. The type B and C concretes showed the highest ultrasonic pulse velocity at the 28 days curing age. But, it was gradually decreased with increase of curing age at those concrete, respectively. Especially, at the curing age 180 days, the ultrasonic pulse velocity was decresed up to 17.6% in type B and 19.6% in type C concrete than the type A concrete, respectively.

3. The expansion of type A and C concrete was increased with increase of curing age, respectively. But, the type B concrete was decreased with increase of curing age. Also, at the curing age 180 days, the rate of expansion of the type A and C concrete was increased 0.0191% and 0.7162%, respectively. But, the type B concrete was decreased 0.0313%. Especially, the rate of expansion of type C concrete was 37 times higher than the type A concrete.

4. The dynamic modulus of elasticity and ultrasonic pulse velocity of type A concrete was increased with increase of expansion. But, the type B and C concrete was decreased with increase of curing age since the curing age 60 days. Also, the dynamic modulus of elasticity was increased with increase and decreased with decrease of ultrasonic pulse velocity.

For the decreasing rate of the dynamic modulus and pulse velocity due to expansion, the dynamic modulus decreased 3 times higher than the pulse velocity at each age, respectively.

5. The rate of losses in engineering properties

of concrete affected by ASR depended on the physical and chemical characteristics of reactive aggregate present in concrete, and did not all occurred at the same rate or in proportion to the expansion. Also, the rate of expansion of the water curing(38± 1℃) was higher than the air curing, and the dynamic modulus of elasticity and pulse velocity were showed smaller.

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