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The Impact of Expansion due to Alkali-Carbonate Reaction on Engineering Properties of Concrete

Ramy Z. Radwan[1], Medhat H. Shehata[2], Gamal E. Abdelaziz[3], M. Osama R. El Hariri[3], Assem M.K. Abdelalim[4]
1 Visiting PhD. Student, Department of Civil Engineering, Ryerson University, Toronto, Ontario, Canada.
2 Associate Professor, Department of Civil Engineering, Ryerson University, Toronto, Ontario, Canada.
3 Associate Professor, Shoubra Faculty of Engineering, Banha University, Egypt.
4 Professor, Shoubra Faculty of Engineering, Banha University, Egypt.

Abstract: This paper investigates the effects of different levels of expansion resulting from alkali-carbonate reaction (ACR) on mechanical properties of concrete at different ages. Concrete prisms and companion cylinders were cast with three aggregates that are non-reactive, marginally-reactive and highly-reactive, and cured under the same conditions. The concrete prisms showed 1-year expansion values of 0.021 %, 0.042 % and 0.271 % for the non-reactive, marginally-reactive and highly-reactive aggregates, respectively. In general, the results showed a reduction in mechanical strengths of concrete with increasing the expansion. However, the mechanical properties and permeability of concrete made with non-reactive and marginally-reactive aggregates were very close. It was concluded that up to 1 year of accelerated testing at 38°C, or up to an expansion value of about 0.04 %, the mechanical performance of concrete made with marginally carbonate reactive aggregates is not adversely affected.

1. Introduction

Alkali-aggregate reactions (AAR) are chemical reactions that may occur between alkalis available in the pore solution of concrete and certain types of aggregate. Sources of alkalis in concrete pore solution include Portland cement, some types of supplementary cementing materials (SCMs), aggregates, or external sources such as de-icing salts, sea water or ground water, The reaction depends on many factors such as alkali content of the cement, the moisture content of concrete, and the potential reactivity of the aggregate. There are two main types of AAR, namely, alkali-carbonate reaction (ACR), and alkali-silica reaction (ASR). Although both reactions have different characteristics and reaction mechanisms, they both lead to expansion and cracking of concrete. AAR may not be the main cause of concrete deterioration in many concrete structures but it may promote other forms of deteriorations such as freezing-thawing, sulphate attack, and reinforcement corrosion through opening the required pathways for aggressive substances to enter concrete and causes deterioration.

Using non-reactive aggregate is considered the best preventive measure against AAR occurring in concrete (Bèrubè et al. 2000, Bragg 2000, Fournier and Bèrubè 2000, Rogers el al. 2000). However, this is not often possible or economical when the non-reactive aggregate source is far from the construction site. In such cases, other mitigating measures are required. Low-alkali cement (LAC), if available, is usually effective in reducing expansions due to ASR (Fournier and Bèrubè 2000, Rogers et al. 2000) however it was found inefficient in controlling expansion due to ACR (Swenson and Gillott 1964, Rogers and Hooton 1992). Stanton's work in 1940 demonstrated that the deleterious reaction due to ASR could be prevented by incorporating LAC which was defined as cement with Na_2O_e< 0.6 %, or by using pozzolans in the mixture (Buck et al. 1953, Fournier and Bèrubè 2000).

Adequate selection of supplementary cementing materials (SCM) such as silica fume, fly ash, and slag can be used also to minimize or sometimes prevent excessive expansions produced by ASR (Swamy and Al-Asali 1990, Fournier and Bèrubè 2000, Rogers et al. 2000). There are many factors that affect the efficacy of SCMs in preventing the damaging reaction due to ASR such as, the quantity of SCM, its chemical composition, the nature and level of reactivity of aggregate and the alkali content of the Portland cement. Shehata and Thomas (2000) found that the amount of fly ash necessary to prevent expansion due to ASR depends on the chemistry of fly ash; low calcium fly ash was the most effective type in mitigating the expansion. On the other hand, there is a general agreement between researchers that there is no preventive measure against expansion due to ACR. Indeed, LAC was not sufficient to prevent the expansion of the highly-reactive carbonate rock from Kingston, Canada (Swenson and Gillott 1960, 1964, Rogers et al. 2000). Blast-furnace slag cement is also not effective in controlling expansion due to ACR (Gifford and Gillott 1996). While it has been found effective in reducing ASR-induced expansion, slag was found to increase expansion due to ACR (Rogers and Hooton 1992, Thomas and Innis 1998).

Since ASR and ACR were first reported by Stanton in 1940 and Swenson in 1957, respectively, most of the research in the area of AAR has been directed to understand the reactions mechanisms and propose mitigating measures to reduce the expansion. Although some research works have been carried out to study the effects of ASR on the various engineering properties of concrete, very limited published data was found on the effect of ACR on the properties of concrete containing marginally or highly-carbonate reactive aggregates. Although alkali-carbonate reactive aggregates are not usually used in concrete, aggregates that marginally meet the expansion criterion are allowed to be used in many parts of the world. Knowing that the identification of the marginal reactivity of such aggregates is not simple (Grattan-Bellew 1997), it is reasonable to assume that such aggregates are used in concrete.

The objective of this paper is to study the impact of ACR-induced expansion on various engineering properties (such as strength and permeability) of concrete with marginally-reactive or highly-reactive carbonate aggregates for up to 1 year. The use of fly ash or low-alkali cement as mitigation measures to suppress expansion of marginally-carbonate reactive aggregates is also studied.

2. Materials and Test Methods

Three coarse aggregates were tested in this study representing a range of composition and reactivity. The origin, rock type and petrographic number of the aggregates are summarized in Table 1. Non-reactive sand from Sunderland (Oak Ridge's moraine deposit) was used in all concrete samples. A CSA Type GU (ASTM Type I) high-alkali cement and ASTM Type I low-alkali cement were used. Fly ash (Type CI, as per CSA) at 25 % replacement level was also utilized as a preventive measure for AAR. The chemical analysis of cements and fly ash is summarized in Table 2.

Table 1: Origin and rock type of the various aggregates investigated in this study.

No.	Aggregate Identification	Origin	Rock Type, ASTM C294	Petrographic No.
1	PITTS	Canada	Argillaceous dolomitic limestone	127
2	Non-R	Canada	Dolomite	115
3	KM101	Egypt	Calcitic dolomite	241

Concrete prisms incorporating the different coarse aggregates were prepared according to CSA A23.2-14A test procedure. For mixes made with low-alkali cement, no NaOH was added to the mixture. For mixes containing SCM, a replacement level of 25 % fly ash and w/c ratio of 0.4 were used and the alkali content of the Portland cement was raised to 1.25 % Na_2O_e, as specified by CSA A23.2-28A. All concrete specimens used throughout this investigation were stored in the same conditions (above water in sealed plastic buckets at 38°C) except the control specimens that were kept in the fog room until testing at 28 days. A concrete mix with coarse aggregate that consists of 10 % Pittsburg (highly reactive aggregate) + 90 % non-reactive aggregate, was used to represent marginally reactive aggregate. The 1-year concrete expansion of this mix was 0.042 %, as will be shown later in this paper.

Table 2: Chemical composition of cements and fly ash.

Oxide	HAPC[1]	LAPC[2]	Fly Ash
Silicon Dioxide, SiO_2	19.52	20.12	53.10
Aluminum Oxide, Al_2O_3	5.31	4.43	21.39
Iron Oxide, Fe_2O_3	2.24	2.80	7.56
Sulfur Trioxide, SO_3	4.30	3.60	0.50
Calcium Oxide, CaO	62.73	62.41	10.46
Sodium Oxide, Na_2O	0.19	0.27	0.59
Magnesium Oxide, MgO	2.57	3.01	2.85
Potassium Oxide, K_2O	1.14	0.44	1.39
Phosphorus Pentoxide, P_2O_5	0.12	0.13	0.07
Titanium Dioxide, TiO_2	0.27	0.23	1.30
Manganese Oxide, Mn_2O_3	0.07	0.13	n/a
Na_2O_e, (Equivalent sodium oxide)[3]	0.94	0.56	1.50

[1] CSA Type GU (ASTM Type I), High-alkali cement.
[2] ASTM Type I, Low-alkali cement.
[3] Acid soluble alkali (Na_2O + 0.658 K_2O).

The compressive and splitting tensile strengths were measured according to ASTM C39 and ASTM C496, respectively using 100 x 200 mm concrete cylinders. At the age of testing, three samples were tested from each mix using a compression machine with a maximum load of 2000 KN. Pull-out test was employed to measure the bond strength between concrete and reinforcing steel. Concrete cylinders of 100 mm diameter by 200 mm length were prepared with a single steel bar protruding at one end only. The bar has a diameter of 20 mm and is embedded in the concrete cylinder to a length of 120 mm. To maintain vertical position of the bar during casting, a wooden piece with a centered hole of 21 mm in diameter was quickly mounted on the cylinder after casting, and the bar was hammered to the required depth. At the testing age, the specimens were placed under a large thick steel plate, rested on four concrete cylinders and with a central 28 mm-diameter hole where the rebar embedded in the test cylinder was passed through. An oil jack with a central hole large enough to capture the steel bar was placed over the steel plate followed by a load cell with a load capacity of 500 KN. Another steel plate was put over the load cell and the steel bar end was embraced with suitable grips. The load was applied gradually using a manual hydraulic pump attached to the hydraulic oil jack. The load was pushing against the two steel plates forcing the grips (and the rebar) to move away from the test cylinder. The load cell was attached to a data logger, where the load was finally recorded at preset intervals. The ion penetrability was evaluated using Rapid Chloride Permeability Test (RCPT) as per ASTM C1202 and Rapid Migration Test as per Nordtest NT Build 492 on concrete cylinders of 100 mm diameter. The average of four specimens was calculated and reported for each test.

3. Test Results

3.1 Expansions of Concrete Prism Test

The alkali-reactivity of the aggregates used in the various concrete mixes was evaluated using the concrete prism test (CPT), and the results are shown in Figure 1. The highly-reactive carbonate aggregate from Kingston showed 1-year expansion of 0.271 %. Both Concrete prisms made with marginally-reactive aggregates KM101 and 10% PITTS, produced expansions of 0.042 % after 1 year. The non-reactive aggregate mixes produced 1-year expansion of 0.021 %. The concrete with 10% PITTS was used to represent concrete with marginally reactive aggregate as the required quantity the aggregate KM101 was not available at the time of conducting this research.

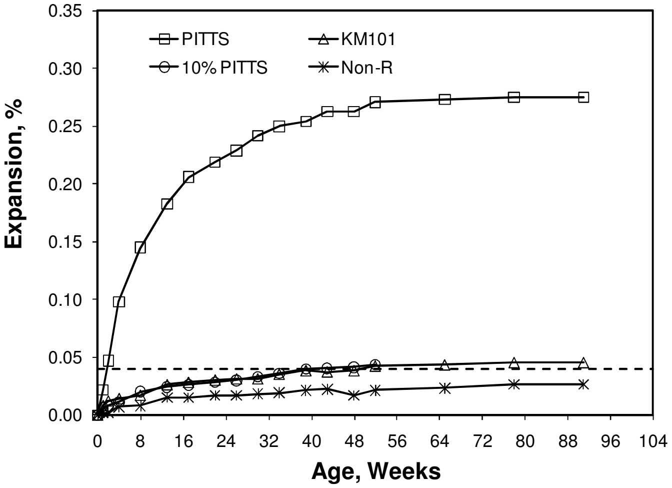

Figure1. Expansion of concrete prisms containing aggregates of different alkali-reactivity.

3.2 Impact of ACR-Induced Expansion on the Mechanical Properties of Concrete

The various engineering properties of concrete mixes made with reactive, marginally-reactive, and non-reactive aggregates were measured using concrete cylinders stored over water in sealed buckets at 38°C for up to 1 year. The control results represent 28 days of standard curing at 23°C in a curing chamber (fog room) at 100% RH. The test results are summarized in Table 3.

Table 3: Engineering properties of concrete with reactive, marginally-reactive and non-reactive aggregate.

Test	Mix	Control	Age of curing at 38°C, weeks		
		4 weeks*	13	26	52
Compressive strength, MPa	PITTS	34.51	30.68	30.10	32.91
	10%PITTS	33.02	41.50	44.32	48.61
	Non-R	35.53	35.53	47.85	50.68
Splitting tensile strength, MPa	PITTS	5.69	4.96	3.57	4.14
	10%PITTS	5.52	6.06	6.34	6.36
	Non-R	6.28	6.25	7.18	5.79
Bond strength, MPa	PITTS	1.66	1.51	1.66	1.68
	10%PITTS	1.75	2.13	1.88	2.25
	Non-R	1.73	2.08	2.07	2.23
Total charge passed, Coulombs (RCPT)	PITTS	5249	5900	3442	2822
	10%PITTS	5051	2378	1769	1272
	Non-R	5079	4343	1815	1289
NSSM Coefficient, x10^{-12} m^2/sec	PITTS	15.36	12.28	11.13	10.75
	10%PITTS	14.69	8.42	7.54	6.49
	Non-R	14.85	8.85	7.41	6.72

*: Samples were cured in a standard curing room at 23 ºC and 100% relative humidity for 28 days

As listed in Table 1, the 1-year compressive strength of concrete containing the reactive-carbonate aggregate Pittsburg was much lower than that of concrete with non-reactive aggregate at the same age. The difference in strengths between the two concretes was smaller at earlier ages as listed in Table 3.

The concrete with marginally-reactive aggregate showed similar strength as that with non reactive at all ages. The table also shows that the obtained strength values at 28 days of standard curing for the three aggregates were very close.

Figure 2 shows the compressive strength of concrete mixes containing aggregates of different alkali-reactivity plotted against the expansion of concrete prisms prepared from the same mixes. Each series represents the expansions and strengths at a particular age, namely 13, 26 and 52 weeks. The horizontal lines on the graph represent the 28-day strengths of the three concretes with the three types of aggregates under standard curing (23 ºC and 100% RH). The graph shows that higher expansion results in lower strength. However, within the range of expansion of non-reactive and marginally reactive aggregates, the difference in strength was not significant. The graph also shows that for the same level of expansion, samples of older ages showed higher compressive strength. This is attributable to higher degree of hydration at later ages. Curing at higher temperature is also a factor that contributes to hydration and strength gain at later ages. For instance, the strength at 52 weeks for marginally and non reactive aggregates cured at 38 ºC were significantly higher than the strength of the same mixes at 28 days of standard curing. The graph also shows that the 1-year strength of the concrete with highly reactive aggregate is not much lower than the strength of the same concrete at 28 days under standard curing. In other words, the reduction in strength at 52 weeks due to expansion and cracking was almost counteracted by the increase in strength resulting from higher degree of hydration achieved under lab conditions.

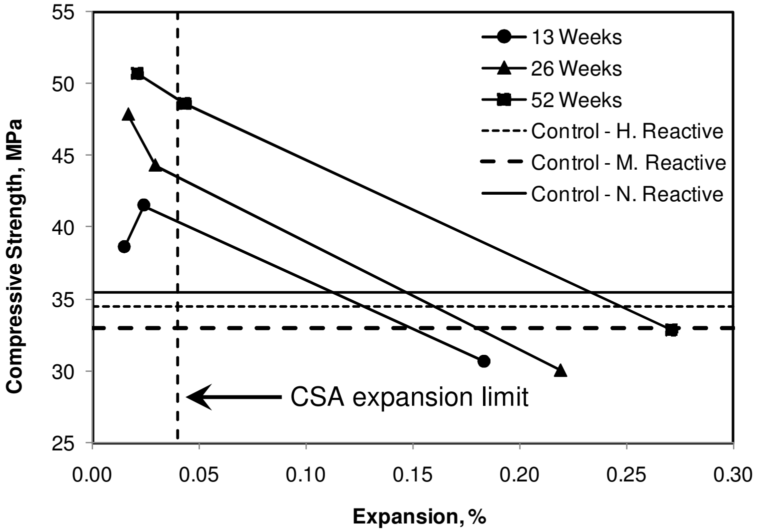

Figure 2. Compressive strength of concrete at various levels of expansion. Control samples are cured in a fog room at 23 ºC for 28 days

The splitting tensile strengths of concrete containing aggregates with different alkali-reactivity at different testing ages are summarized in Table 3 and presented in Figure 3. It is clear from the graph that the tensile strengths for concrete with marginally-reactive and non-reactive aggregates are relatively comparable regardless of the age. Contrary to the findings pertaining to compressive strength, curing for longer time at higher temperature (38 ºC) did not result in higher tensile strength. A reduction in the splitting tensile strength was noticeable in concrete with highly reactive aggregates at all ages starting from 13 weeks. Indeed, the tensile strength of concrete with highly reactive aggregate at ages beyond 13 weeks was much lower than the strength of the same concrete at 28 days. Comparing the data in Figure 3 with those in Figure 2, it is clear that the expansion and disruption due to ACR is better manifested in the splitting tensile strength, compared to compressive strength, especially when a reference is made to the strength at 28 days. This is because, unlike the case for compressive strength, curing at higher temperature did not cause increase in tensile strength.

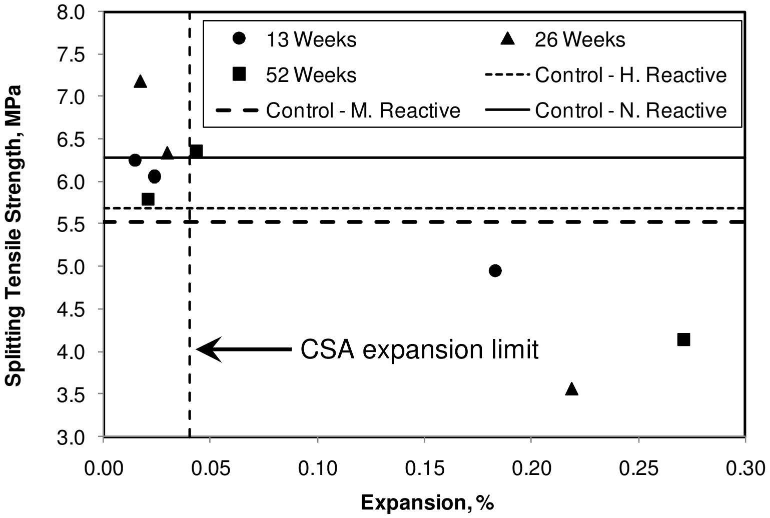

Figure 3. Tensile strength of concrete at various levels of expansion.

The results of bond strength between reinforcing bars and concrete are summarized in Table 3 and presented in Figure 4. The bond strength of concrete containing reactive aggregate remained almost the same up to I year. On the other hand, the bond strength of concrete made with marginally-reactive and non-reactive aggregates generally increased with time where the maximum bond strength was recorded at 1 year. The concrete made with marginally-reactive aggregate showed relatively similar behaviour as concrete containing non-reactive aggregate at all ages. The trend in Figure 4 shows that bond strength is negatively affected by expansion due to AAR. When compared with the bond strength at 28 days, the reduction in strength in concrete with reactive aggregate was balanced by the increase in bond due to higher degree of hydration of cement. This was not the case with tensile strength as discussed earlier.

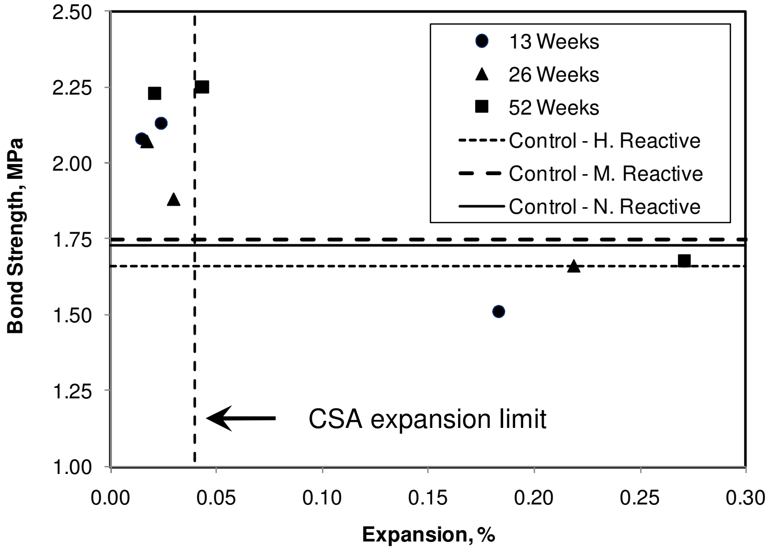

Figure 4: Bond strength of concrete at various levels of expansion.

3.3 Impact of Expansion on the Permeability of Concrete

The mass transport properties in this study were assessed using two test methods: the Rapid chloride Permeability test, ASTM C1202, and the Rapid Migration Test, Nordtest method, NT Build 492. The total charges passed through concrete containing reactive, marginally-reactive, and non-reactive aggregates were measured at different testing ages and the results are summarized in Table 3. The results for the

ASTM C 1202 test are plotted against the expansion in Figure 5. The horizontal dotted line represents the charge at 28 days of standard curing for concrete with reactive aggregate (H. Reactive). The charges for the other two samples with non- and marginally reactive aggregates were almost the same as the one with reactive aggregates. The graph clearly shows that at the same degree of maturity or age, the charge passed through concrete remarkably increased with increasing the expansion due to ACR. Concretes with non- and marginally-reactive aggregates showed the same permeability at each reported age. It is interesting to note that the permeability of samples with reactive aggregate at 52 weeks was better than that of the same sample at the age of 28 days despite the significant high expansion. This suggests that the refinement in pore structure due to higher hydration at that age had larger effects on the permeability compared to that of the expansion. This was not the case at 13 weeks where the negative effect of the expansion on permeability was higher than the positive effect of the pore structure refining, as illustrated in Figure 5.

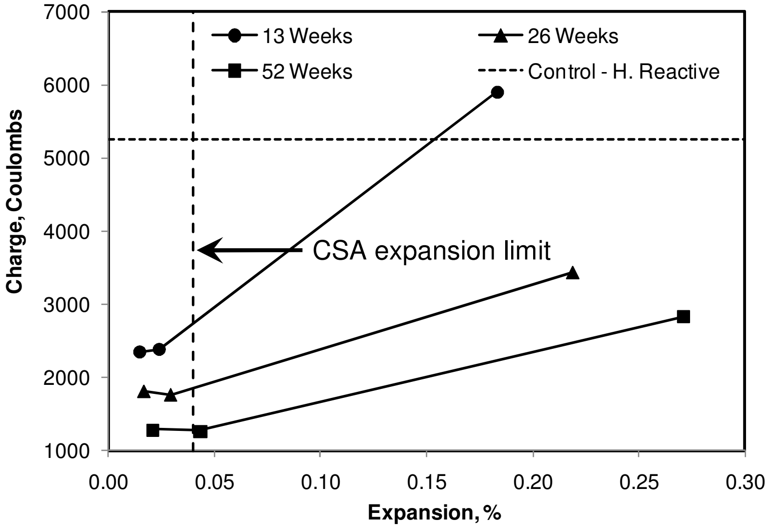

Figure 5. The charges passed in coulombs through concrete at various levels of expansion.

The findings obtained from the results of RCPT were confirmed by the Rapid Migration Test. The test duration for this test is relatively longer than the standard six hours of the RCPT. Moreover, the test method avoids the heating up of the specimens which may take place during RCPT due to increase in current. Table 3 lists the Non-Steady-State Migration (NSSM) coefficient at various testing ages and Figure 6 shows a plot of the results against the expansion. At all testing ages, concrete made with marginally-reactive or non-reactive aggregates recorded similar values which were smaller than the NSSM coefficients for concrete containing reactive aggregate. Figure 6 also demonstrates that the NSSM coefficient increased with increasing expansion at all testing ages. The coefficients at 13 weeks and beyond were lower than that at 28 days of standard curing, which shows the effects of hydration under lab test conditions on reducing the permeability, as was also found from the RCPT results.

3.4 Preventive Measures for AAR-Induced Expansion of Marginally-Reactive Aggregates

Two materials were investigated in this study as preventive measures against expansion due to AAR; low-alkali cement of Na_2O_e= 0.56%, and Type CI fly ash used at a replacement level of 25 % by mass of cementing materials. The 18-month expansion of concrete prisms incorporating reactive and marginally-reactive aggregates containing low-alkali cement or 25 % FA, are shown in Figure 7. It is clear that neither low-alkali cement nor fly ash is effective in suppressing the expansion of reactive aggregates. Both materials, however, showed slight reduction in the expansion for the marginally reactive aggregates KM101 and 10% PITTS. The concrete prisms made with LAC and containing the marginally-reactive aggregates KM101 and 10 % PITTS, showed 1-year expansions of 0.030, and 0.032 %, respectively compared with 1-year expansion of 0.042 % for the same mixes with high alkali cement. This shows that using LAC maintained the expansion below the limit specified by CSA. Fly ash seems to be more effective in suppressing the expansion of concrete with the aggregate KM101 than concrete with 10% PITTS as shown in the graph. However, it should be noted that the efficacy of fly ash or supplementary cementing materials in suppressing the expansion should be evaluated at 2 years. The expansions of these samples are being monitored.

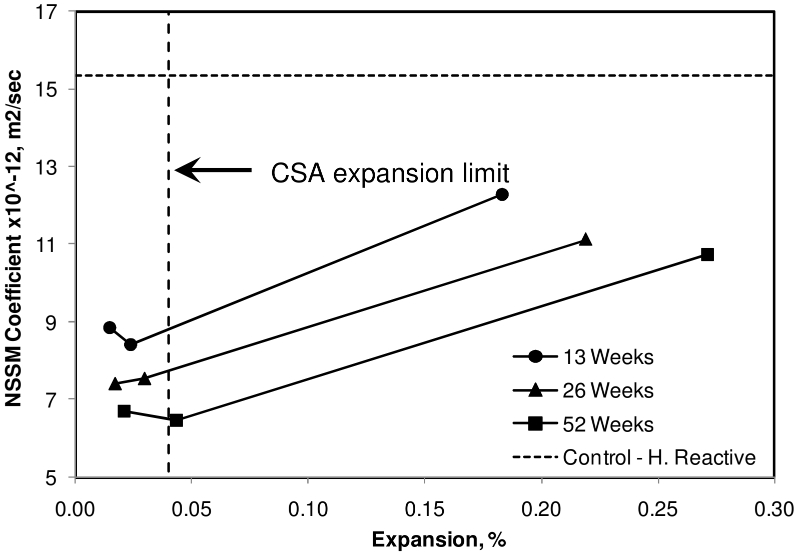

Figure 6. NSSM coefficients of concrete at various levels of expansion.

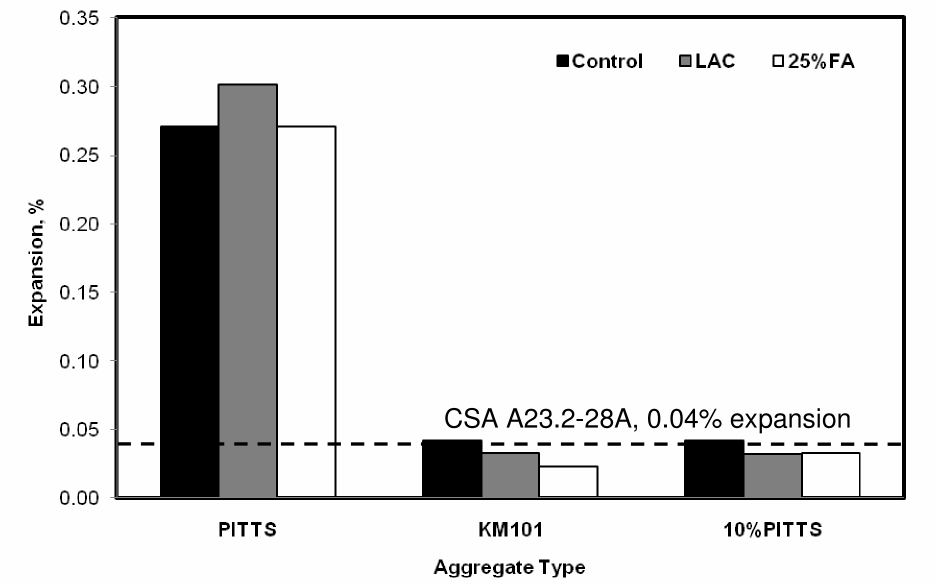

Figure 7. Expansion of concrete prisms made with different aggregates and containing LAC (Na_2O_e= 0.56 %) or FA (CI, as per CSA) after 18 months.

4. Discussion

The results showed that the tensile strength is more sensitive to, or more affected by, expansion due to ACR than compressive strength. This is in agreement with the findings of Swamy and Al-Asali, 1989 who found that the tensile strength tests are very sensitive especially at early ages when the values of expansion are very low. It is also noticeable that the increase in tensile strength with time of samples with non- or marginally reactive aggregates due to hydration of Portland cement was not significant. This finding and the high sensitivity of tensile strength to cracking are among the reasons for the significant impact of expansion on tensile strength. The difference between the control and 1 year values of bond strength reported in this study is consistent with the findings of Swamy and Al-Asali, 1989. They claimed that the ASR-affected beams did not show distress in bond, anchorage, or shear. Moreover, Ahmed et al., 1998 reported slight reductions (3-6 %) in bond strength of reinforcement in ASR-affected concrete beams when tested under static and fatigue loading.

The ACR-induced cracking was found to have significant impact on ion penetrability of concrete. At all ages, concrete with reactive aggregates showed higher permeability or ion penetrability compared to concrete with non- or marginally reactive aggregates as illustrated in Figures 5 and 6. However, all samples tested at ages of 13 weeks and beyond showed reduced ion permeability compared to concrete cured for 28 days at normal curing conditions. The only exception is the result of the RCPT of concrete with reactive aggregate at 13 weeks where slight increase in total charge was found, compared to that at 28 days of normal curing. This can be attributed to the fast rate of crack development in concrete made with Pittsburg aggregate. These cracks normally increased the permeability of concrete at relatively early ages. At later ages, the proceeding of hydration reactions under lab conditions compensated for the negative impact of these cracks through filling the pores and creating denser microstructures thus counteracted the negative effect of ACR-induced expansion. The significant reduction in permeability of concrete incorporating marginally-reactive and non-reactive aggregates can be interpreted as a result of concrete maturity with time especially when curd at 100% RH and 38ºC. As for the case with compressive strength, comparing the ion penetrability of mature ACR-affected concrete to penetrability values obtained at 28-days may provide misleading evaluation of the extent of ACR damage.

It is important to note that the results obtained in this study under laboratory curing may not replicate actual field conditions. Indeed, site conditions may not promote ACR reaction and cement hydration at the same rates as those encountered with lab curing. Specifically, actual field conditions may promote ACR expansion to a higher extent than sustaining the hydration of Portland cement or cementing materials. Better evaluation of concrete properties, particularly mass transport, can be obtained through testing cores from concrete samples (blocks) tested at exposure sites. It should also be noted that samples with 100% marginally reactive aggregate may not have the exact performance as the concrete tested in this study where marginally reactive aggregate was represented by a combination of 90% non-reactive and 10% reactive aggregates. Using aggregate such as KM101 would have provided more realistic results; however, this was not feasible due to the limited amount of aggregate available from this source during the period of this study.

Regarding preventive measures against expansion of marginally-reactive aggregate, the study showed that limiting the alkali content of cement brought the expansion to a level lower than the 0.04% limit. This approach may be an adequate preventive measure provided that no external alkalis will be supplied from external sources during the service life of the structure. LAC is still being produced in many countries of the world. So, the use of such cements can likely provide adequate protection against AAR under normal field conditions for concrete with marginally-reactive aggregates. The use of fly ash is also another option. The efficacy of fly ash is attributed to its ability to reduce the alkalinity of the pore solution of concrete. Fly ash produces hydrates with low Ca/Si ratio compared with normal cement. Such hydrates have high capacity to bind alkalis from the pore solution of concrete (Shehata et al. 1999, Shehata and Thomas 2000). Perhaps the high binding capacity of the hydration products of fly ash can also help in binding external sources of alkalis during the service life of structure, provided that the external supply is limited. This makes the fly ash a better option for preventing expansion of marginally reactive aggregate.

It should be noted that both LAC and fly ash are not effective in mitigating ACR as shown in Figure 7 for concrete with alkali-carbonate reactive aggregate (Pittsburg). The fact that these measures reduce the expansion of concrete with marginally reactive aggregate may not confirm that they completely stop the reaction. They could have merely reduced the rate of reaction but not the ultimate expansion value. Long term measurements of samples with marginally reactive aggregates are ongoing to elaborate on this.

5. Conclusions

For the properties and type of reactive aggregates investigated, the following conclusions are drawn:

1- The presence of marginally reactive aggregate in concrete did not have noticeable effects on the concrete compressive, tensile and bond strengths, and ion migration. However, highly reactive aggregates were found to have negative effects on these properties.
2- Tensile strength was found to be the mechanical property that is most sensitive to ACR expansion.
3- At all tested ages, the permeability or ion penetrability increased with the increase in expansion.
4- When using the 28-day properties as a bench mark to evaluate the properties of concrete structures affected by ACR, it is important to consider the enhancement in concrete properties due to age.
5- LAC was found to reduce the ACR expansion of marginally-reactive aggregates. However, other sources of alkalis could contribute to the expansion during the service life of structures. Intermediate calcium fly ash used at 25% was also able to reduce the expansion at 1.5 year. However, the long-term expansion is still under investigation.

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