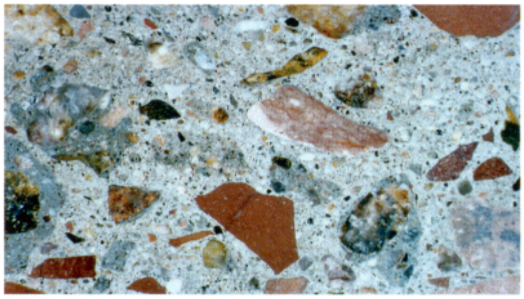
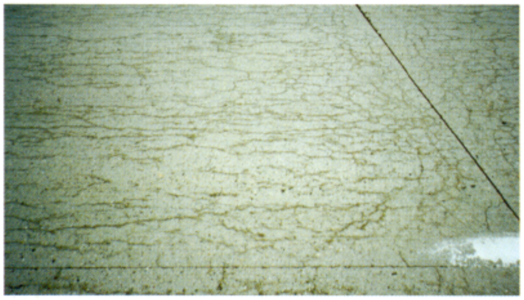
Portland Cement Association





Research and Development Bulletin RD114

The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity

by David Stark

KEYWORDS: aggregate, alkali-silica reactivity, cement alkali level, concrete, expansion, fly ash, pavement, recycled concrete

ABSTRACT: An investigation was made into precautions that were needed to prevent expansive alkali-silica reactivity (ASR) when ASR-affected concrete is recycled as coarse aggregate in new concrete. Cements with alkali levels of 0.50%, 0.75%, and 1.00% equivalent Na_2O were used with highly reactive fine and coarse aggregate in original concretes that were recycled at ages of two months and at about one-half maximum expansion and near maximum expansion. New concretes containing recycled concrete as coarse aggregate were made using innocuous fine aggregate and cements with 0.50% or 1.00% cement alkali, with and without fly ash. Test storage in all cases was over water in sealed containers held at 38°C (100°F). Results indicated that excessive expansions due to ASR can develop in the new concrete containing the recycled concrete particularly when low alkali cement was used in the original concrete and high alkali cement was used in the new concrete. Low lime ASTM Class F fly ash used at a 20% mass replacement level for cement, for the most part, reduced expansions to safe levels. Observations of pavement concrete indicate successful control of potential ASR in ASR-affected concrete recycled as aggregate in which fly ash is included in the concrete mixture.

REFERENCE: Stark, David, *The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity*, Research and Development Bulletin RD114, Portland Cement Association, Skokie, Illinois, U.S.A., 1996.

MOTS CLÉS: béton, béton recyclé, cendres volantes, expansion, granulats, niveau d'alcali du ciment, pavages, réactivité alcali-silice

RÉSUMÉ: Une recherche a été faite sur les précautions à prendre pour prévenir l'expansion due à la réactivité alcali-silice lorsque l'on recycle du béton, affecté de cette réaction, en granulats pour nouveau béton. Des ciments avec des niveaux d'alcalis de 0.50%, 0.75% et 1.00% (en équivalent Na_2O) ont été combinés avec des granulats fins et gros hautement réactifs pour produire le béton original qu'on a ensuite recyclé à deux mois d'âge, à la moitié de l'expansion maximum et à expansion maximum. Les nouveaux bétons contenant du béton recyclé pour les gros granulats ont été réalisés avec des sables neutres et des ciments avec teneur en alcali de 0.50% et 1.00%, avec ou sans cendres volantes. Dans tous les cas, les échantillons ont été conservés dans l'eau, dans des contenants scellés et à une température de 38°C (100°F). Les résultats indiquent qu'une expansion excessive due à la réactivité alcali-silice peut se développer dans les nouveaux bétons contenant du béton recyclé particulièrement lorsqu'un ciment à faible teneur en alcali était utilisé dans le béton original et une haute teneur en alcali était utilisée dans le nouveau béton. Dans la plupart des cas, une cendre volante ASTM classe F à faible taux de chaux utilisée à un taux de remplacement du ciment de 20% (en masse) a réduit l'expansion à un niveau sécuritaire. L'observation de bétons de pavage indique que l'on peut contrôler avec succès la réaction potentielle alcali-silice dans des bétons contenant des granulats en béton recyclé déjà affectés par la réaction lorsque l'on y ajoute des cendres volantes.

RÉFÉRENCE: Stark, David, *The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity*, Research and Development Bulletin RD114, Portland Cement Association [*Utilisation de granulats de bétons recyclés provenant d'un béton affecté par la réactivité alcali-silice*, Bulletin de Recherche et Développement RD114, Association du Ciment Portland], Skokie, Illinois, U.S.A., 1996.

Cover Illustrations:

Top Left: Illustration of cross-section of concrete containing recycled concrete aggregate (#65256).

Bottom Left: Illustration of deterioration due to alkali-silica reactivity in a highway pavement (#65257).

Right: Broken highway pavement being hauled away to be made into recycled aggregate for new concrete pavement (#42534).

PCA R&D Serial No. 2033

The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity

by David Stark*

INTRODUCTION

Recycling existing concrete for use as aggregate in new construction has gained attention in recent years because of increased costs of disposal of old concrete and greater costs of virgin aggregate to the job site. However, when the old concrete is recycled as aggregate in new concrete, durability concerns will still exist with the new concrete. This has been a particular issue in pavement construction where such factors as freezing and thawing and alkali-silica reactivity (ASR) in old concrete might cause progressive deterioration of new concrete containing the recycled concrete as aggregate.

This report describes an investigation into the importance of possible continued ASR as it affects new concrete containing recycled concrete as aggregate. Special reference is given to highway pavement where recycled concrete, in several instances, has been used as coarse aggregate.

BACKGROUND

As ASR proceeds in concrete, both alkali (sodium and potassium) and potentially reactive silica and silicate are consumed while, in highway structures for example, practically unlimited moisture will be available for absorption and swelling of ASR gel reaction products. Since excessive quantities of potentially reactive silica or silicate relative to alkali normally are present in concrete, the factor limiting expansive ASR probably will be depletion of alkali available in sufficient concentration in the pore solution in the concrete to produce potentially expansive reaction product. Because some alkali combined in the reaction product may be regenerated into the pore solution by replacement by dissolved calcium, it becomes difficult to determine by pore solution analysis whether the potential remains for continued expansive reactivity. In addition, diffusion and interaction of "new" pore solution in recycled concrete is not readily, if at all, predictable. Thus, determining expansion resulting from ASR is the preferred method of evaluation of continuing expansive reactivity.

SCOPE OF THE TEST PROGRAM

Tests carried out in this investigation consisted of fabricating new concrete prisms containing coarse aggregate made from old concrete previously tested to certain levels of expansion. The original concretes were made using highly reactive fine and coarse aggregate in combination with cements with 0.50%, 0.75%, and 1.00% alkali as equivalent Na_2O. The concretes were cast as 150 x 300-mm (6 x 12-in.) cylinders for subsequent processing to provide the recycled coarse aggregate, and as 75 x 75 x 275-mm (3 x 3 x 11-1/4-in.) concrete prisms for expansion determinations for the full duration of the 48-month test period. At two months and at expansion levels corresponding to approximately one-half and to essentially maximum expansion, a sufficient number of cylinders were crushed, processed, and used as coarse aggregate in sets of concrete prisms made for subsequent expansion determinations. These prisms thus contained the recycled concrete as coarse aggregate and a known innocuous unused fine aggregate. The recycled aggregate obtained from each original concrete mixture was used with high- and low-alkali cements, both with and without a 20% mass replacement of the cement by a low-lime ASTM Class F fly ash with known capability to prevent expansion due to ASR. Comparator readings then were taken on the new concrete prisms up to a test age of 46

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months. For prisms containing recycled-concrete aggregate, the test period was shortened by two months or by the number of months required to reach the targeted 50% and maximum expansion levels. Despite this shortened test period, meaningful trends were observed for all concretes.

MATERIALS

Two ASTM cements were blended to provide the required alkali contents for all the concrete mixtures. Characteristics of the test cements are given in Table 1. The cements with 1.00% or 0.50% equivalent Na_2O were used in both the original concrete and the new concrete containing recycled concrete as coarse aggregate. The cement with 0.75% equivalent Na_2O was used only in the original concrete.

The highly reactive coarse and fine aggregates were from New Mexico and contain 10 to 20% reactive glassy to cryptocrystalline volcanic material of rhyolitic to andesitic composition. More slowly reactive chert was present in much smaller amounts. These aggregates are known to be deleteriously reactive with portland cements with equivalent Na_2O contents as low as 0.50 to 0.60%. Other components of the aggregate are innocuous granitic-textured rock types, limestone, quartz, and feldspar.

The innocuous fine aggregate used in mixtures with recycled concrete as coarse aggregate was a well rounded glacial material from Elgin, Illinois. It consisted of about 50% dolomite, 40% quartz and feldspar, and minor amounts of limestone, quartzite, crystalline basalt, and granitic-textured material.

A fly ash meeting ASTM Class F requirements was used in some of the new concrete prisms. Characteristics of this material are given in Table 1. It should be noted that this is a low lime fly ash containing 5.47% calcium oxide. A low lime content is a desirable characteristic of the fly ash because its use at a 20% dosage rate should significantly reduce lime-silica ratios of the calcium silicate hydration product of the cement plus fly ash, thereby providing greater capability to retain alkali from the pore solution in the concrete and minimizing expansion due to ASR.[1]

Table 1. Composition and Properties of Portland Cements and Fly Ashes Used in this Investigation

Analyte	Cement			Fly ash
	1.00% Alkali	0.75% Alkali	0.50% Alkali	J
CaO	62.11	62.99	63.94	5.10
SiO_2	20.35	20.60	20.86	46.10
Al_2O_3	4.48	4.59	4.70	20.10
Fe_2O_3	3.32	3.34	3.36	16.96
$SiO_2+Al_2O_3+Fe_2O_3$				83.16
SO_3	2.78	2.66	2.55	1.36
MgO	4.03	3.02	2.01	1.33
Total Na_2O	0.42	0.30	0.18	0.53
Total K_2O	0.88	0.68	0.49	2.23
Total Na_2O equivalent	1.00	0.75	0.50	2.00
Avail. alkali as Na_2O equivalent				0.65
Free CaO				1.49
Moisture content				0.15
LOI	1.18	1.16	1.15	4.86
Insoluable residue	0.12	0.14	0.16	
C_3S	53	54	54	
C_2S	18	18	18	
C_3A	7	7	8	
C_4AF	10	10	10	
Blaine m^2/kg	383	378	374	375
No. 325 sieve, % retained				14.4
Pozzolanic activity index				
Portland cement, %				90
Lime, psi				920

MIXING AND CASTING PROCEDURES

All original concretes were mixed in a $0.112m^3$ ($4 ft^3$) rotating pan-type mixer on a 3-3-2, mix-rest-mix cycle. Sufficient material was batched and mixed to provide concrete for three 75 x 75 x

286-mm (3 x 3 x 11-1/4-in.) prisms, and 24 150 x 300-mm (6 x 12-in.) cylinders. The latter were used to supply recycled concrete for the coarse aggregate in the new concrete. After casting, all specimens were cured in the molds for one day under damp burlap covered with polyethylene sheeting. All batching, mixing, casting, and storage in the molds was carried out at 23°C (73°F). After one day all specimens were stripped from the molds and transferred to test storage over water in sealed containers at 38°C (100°F). Just prior to transfer, comparator readings were taken on the concrete prisms to serve as the basis for calculating subsequent expansions during test storage.

At a test age of two months, and at the appropriate test time based on expansion levels of the three companion prisms, six concrete cylinders were removed from test, allowed to dry for one day at 38°C (100°F) and 30% RH, then crushed to provide the required quantity and gradation of recycled-concrete coarse aggregate. None of this aggregate was subjected to washing during processing according to common commercial practice. Thus, alkali present in the pore solution in the original concrete also was present in the recycled concrete used as coarse aggregate in the new concrete.

Table 2. Aggregate Gradings for Concrete Mixtures

Sieve size	Reactive coarse and fine aggregate, %	Recycled coarse and innocuous fine aggregate, %
Coarse aggregate		
31.8 mm to 19.0 mm ($1\frac{1}{4}$ in. to $\frac{3}{4}$ in.)	18	18
19.0 mm to 9.5 mm ($\frac{3}{4}$ in. to $\frac{3}{8}$ in.)	60	60
9.5 mm to 4.75 mm ($\frac{3}{8}$ in. to No. 4)	20	22
4.75 mm to 2.36 mm (No. 4 to No. 8)	2	0
Fine aggregate		
9.5 mm to 4.75 mm ($\frac{3}{8}$ in. to No. 4)	4	2
4.75 mm to 2.36 mm (No. 4 to No. 8)	12	16
2.36 mm to 1.18 mm (No. 8 to No. 16)	10	20
1.18 mm to 600 µm (No. 16 to No. 30)	20	23
600 µm to 300 µm (No. 30 to No. 50)	34	25
300 µm to 150 µm (No. 50 to No. 100)	17	12
-150 µm (- No. 100)	3	3

Three companion 75 x 75 x 286-mm (3 x 3 x 11-1/4-in.) concrete prisms were cast using only recycled concrete as coarse aggregate, together with natural Elgin fine aggregate. Fly ash was incorporated into selected mixtures at the 20% dosage level. The same procedures were used for batching, mixing, casting, and storage in the molds as described previously. Again the initial comparator readings were taken just prior to transfer to storage over water in sealed containers at 38°C (100°F). As stated previously, the initial set of prisms containing recycled concrete as aggregate was fabricated two months after casting the original concretes. Subsequent sets were fabricated when the original concretes reached a projected 50% and 90% to 100% of the maximum expansion, based on previous experience using other samples of aggregate from this source.

TEST REGIME

All concrete specimens were stored under ASTM C 227 test conditions. That is, immediately following stripping from the molds and the initial comparator reading, the specimens were placed over water in sealed containers stored at 38°C (100°F). Further readings were taken periodically over a period up to 48 months. A test failure criterion of 0.10% expansion was used as suggested for mortar bars in the Appendix of ASTM C 33. In the present series, this expansion level was applied because it has been observed microscopically by the writer

Table 3. Proportions for Concrete Mixtures, kg/m^3 (lb/yd^3)

Component	Original mixtures		Recycled mixtures	
	Without fly ash	With fly ash	Without fly ash	With fly ash
Cement	356 (600)	285 (480)	356 (600)	285 (480)
Fly ash	—	71 (120)	—	71 (120)
Coarse aggregate	1130 (1905)	1130 (1905)	—	—
Recycled concrete	—	—	1016 (1712)	1016 (1712)
Fine aggregate	706 (1190)	706 (1190)	706 (1190)	706 (1190)
Water	167 (281)	161 (272)	171 (288)	171 (288)

that cracks attributed to ASR are present in either mortar or concrete by the time this expansion level is reached.

TEST RESULTS

Results for all tests are plotted in Figs. 1 through 17 as expansion versus time for the various combinations of cement, fly ash, and unused and recycled concrete aggregate.

Results for Concrete Containing Unused Aggregate

Fig. 1 shows 48-month expansions of concrete containing unused fine and coarse aggregate and cements with 0.50, 0.75, or 1.00% alkali as equivalent Na_2O. Curves in this figure illustrate the reactive nature of the aggregate and the dependence of expansion on the alkali content of the cement. As expected, the greatest expansions (0.35%) were reached by the mixture containing cement with 1.00% alkali. It should be noted that, for all practical purposes, maximum expansions were reached within 24 months for mixtures made with cements with 1.00% or 0.75% alkali as equivalent Na_2O. For the mixture containing the cement with 0.50% alkali, expansions reached only 0.05% at about 42 months. This relatively low expansion level has been found to be associated with the early stages of ASR in other work by the writer.

Results for Mortar Containing Unused Aggregate and Fly Ash

The effectiveness of the fly ash in reducing expansions due to ASR in C 227 mortars containing the highly reactive fine aggregate is shown in Fig. 2. Here, expansions were reduced to below the suggested ASTM C 33 test criterion of 0.10% when the dosage of fly ash was in the range of 15% to 20% for cements with 0.50% and 1.00% equivalent Na_2O respectively. Accordingly, the 20% dosage rate was selected as sufficient to safely control expansion due to ASR in the test concretes.

Results for Concrete Containing Recycled Concrete as Coarse Aggregate*

Examples of results of recycling potentially reactive concrete into coarse aggregate for new concrete are shown in Figs. 3 through 5. Here, cumulative expansions for new concrete containing recycled concrete as coarse aggregate are plotted from the age and level of expansion at which recycling of the original concrete was done. For example, Fig. 3 (solid-dot graph line) shows that about 0.24% real expansion (0.32% original concrete expansion plus 0.24% new concrete expan-

* From this point onward, concretes made with cement containing 1.00% alkali as equivalent Na_2O will be referred to as high-alkali concrete. Those containing cement with 0.75% alkali will be referred to as medium-alkali concrete, and those made with cement with 0.50% alkali will be referred to as low-alkali concrete.

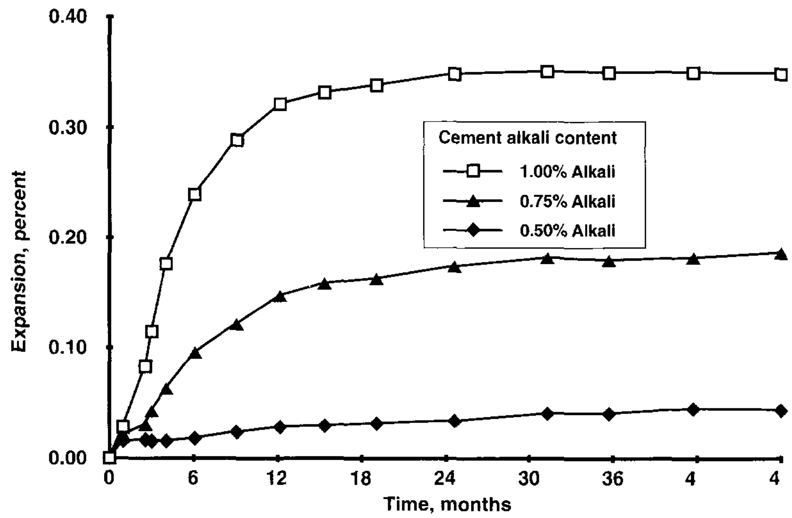

Fig. 1. Expansion of concrete containing unused aggregate and cements with different alkali contents. Tests were conducted under ASTM C227 storage conditions.

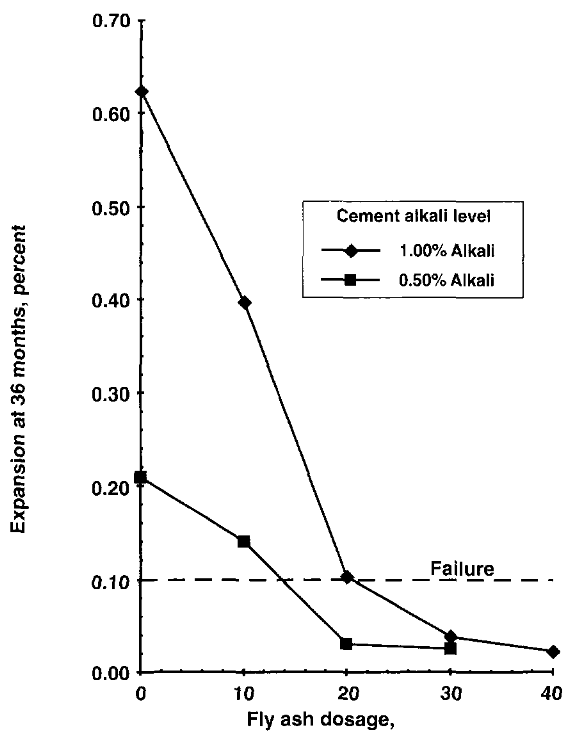

Fig. 2. Expansion of mortars containing different dosages of fly ash and cements with alkali contents 0.50% and 1.00%. Storage was under ASTM C227 test conditions.

sion equals 0.56% cumulative expansion) developed when high-alkali concrete was recycled at 15 months into new high-alkali concrete with no fly ash, even after no further expansion developed in the original concrete. The result indicates that ASR in the original concrete consumed sufficient alkali to virtually terminate further expansion, and that the introduction of additional alkali in the new high-alkali concrete reinitiated expansive ASR, despite much reduced quantities of potentially reactive material in the aggregate (only the coarse aggregate was reactive in the new concrete).

Fig. 4 illustrates the effects when low-alkali concrete is recycled into high-alkali concrete with no fly ash. In this case, little if any ASR occurred in the original concrete prior to recycling. Major expansion developed in the new concrete, probably as a result of the use of high-alkali cement in combination with only slightly reacted recycled aggregate from the original low-alkali concrete. Results in Fig. 5 indicate that a 20% dosage of fly ash in new high-alkali concrete, which contained recycled low-alkali concrete as coarse aggregate, reduced expansions to approximately 0.12%. This is greater than subsequent expansion of the original concrete made with low-alkali cement.

These three examples are illustrated in the above fashion to provide some indication of the nature of the test results. Comparisons for each test combination are more clearly seen in the following discussions where expansions are plotted from "zero" time and expansion level.

High-Alkali Concrete Recycled into High-Alkali Concrete With and Without Fly Ash

Fig. 6 presents results in which original high-alkali concrete was recycled into new high-alkali concrete without fly ash. In this combination, new concrete expansions were lower than those for the original concrete (0.35%) but still in the range of 0.10 to 0.25%, which is considered excessive. Among the three times of recycling, the lowest expansion developed for recycling of original concrete at two months. The other two ages, at about half and at maximum expansion, showed expansion levels that were greater than those for prisms with two-month recycled concrete. Reasons for this difference are not fully known, but it may be due, in part, to greater ASR after the first two months, with accompanying opening or cracking of reactive particles and subsequent penetration of new alkali pore solution into the recycled concrete. It also is possible that the additional alkali may alter existing ASR gel to render it more expansive in the new concrete. In any case, it appears that high-alkali cement should not be combined with previously reacted concrete recycled as coarse aggregate in new concrete, without the addition of a suitable fly ash.

When a 20% dosage of fly ash was used, maximum expansions reached only about 0.10%, as shown in Fig. 7. Expansions were reduced by about 75% to less than 0.10% for the new concrete containing original concrete recycled at about one-half and at maximum expansion. New high-alkali concrete containing original concrete recycled at two months expanded to about the same level as the new concrete made without fly ash. That is, the use of fly ash appeared to have no meaningful effect on reducing expansions in the new concrete when the original concrete was recycled at two months. This may reflect the relatively low margin for reduction of expansion given the short test time prior to recycling. Collectively, the results indicate that cement-fly ash hydration products effectively reduced alkali concentrations in the pore solutions, thereby effectively reducing expansions due to ASR.

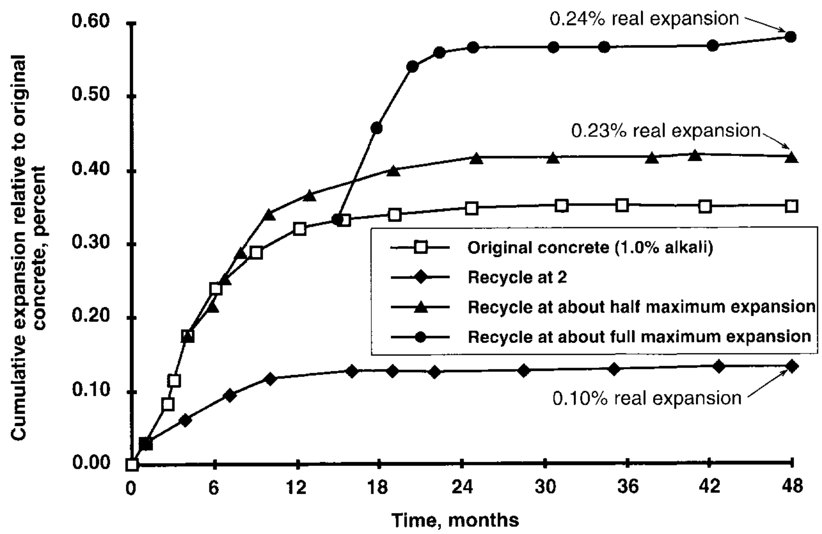

Fig. 3. Cumulative expansions for mixtures in which original high-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with no fly ash. Cumulative expansions for new concrete containing recycled concrete as coarse aggregate are plotted from the age and level of expansion at which recycling of original concrete was done. The old and new concrete expansion values are combined to provide a cumulative value. Time zero (actual) expansions are shown in Fig. 6.

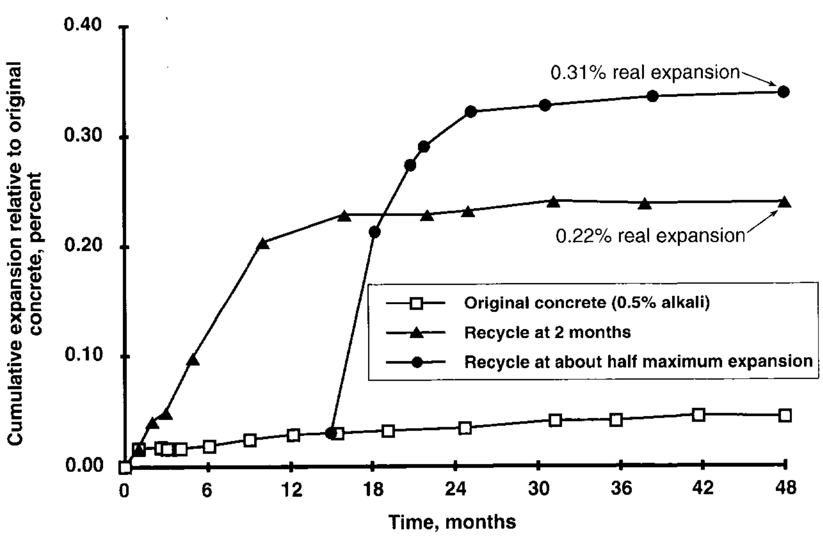

Fig. 4. Expansions for mixtures in which original low-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with no fly ash. Cumulative expansions for new concrete containing recycled concrete as coarse aggregate are plotted from the age and level of expansion at which recycling of original concrete was done. The old and new concrete expansion values are combined to provide a cumulative value. Time zero (actual) expansions are shown in Fig. 14.

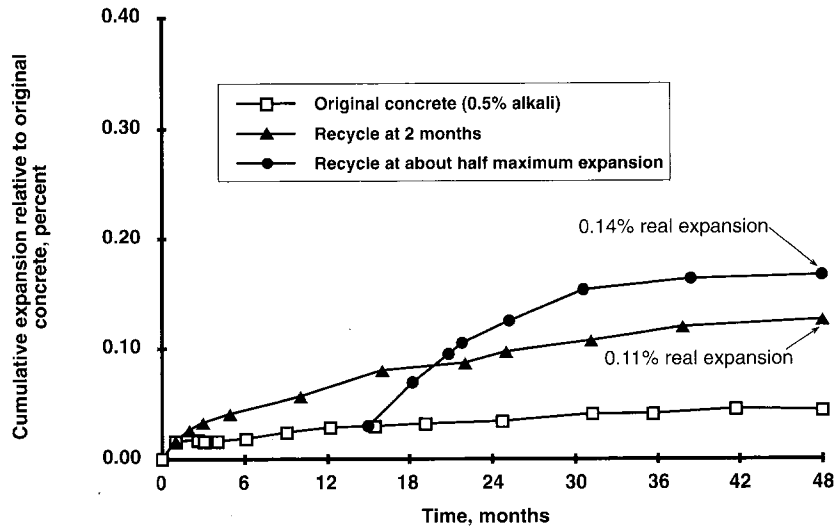

Fig. 5. Expansions for mixtures in which original low-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with fly ash. Cumulative expansions for new concrete containing recycled concrete as coarse aggregate are plotted from the age and level of expansion at which recycling of original concrete was done. The old and new concrete expansion values are combined to provide a cumulative value. Time zero (actual) expansions are shown in Fig. 15.

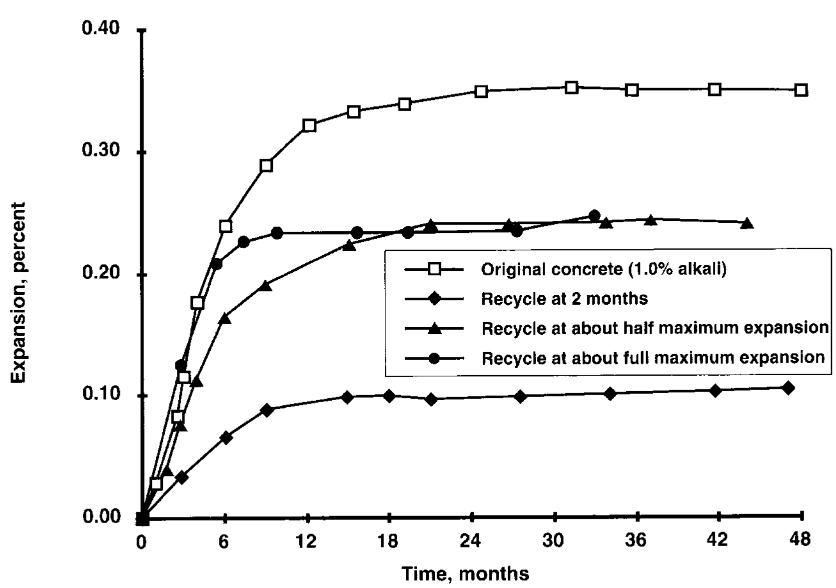

Fig. 6. Expansions for mixtures in which original high-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with no fly ash.

High-Alkali Concrete Recycled into Low-Alkali Concrete With and Without Fly Ash

Fig. 8 summarizes results for high-alkali concrete recycled into new low-alkali concrete without fly ash. In this series of tests, the low-alkali cement in the new concrete was effective in reducing expansions to safe levels (less than 0.10%) when recycling of the original concrete was done at about half and near maximum expansion. Recycling the original concrete at two months resulted in slightly greater expansions which, however, were still in the range of 0.10 to 0.15%. This is well below the 0.35% maximum expansion for the original concrete. The data thus indicate that the use of low-alkali cement greatly reduced expansion due to ASR when the original concrete that was recycled previously exhibited deleterious ASR. This reduction may as well be attributed to consumption of alkali in previous ASR in the original concrete.

Results for high-alkali concrete recycled into low-alkali concrete containing fly ash are shown in Fig. 9. Here expansions were reduced still further than those where low-alkali cement was used in new concrete without fly ash. When fly ash was used in the new concrete, expansions were reduced to less than 0.05%, regardless of the level of expansion previously reached in the original concrete.

Medium-Alkali Concrete Recycled into High-Alkali Concrete With and Without Fly Ash

Fig. 10 presents results for original medium-alkali (0.75% equivalent Na_2O) concrete recycled into new high-alkali concrete with no fly ash. Here expansions either approximately equaled or greatly exceeded expansions for the original concrete.

New concretes that exceeded expansions of the original concrete were those containing concrete recycled as aggregate at two months, and at about half the maximum expansion of the original concrete. Expansions were essentially the same for new high-alkali concrete containing concrete recycled at approximately maximum expansion of the original concrete. The greater expansions for the two new concretes containing concrete recycled as coarse aggregate at two months and about one-half the maximum expansion are possibly due to more alkali being available from the original concrete, in addition to that introduced in the new concrete.

Comparison of data in Fig. 11 indicates that all high-alkali concrete mixtures containing concrete recycled as coarse aggregate and made with fly ash produced expansions less than the original medium-alkali concrete, regardless of age or of level of expansion at which recycling was done. However, expansions of new concrete containing recycled concrete as coarse aggregate still were between 0.10% and 0.15%. This suggests that the fly ash in the new concrete greatly reduced expansions but not to safe levels, and that perhaps existing ASR gel in the recycled concrete continued to expand after pore solutions penetrated into the recycled concrete aggregate before fly ash in the new concrete could reduce the alkalinity of the pore solution in the new concrete to safe levels.

Medium-Alkali Concrete Recycled into Low-Alkali Concrete With and Without Fly Ash

Results for medium-alkali concrete recycled as coarse aggregate in new low-alkali concrete without and with fly ash are similar, as shown in Figs. 12 and 13, respectively. In most cases the alkalinity of the pore solutions was sufficiently low to prevent exces-

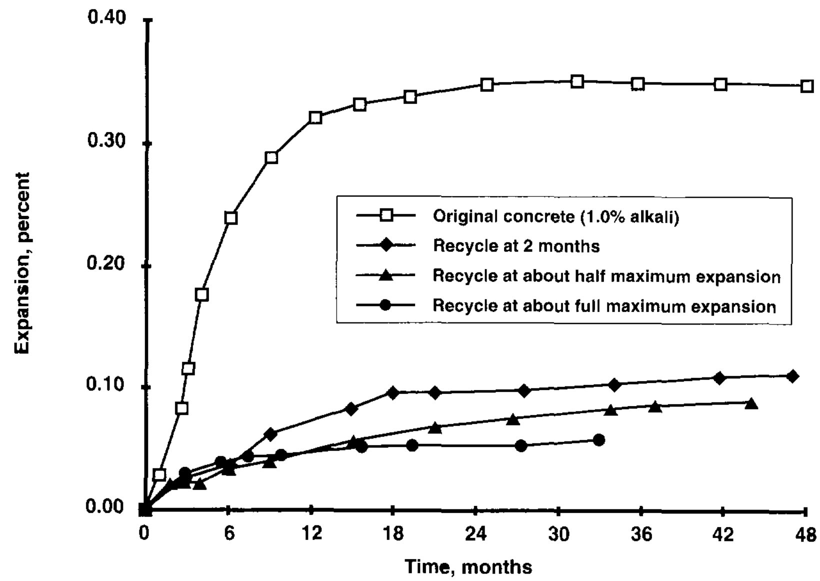

Fig. 7. Expansions for mixtures in which original high-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with fly ash.

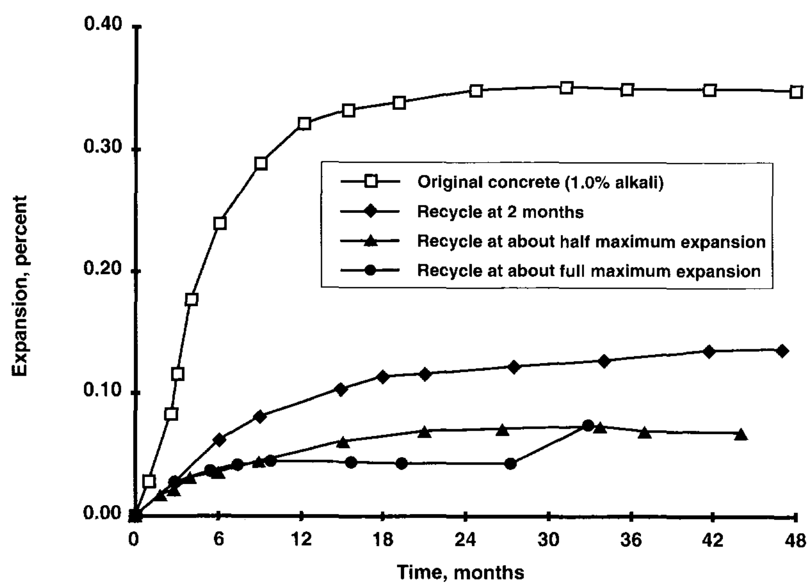

Fig. 8. Expansions for mixtures in which original high-alkali concrete was recycled as coarse aggregate in new low-alkali concrete with no fly ash.

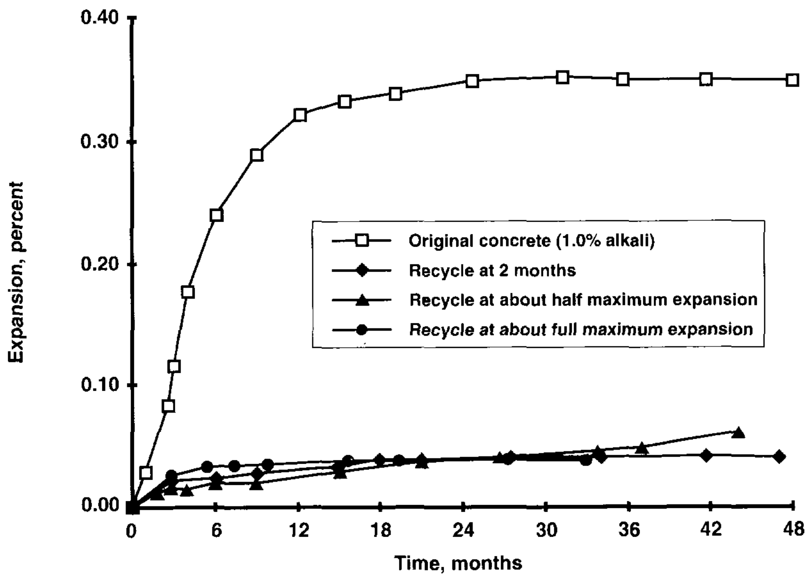

Fig. 9. Expansions for mixtures in which original high-alkali concrete was recycled as coarse aggregate in new low-alkali concrete with fly ash.

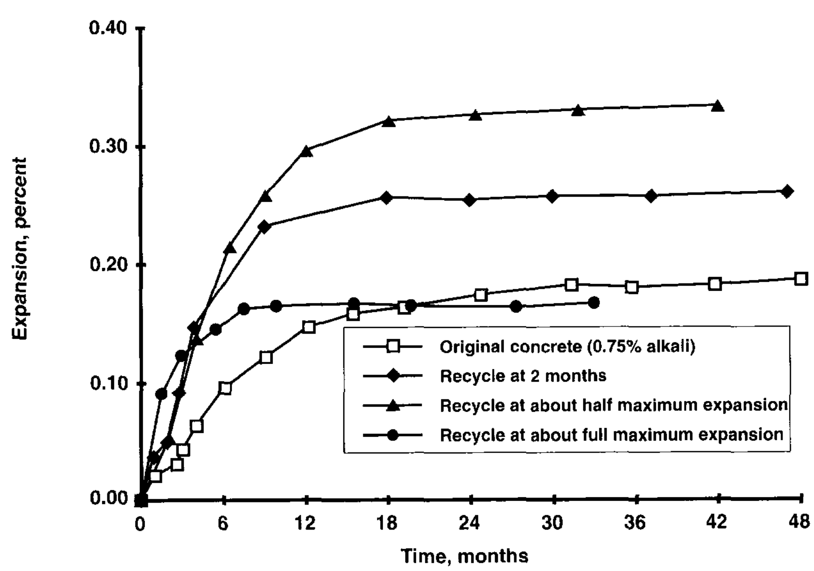

Fig. 10. Expansions for mixtures in which original medium-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with no fly ash.

sive expansions due to ASR, regardless of whether fly ash was used in mixtures containing recycled concrete as aggregate. Only in the mixtures containing concrete as aggregate recycled after reaching about half the maximum expansion of the original concrete did expansion of the new concrete approach or slightly exceed 0.10%. Reasons for these results are not readily apparent. However, in the other mixtures, alkalinity of the pore solutions apparently was sufficiently low to reduce expansions to well below the 0.10% to 0.20% expansion for the original concrete made with the medium-alkali cement.

Low-Alkali Concrete Recycled as Coarse Aggregate into High-Alkali Concrete With and Without Fly Ash

Results for low-alkali concrete recycled as coarse aggregate in new high-alkali concrete with no fly ash are shown in Fig. 14. Here, expansions for the new concrete greatly exceeded those for the original concrete when recycled at either two months or after reaching about one-half the maximum expansion of the original concrete (recycling at about maximum expansion was not done for original low-alkali concrete because of its extremely low rate of expansion and consequent delay in further testing). In these cases, expansions for the original concrete were less than about 0.05% which is well below the 0.10% test criterion, and reflects the innocuous behavior of this cement-aggregate combination. However, after recycling into new high-alkali concrete, expansions of the new concrete reached about five to eight times the expansion of the original concrete. This indicates that the higher alkalinity of the pore solution of the new concrete initiated deleterious ASR involving the recycled aggregate, even though the original concrete failed to exhibit evidence of excessive expansion. This result implies that concrete should not be recycled as aggregate unless petrographic examination reveals that ASR has not developed to any degree and that the concrete does not contain aggregate that may be potentially deleteriously reactive.

When fly ash was used in the new high-alkali concrete, expansions were reduced compared to the mixture made with no fly ash, as shown in Fig. 15. However, expansions still reached several times that for the original concrete and also were somewhat greater than the 0.10% test criterion. This indicates that the fly ash was only marginally, or not at all, able to safely control ASR, in this case, when no deleterious ASR had developed in the original low-alkali concrete.

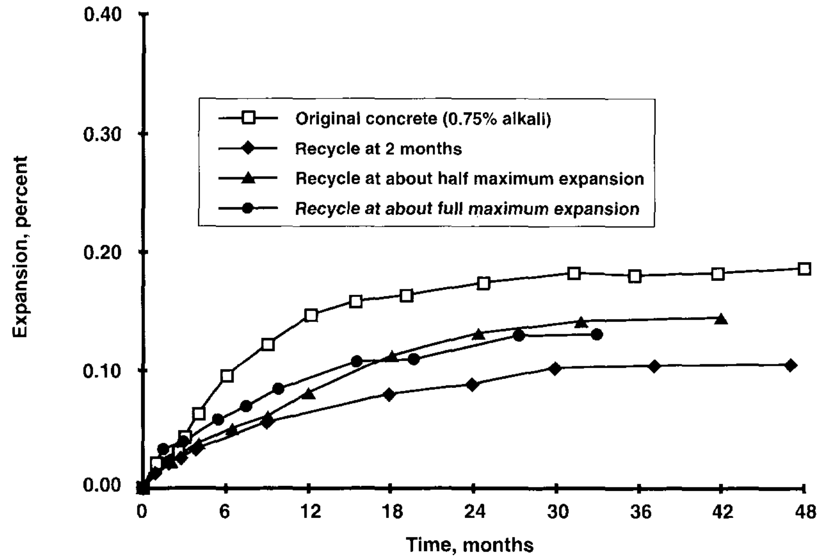

Fig. 11. Expansions for mixtures in which original medium-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with fly ash.

Low-Alkali Concrete Recycled as Coarse Aggregate into Low-Alkali Concrete With and Without Fly Ash

Results shown in Fig. 16 indicate similar or somewhat greater expansions than the original low-alkali concrete when it is recycled as coarse aggregate into new low-alkali concrete. In this case, expansion for new concrete reached about 0.10% when recycling at approximately one-half the maximum expansion of the original concrete. Recycling at two months resulted in expansions of only 0.05%, which is equivalent to that for the original low-alkali concrete. The difference between expansion levels for these two new concretes is not considered significant since neither exceeds the 0.10% expansion criterion.

Fig. 17 summarizes results for low-alkali concrete recycled as coarse aggregate in new low-alkali concrete made with fly ash. Here, expansions for both original and new concrete were similar regardless of whether the original concrete was recycled at

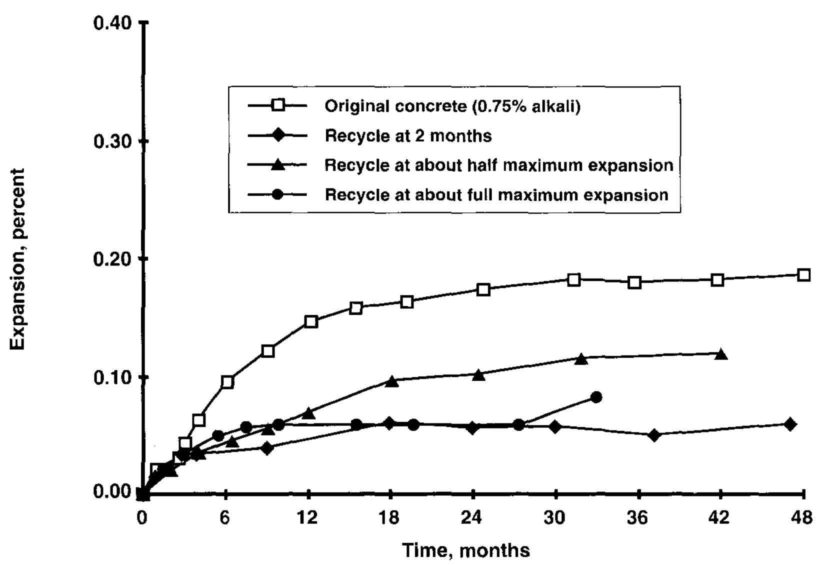

Fig. 12. Expansions for mixtures in which original medium-alkali concrete was recycled as coarse aggregate in new low-alkali concrete with no fly ash.

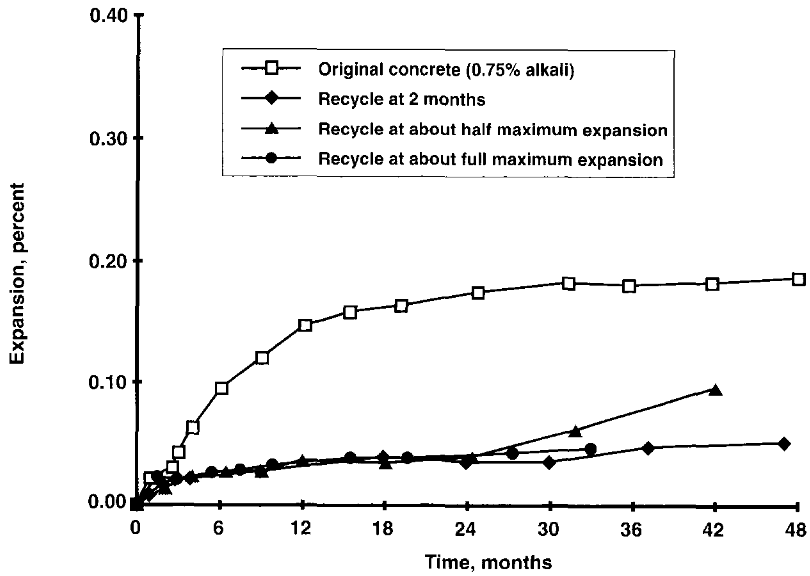

Fig. 13. Expansions for mixtures in which original medium-alkali concrete was recycled as coarse aggregate in new low-alkali concrete with fly ash.

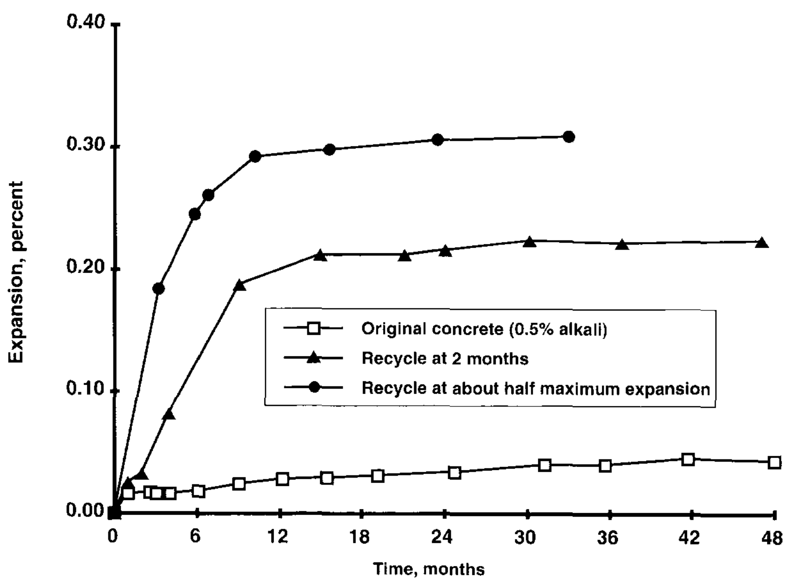

Fig. 14. Expansions for mixtures in which original low-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with no fly ash.

two months or at about one-half the maximum expansion, which was taken to have developed at the age of 15 months of the original concrete. Thus, the use of both control measures, fly ash and low-alkali cement, was effective in controlling ASR expansion in the concrete mixture containing recycled concrete as coarse aggregate. However, the difference in performance between new concretes made with low-alkali cement, with and without fly ash, appears to be negligible and of little or no significance.

PAVEMENT PERFORMANCE

Several pavements are currently in service in the United States in which concrete previously exhibiting ASR was recycled as coarse and fine aggregate for new pavement. One of these pavements, located in Wyoming, has been inspected in the field, and cores taken from the pavement have been examined petrographically for possible evidence of ASR associated with the recycled concrete aggregate.

The original concrete pavement was built in the 1970's under a specification calling for the use of ASTM low-alkali cement with no mineral admixtures. By 1976, pavement inspection and petrographic examination of concrete cores confirmed the development of ASR. Several sources of aggregate were used along this length of pavement, and the severity of distress attributed to ASR appeared to vary with the source. The primary reactive constituent in each of the aggregate sources was weathered poorly crystalline volcanic rock of rhyolitic to andesitic composition, the proportions of which ranged between approximately 5 to 10% of the aggregate. By the mid-1980's, distress from ASR as well as from traffic required that the pavement be replaced. Accordingly, between 1985 and 1988, various sections of the original concrete were replaced with new concrete containing low-alkali cement (0.5 to 0.6% alkali as equivalent Na_2O), and ASTM Class F fly ash used as a 20% mass replacement for cement. Coarse aggregate consisted of about two-thirds recycled concrete and one-third unused limestone. Fine aggregate contained approximately 25 to 30% recycled concrete and unused sand of the same general type that exhibited ASR in the original concrete. Pavement thickness was 305 mm (12 in.) with skewed joints at random spacings less than 6.1 m (20 ft).

A pavement inspection was conducted in mid-1993, and cores were taken at that time for petrographic examination. The following observations were made:

1) 1985 concrete - The wearing surface displayed no evidence of cracking typically associated with ASR. Examination of cores revealed no evidence of ASR-related distress that may have developed in the new concrete.
2) 1987 concrete - This section of pavement displayed short, tight, longitudinal cracks along transverse joints, and very faint map cracking in mid-panel areas. Occasional transverse cracks also occur at mid-panel locations. Cores revealed no evidence of ASR that may have formed in the new pavement concrete. A few microcracks observed in coarse limestone particles extended into surrounding mortar. Several films of glassy ASR gel partially lined a few entrapped air voids. Surface cracks that were observed in the field inspection extended only to depths of about 12 to 30 mm (1/2 to 1-1/4 in.).
3) 1988 concrete - No abnormal cracking was observed at the wearing surface during the field inspection. Also, petrographic examination of cores revealed no abnormal microcracking nor ASR gel.

In summary, after six to nine years of service, only very limited evidence

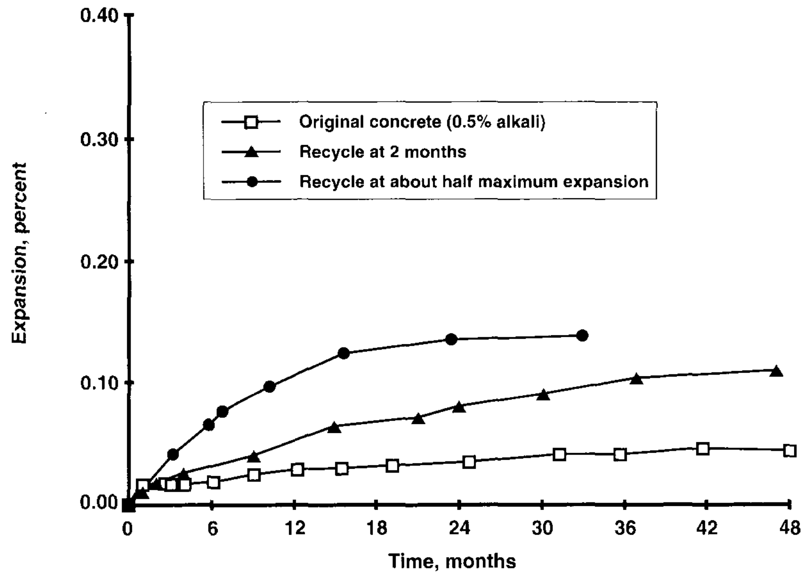

Fig. 15. Expansions for mixtures in which original low-alkali concrete was recycled as coarse aggregate in new high-alkali concrete with fly ash.

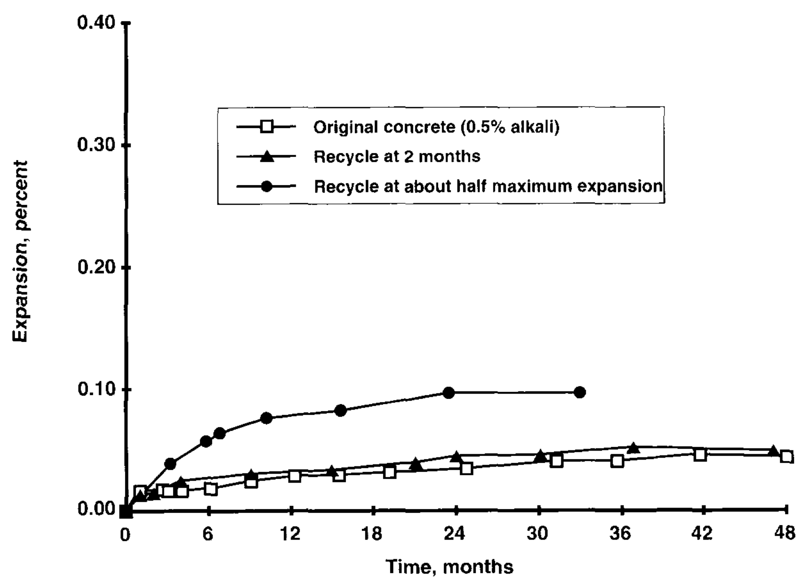

Fig. 16. Expansions for mixtures in which original low-alkali concrete was recycled as coarse aggregate in new low-alkali concrete with no fly ash.

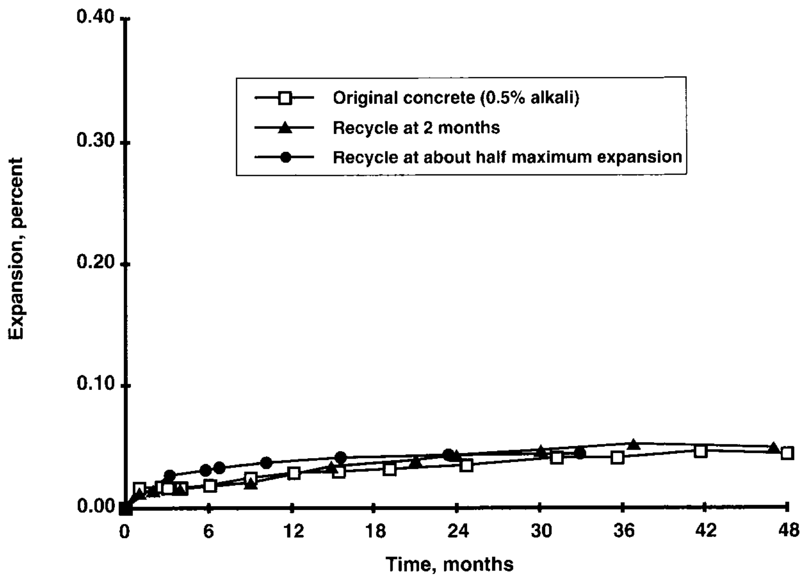

Fig. 17. Expansions for mixtures in which original low-alkali concrete was recycled as coarse aggregate in new low-alkali concrete with fly ash.

of ASR was found that might have developed in the new concrete containing ASR-affected recycled concrete as aggregate . Thus far, this finding substantiates the laboratory finding of apparent elimination of expansive ASR when low-alkali cement with a 20% dosage of low lime fly ash is used.

DISCUSSION

This investigation concerned the development of expansive ASR in original concrete that was later recycled as coarse aggregate, and precautions required to prevent its development when used in new concrete. Original concretes made with unused but potentially reactive aggregate and cements with alkali contents of 0.50, 0.75, or 1.00% equivalent Na_2O were processed and used as recycled coarse aggregate in new concrete containing cements with 0.50 or 1.00% equivalent Na_2O, both with and without fly ash. The original concrete was recycled at an age of two months and at ages of about one-half and near maximum expansions.

Results indicate that recycled concrete used as coarse aggregate retained potential for continued ASR, and that resulting expansion depends on the alkali content of the cement in the new concrete and the presence of fly ash. It appeared that the factor limiting expansion in the original concrete was the availability of alkali (hydroxyl ion concentration) in the pore solution, and that the reintroduction of alkali from cement used in making the new concrete reinitiated expansive ASR. This is best illustrated in Figs. 3 and 4, where major expansion developed in the new concrete with the use of cement with 1.00% equivalent alkali after further expansion essentially ceased when high-alkali cement was used in the original concrete. Also, essentially no expansion developed when low-alkali cement was used in the original concrete. These results appear to indicate that unreacted but potentially reactive aggregate still remained in the original concrete at the time of recycling.

In the time frame of this investigation, the maximum level of expansion reached in the original concrete depended on the alkali content of the cement as would be expected. Expansions reached in the new concrete made with recycled concrete as coarse aggregate but without fly ash also depended to a major extent on the alkali content of the cement, regardless of the alkali content of the cement in the original concrete. Again, this finding, as expected, provided evidence that significant amounts of unreacted but potentially reactive natural aggregate remained in the recycled concrete. In this respect it also is possible that some reaction between alkalies introduced in the new concrete may have reacted with preexisting ASR gel to increase expansions. This was not investigated in this study.

Among the new concretes made without fly ash, only those containing low-alkali recycled concrete as aggregate and made with low-alkali cement met the 0.10% maximum expansion criterion used in these tests. All other new concretes made without fly ash exceeded this criterion to varying degrees, generally, by increasing amounts as cement alkali level increased in the new concrete. The important point from this finding is that even though original concrete in a field structure such as pavement might not exhibit ASR at the time of recycling, it still could produce excessive expansions due to ASR in new concrete containing the recycled concrete as aggregate if special precautions are not taken to prevent the reaction. In this respect, petrographic examination of the original concrete should be done to determine if potential for ASR exists in the new concrete prior to recycling.

Using fly ash in new concrete containing recycled concrete as coarse aggregate reduced expansions in all cases compared with companion mixtures without fly ash. As expected, the largest reductions occurred for new high-alkali concretes, regardless of the alkali content of the cements in the original concrete. In most cases where high-alkali cement was used with fly ash in the new concrete, expansions were reduced to below or only slightly above (up to about 0.15%

expansion) the test criterion of 0.10%. Where low-alkali cement was used with fly ash in the new concrete, expansions in all cases were reduced to, or well below, the 0.10% criterion. Thus, the use of certain fly ashes with low- or high-alkali cement appeared to be the surest way to reduce to safe levels expansions of new concrete containing recycled concrete as aggregate. The exact reasons why the fly ash was unable to reduce expansions of all mixtures of new concretes are uncertain, but it may be related to the fact that the recycled concrete aggregate was produced and introduced into the new mixture without washing. This would allow the relatively highly alkaline solution of the new fresh concrete to be absorbed more readily by the recycled aggregate before appreciable reaction of the fly ash. This would temporarily establish a condition similar to that if the fly ash had not been included as a component of the new concrete mixture.

Observations of the Wyoming pavement that contain ASR-affected recycled concrete as aggregate thus far agrees with the laboratory findings. That is, the combination of low-alkali cement plus fly ash has successfully controlled deleterious ASR in recycled concrete used as aggregate in new concrete. Whether low- (< 0.60%) alkali cement would have been required in the pavement is not known since high-alkali cements were not used. The only occasional appearance of very faint, short longitudinal cracks at transverse joints is suggestive of very limited ASR, thus endorsing the use of fly ash in the pavement.

CONCLUSIONS

Based on observations in this investigation, using highly reactive aggregate, the following conclusions are drawn:

1. Recycled concrete used as coarse aggregate in new concrete possesses potential for ASR in the new concrete if the original concrete contained aggregate that was susceptible to ASR.
2. The alkali content of the cement in the original concrete where expansion due to ASR developed had little bearing on expansions due to ASR in new concrete containing the original concrete as recycled coarse aggregate.
3. The alkali content of the cement in the new concrete containing recycled concrete as coarse aggregate had a significant effect on subsequent expansions due to ASR. However, the use of low-alkali cement without fly ash did not always reduce expansions due to ASR to safe levels.
4. The use of a low-lime ASTM Class F fly ash in new concrete containing recycled concrete as coarse aggregate greatly reduced expansions due to ASR in the new concrete. However, to bring expansions to less than the test criterion, without exception, also required the use of low-alkali cement with the fly ash. It is not certain whether such stringent methods would be required for other, less reactive, recycled concretes used as coarse aggregate.
5. The pavement engineer should not assume that, because expansive ASR did not develop in original concrete to be recycled as aggregate, it will not develop in the new concrete. Petrographic examination of the original concrete is recommended in this judgment.

ACKNOWLEDGMENT

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REFERENCES

1. Bhatty, M.S.Y., "Mechanisms of Pozzolanic Reactions and Control of Alkali-Aggregate Expansion," *Cement, Concrete and Aggregates*, Vol. 7, No. 2, American Society for Testing and Materials, West Conshohocken, Pennsylvania, pp. 69-77, 1985.

Metric Conversion Table

Following are metric conversions of the measurements used in this text. They are based in most cases on the International System of Units (SI).

1 in.	= 25.40 mm
1 sq in.	= 645.16 mm^2
1 ft	= 0.3048 m
1 sq ft	= 0.0929 m^2
1 sq ft per gallon	= 0.0245 m^2/L
1 gal	= 3.785 L
1 kip = 1000 lbf	= 4.448 kN
1 lb	= 0.4536 kg
1 lb per cubic yard	= 0.5933 kg/m^3
1 psf	= 4.882 kg/m^2
1 psi	= 0.006895 MPa
No. 4 sieve	= 4.75 mm
No. 200 sieve	= 75 mm
1 bag of cement (U.S.)	= 94 lb = 42.6 kg
1 bag of cement (Canadian)	= 88 lb = 40 kg
1 bag per cubic yard (U.S.)	= 55.8 kg/m^3
deg. C	= (deg. F - 32)/1.8

PALABRAS CLAVE: agregados, reactividad álcali-sílice, nivel alcalíno del cemento, concreto, expansión, ceniza volante, pavimento, concreto reciclado

SINOPSIS: Se realizó una investigación acerca de las precauciones que son necesarias para evitar la expansión de la reactividad álcali-sílice (RAS) en los concretos en los cuales se utiliza agregado grueso reciclado que previamente ha sido afectado por dicha reacción. Cementos con niveles de álcali de 0.50%, 0.75%, y 1.00% de Na_2O equivalente, se utilizaron con agregados gruesos y finos altamente reactivos para la fabricación de concretos que posteriormente fueron reciclados a edades de dos meses, y cuyas expansiones se aproximaron a un medio de la máxima expansión y muy cerca de la misma. Concretos nuevos fueron fabricados utilizando concreto recliclado como agregado grueso, agregados finos innocuos, cementos con contenido alcalino de 0.50% y 1.00%, y con o sin la utilización de ceniza volante. En todos los casos los ensayes se realizaron almacenando los especímenes dentro de recipientes con agua sellados y mantenidos a una temperatura de 38° C (100° F). Los resultados indicaron que expansiones excesivas debidas a la RAS pueden desarrolarse en el concreto nuevo conteniendo concreto reciclado; particularmente, cuando cemento de bajo contenido alcalíno fue utilizado en el concreto original y cemento de alto contenido alcalíno fue utilizado en el concreto nuevo. La substitución de cemento, en un 20% en masa, por ceniza volante ASTM-Clase F con bajo contenido de limo, redujo la expansión a niveles adecuados de seguridad en el mayor numero de los casos. Observaciones de pavimentos de concreto indicaron que la utilización de ceniza volante en el agregado de la mezcla de concreto, puede controlar exitosamente el potencial de la RAS en aquellos concretos reciclados que previamente han sido afectados por dicha reacción.

REFERENCIA: Stark, David, *The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity*, Research and Development Bulletin RD114, Portland Cement Association, [*El uso de agregado de concreto reciclado proveniente de concreto que exhibe actividad álcali-sílice*, Boletín de Investigación y Desarrollo RD114, Asociación de Cemento Portland], Skokie, Illlinois, U.S.A., 1996.

STICHWÖRTER: Zuschlagstoff, Alkali-Kieselsäure-Reaktion, Alkaligehalt von Zement, Beton, Treiben, Flugasche, Gehweg, wiederverwerteter Beton

AUSZUG: Eine Untersuchung wurde durchgeführt, um festzustellen, welche Vorsichtsmaßnahmen getroffen werden müssen, um die treibende Alkali-Kieselsäure-Reaktion (AKR) zu verhindern, wenn AKR-beinflußter Beton als grober Zuschlagsstoff bei neuem Beton wiederverwertet wird. Verwendet wurden Zemente mit Alkaligehalten von 0.50%, 0.75%, und 1.00% Na_2O äquivalent mit hochreaktiven feinen und groben Zuschlagsstoffen in wiederverwerteten Ursprungsbetonen, die im Alter von 2 Monaten und bei ca. 50% maximalem Treiben und bei fast maximalem Treiben wiederverwendet wurden. Neue Betone mit wiederverwertetem Beton als groben Zuschlagstoff wurden mit nichtreaktivem feinen Zuschlagstoff und Zementen mit 0.50% oder 1.00% Alkaligehalt sowie mit und ohne Flugasche hergestellt. Lagerung für alle Fälle war über Wasser in geschlossenen Behältern bei 38 °C. Die Ergebnisse zeigten, daß übermäßiges Treiben wegen AKR in den neuen Betonen mit dem wiederverwerteten Beton stattfinden kann, besonders wenn Zement mit niedrigem Alkaligehalt im Originalbeton und Zement mit hohem Alkaligehalt im neuen Beton benutzt wird. ASTM Klasse F Flugasche mit niedrigem Kalziumgehalt als Ersatz für 20 Gew.-% Zement hat das Treiben fast immer auf ein sicheres Minimum reduziert. Beobachtungen an Betongehwegen deuten darauf hin, daß AKR erfolgreich unter Kontrolle gebracht werden kann bei AKR-beinflußtem Beton, der als Zuschlagstoff wiederverwertet wird, wenn Flugasche in der Zementmischung mitverwendet wird.

REFERENZ: Stark, David, *The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkai-Silica Reactivity*, Research and Development Bulletin RD114, Portland Cement Association, [*Gebrauch von wiederverwertetem Beton, der Alkali-Kieselsäure-Reaktion zeigt*, als Zuschlagstoff Forschungs-und Entnicklungsbulletin RD114, Portlandzementverband], Skokie, Illinois, U.S.A., 1996.

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