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The effect of alkali-aggregate reactivity on the mechanical properties of high and normal strength concrete

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Abstract

In this investigation, a potentially highly reactive aggregate, and a potentially moderately reactive aggregate (identified by accelerated mortar bar testing and petrographic examination) were used in the preparation of concrete of normal and high strength concretes. After the initial 28 day curing period, the specimens were equally divided, and then submerged in a holding tank containing either a solution of a sodium hydroxide or de-ionised water at 80 °C for a period of 12 weeks. Normal strength concrete specimens containing the potentially highly reactive aggregate and exposed to the sodium hydroxide solution experienced more losses in mechanical properties than the concrete specimens prepared with potentially moderately reactive aggregates. However, in high strength concrete specimens exposed to the sodium hydroxide solution, there was a minimal loss in mechanical properties for both the specimens containing the highly reactive or moderately reactive aggregates. The superior performance of high strength concrete can be explained by the improved micro-structure and decreased permeability due to the formation of secondary calcium silicate hydrate formed as a result of the pozzolanic reaction.

Keywords: Aggregates; Alkali-aggregate reaction; Concrete properties; Petrographic examination

1. Introduction

Alkali-aggregate reaction (AAR) is an internal chemical reaction between the alkaline components in the cement and certain active mineral constituents in some aggregates. The reaction results in the formation of a gel which absorbs water, expands, and therefore exerts internal pressure which sometimes can be far in excess of that which concrete can sustain, thereby causing the formation of micro-cracks.

Evidence of AAR can be seen in almost all regions of Canada, even in concrete prepared with different types of aggregates. In general, there are three types of AAR, namely, alkali–silica reaction (ASR), alkali-carbonate reaction (ACR), and alkali–silicate reaction. However, ASR is more widespread, and is more harmful to the mechanical properties of concrete. ASR is an internal chemical reaction between the alkaline components in the cement and active silica-based mineral constituents of some aggregates. The reaction results in the formation of a gel that absorbs water, expand, and therefore exerts internal pressure which sometimes can be far in excess of what concrete can sustain, thereby causing the formation of micro-cracks.

There are three main components necessary to facilitate ASR, namely; sufficient alkalis in the pore solution, a critical amount of reactive mineral phases in the aggregate particles, and sufficient moisture. Currently, there are several methods used for determining the potential reactivity of a given aggregate. The widely used tests in Canada include the accelerated mortar bar test CSA A23.2-25A [1], and the mortar bar test ASTM C227 [2].

The alkaline components, such as sodium and potassium that are derived from cement, as well as other constituents, cause the dissolution of the siliceous components of the aggregate resulting in the formation of a non-deforming gel. As the gel continues to absorb moisture, the micro-cracks widen. On the surface, the cracks are exhibited in the form of map cracking, and often resemble the formation of a spider web. Extensive research on field structures has indicated that crack widths can range from 0.1 to 10 mm in extreme cases, and can even extend beyond the reinforcement as reported by

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Neville [3], Swamy [4] and Vivian [5]. Rodgers [6] has conducted extensive research to determine the testing procedures that could provide the most accurate evaluation of the potential reactivity of the aggregate.

ACR is attributed to a reaction between certain carbonate minerals in the aggregate and the alkaline pore solution of concrete. The use of low alkali cement does not ensure that the overall alkali content of the mix will not increase after the mix has been put into place. Moreover, laboratory investigations by Swamy and Al-Asali [7] have indicated that the use of even low alkali cement does not effectively prevent AAR when concrete is used in a severe alkaline environment.

The objective of this investigation was to evaluate the potential reactivity of Newfoundland aggregates and to compare the effect of ASR on the mechanical properties of concrete containing both a highly reactive and a moderately reactive aggregate obtained from different local aggregate quarries. The paper introduces the use of the direct tension test to evaluate the ASR effects on the mechanical properties of concrete. The direct tension test is more accurate than the compressive strength test or the indirect tension test in evaluating other concrete properties, such as shear strength, bond strength, fracture energy and tensile strength. Other mechanical properties, including the compressive strength, modulus of elasticity, and modulus of rupture, were recorded for normal and high strength concrete specimens.

Table 1
Petrographic analysis of aggregate samples

Aggregate samples	Composition	% per sample	Petrographic rating
A	Granite	35	
	Diorite	50	Fair
	Siltstone	15	
B	Granite	75	
	Sandstone	15	Low
	Basalt	5	
	Felsic tuff	5	
C	Greywacke	60	
	Siltstone	25	
	Diorite	5	High
	Mafic volcanic (Basalt)	10	
D	Green siltstone	98	High
	Red siltstone	2	
E	Granite	50	
	Sandstone	25	
	Diorite	5	
	Basalt	10	High
	Rhyolite	5	
	Tuff	5	
F	Gabbro	40	
	Granite	5	
	Diorite	15	
	Micaceous sandstone	20	Fair to low
	Mafic volcanics	15	
	Felsic volcanics	5	
G	Limestone	100	Very low

2. Experimental investigation

2.1. Petrographic examination

The geology of eastern Newfoundland is composed mainly of sedimentary and volcanic rocks with sporadic occurrences of granite rocks. In central Newfoundland, volcanic, sedimentary and granite rocks with some occurrences of metamorphic rocks are noted. The rocks on the Avalon Peninsula which have been proven to show alkali-aggregate reactivity are siliceous siltstone, argillites, sandstone, rhyolite, andesite, and their associated tuffs.

Samples of fine aggregates were obtained from seven different ready mix concrete suppliers and tested according to ASTM C295 [8]. Petrographic examination is an initial screening process by which the potential reactivity of an aggregate source may be assessed. The petrographic examination was used to determine the composition of the aggregates. If the aggregates contain specific minerals that are known to be reactive in concrete, it may be rejected. Petrographic analysis using microscopic techniques described in CSA A23.2-23C [9] were also used. Some information on that can be revealed by a petrographic examination include cement type, micro-cracks, porosity, gel, aggregate, supplementary cementing materials, alkali-aggregate reactivity, and other aspects. The results of the petrographic analysis for the seven sites are given in Table 1. After each petrographic examination, a petrographic rating was assigned based on the criteria recommended by Bragg and Foster [10]. Very low and low ratings were assigned to samples with no or up to 5% alkali-reactive minerals, respectively. A fair rating indicates that the alkali-reactive rocks or minerals are between 5% and 10%. For known alkali reactive minerals between 10% and 20% and over 20% the ratings are classified as moderate and high, respectively.

2.2. Accelerated mortar bar expansion tests

After the initial assessment of the aggregate sources by petrographic examination, the accelerated mortar bar expansion test CSA A23.2-25A [1] was conducted on each sample to substantiate its potential reactivity. This particular testing procedure was chosen because it can be carried out in fourteen days, whereas, other appli-

Table 2
Expansion of mortar bar in AMB test

Aggregate samples	Expansion after 14 days (%)
A	0.081
B	0.081
C	0.366
D	0.298
E	0.502
F	0.164

cable testing procedures require a much longer testing time. This testing procedure is similar to ASTM C1260 [11]. The average results for a minimum of four specimens for each sample after 14 days are given in Table 2. Expansions exceeding 0.15% at 14 days, 0.30% at 28 days, and 0.45% at 56 days cause the aggregate to be classified as potentially reactive. The mechanical properties of concrete specimens containing highly reactive aggregates or moderately reactive aggregates were also determined.

2.3. Concrete aggregates and mix design

The properties of the selected aggregates are shown in Table 3. Fine and coarse aggregates usually represent 70–85% of concrete mass; therefore, it was important to ensure that both sources were of similar quality. Both fine and coarse aggregates were washed by hand and air-dried to free the samples of silt, clay, or other fine materials that may affect the hydration cement and hence the bond between the cement paste and aggregates. The coarse aggregates were graded as shown in Table 4. The target concrete compressive strength for normal strength and high strength concrete was 35 and 80 MPa, respectively. Table 5 details the weights of the constituents in the normal and high strength concrete mixtures.

Table 3
Results of aggregate testing (sample E—potentially highly reactive)

Property	Test method	Result	Specified maximum
Los Angeles abrasion (%)	CSA A23.2-16A	18.1	35
Absorption (%)			
Fine aggregates	CSA A23.2-6A	0.160	
Coarse aggregates	CSA A23.2-12A	0.524	
Bulk specific gravity (g/cm^3) (oven dry)			
Fine aggregates	CSA A23.2-6A	2.632	
Coarse aggregates	CSA A23.2-12A	2.606	
Petrographic number	CSA A23.2-15A	121.3	135
Material finer than 80 μm (%)			
Fine aggregates	CSA A23.2-5A	5.3	
Coarse aggregates		1.2	
Fineness modulus		2.638	3.1
Freezing and thawing (%)	CSA A23.2-24A	1.284	6%
Accelerated mortar bar expansion (%)	CSA A23.2-23A	0.502	0.15% (14 days)
Micro Deval—fine aggregates (%)	CSA A23.2-23A	5.28	20%
Micro Deval—coarse aggregates (%)	MTO (Draft)	2.65	

Table 4
Coarse aggregate grading

Sieve opening (mm)	Percent of total passing
19.5	50
9.5	35
4.75	15

Table 5
Weights of constituents in normal and high strength concrete mixtures (per 0.1 m^3)

Constituent	Normal strength concrete	High strength concrete
Cement (Type I ASTM) (kg)	35.5	45.0
Fine aggregate (kg)	79.0	65.0
Coarse aggregate (kg)	104.0	107.0
Water (l)	16.1	15.4
Superplasticer (ml)	111.0	550.0
Air-entraining agent (ml)	18.0	18.0
Silica fume (kg)	0	6.0
Retarding agent (ml)	0	230
Water/cement ratio	0.45	0.342
Slump (mm)	95	180
Air (%)	7	3
Density (kg/m^3)	2300	2410

2.4. Exposure

Two mild steel tanks were constructed to expose the concrete specimens. The inner surfaces of these tanks were coated with an epoxy coating. Two stainless steel coiled element submersion heaters were mounted at the side of each tank. The heaters were equipped with a calibrated automatic temperature control dial, having sensitivity as low as 1 °C, and a range of 20–120 °C. The heating elements were made of stainless steel that had minimal reaction with the NaOH solution. Fig. 1 is a photograph of one of the exposure tanks.

2.5. Test procedure

The effect of ASR on the compressive strength, modulus of elasticity, uniaxial tension, and modulus of rupture was evaluated over a 12 week period. The concrete specimens were equally divided, with half of them being placed in the aggressive NaOH solution. The other half of the specimens were exposed to de-ionised water in a separate tank. Each tank was then heated to 80 °C. The tests were conducted on both of high and normal

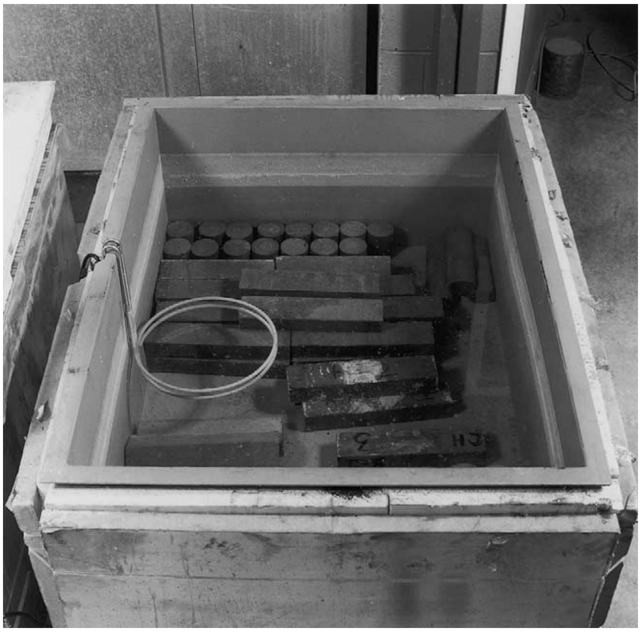

Fig. 1. Specimen exposure tank.

strength specimens, containing both highly reactive and moderately reactive aggregates.

The compressive strength and modulus of elasticity were evaluated on 75×150 concrete cylinders in accordance with ASTM C39 [12]. A standard metal frame with two mechanical dial gauges was used to record the concrete strains. The accuracy of each dial gauge was 1.27×10^{-3} mm.

A concrete prism $37 \times 75 \times 300$ mm was used to assess direct tension. Two wedge type frictional grips consisting of self-clamping steel and aluminium plates were used to attach the test specimen to the loading frame. A universal joint connection to the loading frame was used to apply the load on the direct tension specimen.

The modulus of rupture was evaluated according to ASTM C293 [13] on a concrete prism $75 \times 75 \times 250$ mm. The concrete prism was simply supported over 250 mm span using a central point loading.

3. Results and discussion

3.1. Compressive strength

The effect of ASR on the compressive strength of concrete is a function of time. It has been found that compressive strength decreases as damage due to the reaction increases at the micro-structural level. Many researchers, including Swamy [4], Swamy and Al-Asali [7], Ono [14], and Clark [15], reported that the loss in compressive strength can be as high as 40–60% with a reduction of 20% being likely to occur for expansions found in practice. The losses in compressive strength from each experiment depended greatly on several parameters, such as mix design, aggregate type, and storage conditions; none of whom have been duplicated in the earlier studies. However, the general trends observed are applicable. The cylinder compressive strength (f'_c), and the secant modulus of elasticity (E) at different exposure periods are summarised in Table 6. The secant modulus of elasticity was determined by dividing the concrete stress at a stress level equal to 0.45 of the ultimate compressive strength by the corresponding concrete strain.

3.1.1. Compressive strength of normal strength concrete

Maximum reduction in compressive strength was noted for the normal strength concrete prepared with the highly reactive aggregates. For specimens exposed to NaOH solution, an overall reduction of 24% in the compressive strength and 81% in the modulus of elasticity was observed after 12 weeks of exposure. However, in the specimens stored in de-ionised water, an overall increase in strength of 14% was observed after the same exposure period. The increase in strength of the specimens exposed to the de-ionised water may be attributed to the elevated storage temperature (80 °C) probably accelerated the hydration of cement. Despite an increase in the compressive strength of specimens exposed to de-ionised water, the modulus of elasticity of normal strength concrete decreased with exposure time for the specimens containing highly reactive aggregate.

Table 6
Compressive strength and modulus of elasticity of normal and high strength concretes

Aggregates	Period of exposure	Normal strength concrete				High strength concrete			
		Cured in water		Exposed to NaOH solution		Cured in water		Exposed to NaOH solution	
		f'_c (MPa)	E_c (GPa)	f'_c (MPa)	E_c (GPa)	f'_c (MPa)	E_c (GPa)	f'_c (MPa)	E_c (GPa)
Highly reactive	28 days	41.25	39.14	41.25	39.14	77.70	30.59	77.70	30.59
	12 weeks	46.60	28.78	30.42	–	95.59	35.67	79.98	25.97
Moderately reactive aggregate	28 days	47.98	33.46	47.98	33.46	74.52	31.75	74.52	31.75
	12 weeks	57.93	53.95	48.70	23.04	93.64	44.17	91.69	37.28

f'_c: Ultimate compressive strength of concrete cylinder, E_c: secant modulus of elasticity.

This anomaly can be explained due to the high variability in measurement of concrete strains.

For specimens exposed to the NaOH solution and containing moderately reactive aggregates, the compressive strength of the specimens after a 12 week period stayed virtually the same whereas the modulus of elasticity was reduced at the same period of exposure. This behaviour can be explained due to the fact that, the change of the modulus of elasticity can be different from the change in compressive strength due to the effect of ASR on the hydrated cement gel. However, both of the compressive strength and modulus of elasticity were increased during the same exposure period for the specimens subjected to de-ionised water due to increased maturity of concrete.

3.1.2. Compressive strength of high strength concrete

Due to the improved properties of high strength concrete, it is believed that the negative effects of NaOH solution will be minimal on these specimens. The compressive strength and modulus of elasticity of high strength concrete prepared with both types of aggregates increased significantly after 12 weeks of exposure to deionised water. This behavior is attributed to the improved micro-structure of high strength concrete during the first three months after casting, as a result of the formation of the secondary C–S–H gel that forms due to the pozzolanic reaction.

High strength concrete specimens exposed to NaOH solution exhibited 3% and 23% increase in the compressive strength for highly reactive and moderately reactive aggregates, respectively. This can be explained due to the improved grain refinement, and decreased permeability that reduces the mobility of aggressive agents. In addition, the additional calcium silicate hydrate, provided to the mix by the silica fume, chemically hold in the concrete alkalis that may otherwise be available to initiate AAR.

The modulus of elasticity of the highly reactive specimens indicated a decrease during the same exposure period, in spite of the small increase in the compressive strength. This can be attributed to the fact that the modulus of elasticity is more sensitive to ASR effects on the micro-structure changes than the compressive strength.

3.2. Direct tension

Philips and Binsheng [16], as well as Marzouk and Chen [17] investigated the response of normal and high strength concrete specimens in direct tension. Uniaxial tests are commonly utilized to obtain the stress–strain relationship as they better reflect the mechanical behaviour of concrete in tension, shear and bond than indirect tension tests. Furthermore, Marzouk and Chen [17] reported that the direct tensile strength of high strength concrete was recorded as 4–5% of f'_c. Testing of the normal strength concrete specimens revealed that the direct tensile strength was approximately 8–10% of f'_c. The set up of direct tension test used in the present investigation is shown in Fig. 2. The results of the direct tension test are more sensitive to any changes in the C–S–H gel than the compressive strength tests. However, the effect of specimen size on the results of the tension test is more profound than that on the compression test results. The compressive strength tests are load controlled, while the tension tests are displacement rate controlled. A special type of instrumentation, data acquisition and signal feed back from the concrete specimen are needed for a displacement rate control test. The tension test requirements are much more complicated than the standard compressive strength load control measurement as detailed by Marzouk and Chen [17]. The reported results of the direct tension test represent the average of three specimens for each reading, standard deviation of the three specimens and the corresponding change in compressive strength are given in Table 7.

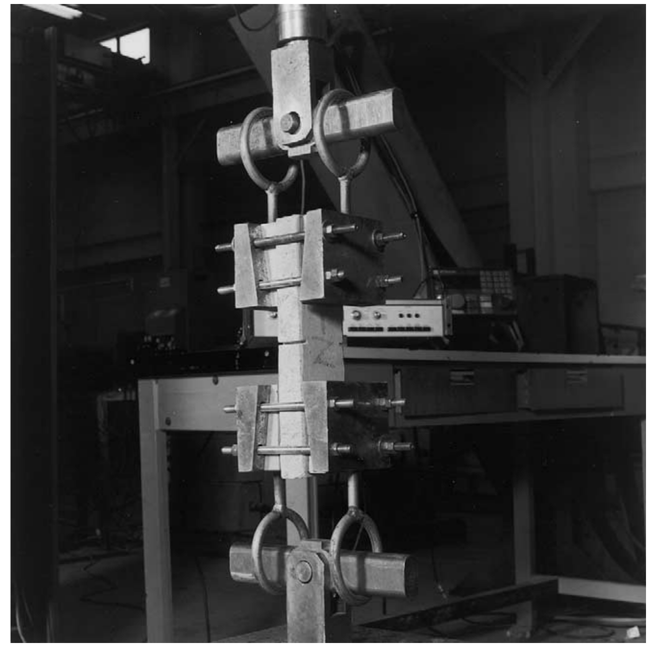

Fig. 2. Direct tension test set-up.

3.2.1. Direct tension of normal strength concrete

A decrease in the tensile strength of normal strength concrete specimens containing either the highly reactive aggregates or moderately reactive aggregates was noted after 12 weeks of exposure. In the specimens exposed to the NaOH solution the tensile strength decreased by 37% and 31% in the specimens prepared with

Table 7
Uniaxial tensile strength of normal and high strength concretes

Aggregates	Period of exposure	Normal strength concrete						High strength concrete					
		Cured in water			Exposed to NaOH solution			Cured in water			Exposed to NaOH solution		
		f_t (MPa)	Std. dev. (MPa)	% Change f'_c	f_t MPa	Std. Dev. (MPa)	Change f'_c (%)	f_t (MPa)	Std. dev. (MPa)	Change f'_c (%)	f_t (MPa)	Std. dev. (MPa)	Change f'_c (%)
Highly reactive	28 days	2.85	0.26	6.72	2.85	0.26	6.72	3.58	0.13	4.90	3.58	0.13	4.90
	12 weeks	2.66	0.41	6.28	1.80	0.12	4.25	3.82	0.23	6.70	2.71	0.16	3.71
Moderately reactive	28 days	2.62	0.37	5.59	2.62	0.37	5.59	2.17	0.11	3.01	2.17	0.11	3.01
	12 weeks	2.79	0.22	4.94	1.82	0.17	3.88	2.50	0.08	3.48	2.04	0.22	2.83

f_t : Direct tensile strength of concrete (uniaxial tension).

moderately reactive highly reactive and moderately reactive aggregates, respectively.

No apparent loss in the tensile strength was noted in the specimens prepared with moderately reactive aggregates and placed in the deionised water for 12 weeks. However, the specimens prepared with highly reactive aggregates showed a slight decrease in the tensile strength of approximately 7% over a 12 week testing period. This small decrease can be explained to the high variability of tensile strength values of concrete.

3.2.2. Direct tension of high strength concrete

The 28 day tensile strength of high strength concrete specimens tested throughout this investigation was 3.52 MPa. The change in the tensile strength of high strength concrete specimens using the highly reactive aggregates was 4.9%. The samples exposed to NaOH solution experienced a continual decrease in the tensile strength throughout the testing duration for both the types of aggregates. At the end of the 12 week test period, the tensile strength had decreased approximately by 25% for the highly reactive aggregate, resulting in an average tensile strength of 2.71 MPa. The same trend of tensile strength reduction, due to exposure time, was observed in the specimens containing moderately reactive aggregates. However, for all specimens exposed to de-ionised water for a 12 week period, a continual increase in tensile strength was evident. This increase is attributed to the maturity and improved micro-structure of high strength concrete during the first three months, as a result from the secondary pozzolanic reaction of the silica fume. Moreover, the improved grain refinement, and decreased permeability reduces the mobility of aggressive agents.

3.3. Indirect tension (modulus of rupture)

ASTM C293 [12] allows for the determination of the ultimate tensile strength of concrete prisms subjected to a central point loading, which is called the modulus of rupture (f_r). This parameter is used to determine the effects of AAR on the indirect tensile properties of concrete. The test set-up used in the present investigation is shown in Fig. 3. Research conducted by Swamy and Al-Asali [7], and Swamy [18] indicated that losses of 30–87% could occur depending on the aggregate type, and the testing regime utilized. The results of the indirect tension tests (modulus of rupture) are summarized in Table 8.

3.3.1. Modulus of rupture of normal strength concrete

The modulus of rupture of normal strength concrete specimens containing the highly reactive or moderately reactive aggregate, did, follow a trend similar to that reported by other researchers, like Swamy and Al-Asali

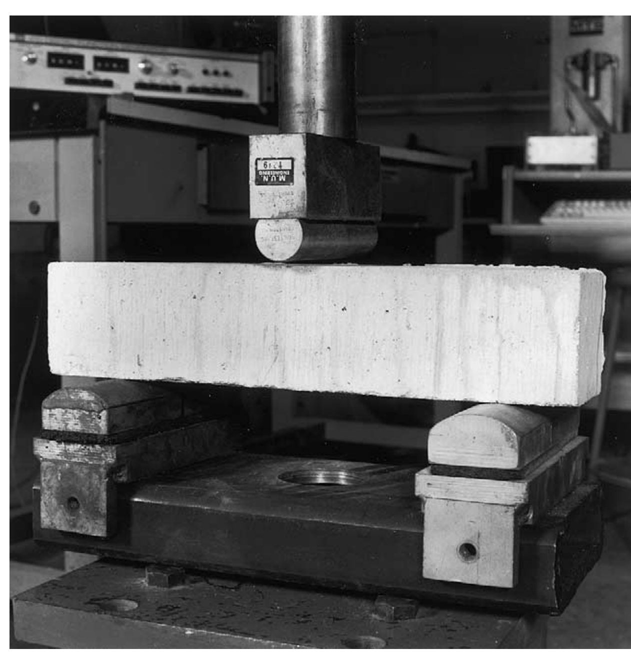

Fig. 3. Indirect tension test.

Table 8
Indirect tension (modulus of rupture) results

Types of aggregate	Time	Normal strength concrete						High strength concrete					
		Water			Solution			Water			Solution		
		f_r (MPa)	Std. dev. (MPa)	Change f'_c (%)	f_r (MPa)	Std. dev. (MPa)	Change f'_c (%)	f_r (MPa)	Std. dev. (MPa)	Change f'_c (%)	f_r (MPa)	Std. dev. (MPa)	Change f'_c (%)
Highly reactive aggregate	28 days	4.16	0.51	9.81	4.56	0.51	9.81	8.39	0.88	11.49	8.39	0.88	11.49
	12 weeks	5.65	0.24	13.34	4.16	0.28	12.88	12.48	1.17	17.10	9.38	0.80	12.84
Moderately reactive aggregate	28 days	5.45	0.31	11.63	5.45	0.31	11.63	5.91	0.61	8.21	5.91	0.61	8.21
	12 weeks	5.38	0.48	11.48	4.14	0.42	8.84	7.36	0.50	10.23	7.20	0.53	10.10

f_r: Modulus of rupture of concrete.

[7] and Swamy [18]. Samples containing highly reactive aggregates exposed to the NaOH solution experienced a decrease in the modulus of rupture from 4.56 MPa (tested after the initial 28 day curing period) to 4.16 MPa, (after a 12 week exposure period to the solution). A similar trend was observed for the specimens containing moderately reactive aggregates. However, all the specimens exposed to the de-ionised water, experienced a small increase in the modulus of elasticity after a 12 week period of exposure due to the increased maturity of concrete.

3.3.2. Modulus of rupture of high strength concrete

Samples containing highly reactive and moderately reactive aggregates placed in the NaOH solution experienced an increase in the modus of rupture of approximately 10% and 21%, respectively. Samples exposed to de-ionised water experienced an overall increase in the modulus of rupture throughout the testing period, for both the types of aggregates. These results confirm the superior performance of high strength concrete in delaying AAR due to the improved micro-structure and low permeability as discussed earlier.

4. Summary and conclusions

Petrographic examination and accelerated mortar bar testing were conducted on aggregates from seven locations in Newfoundland Canada to evaluate the potential for aggregate reaction. Based on petrographic examination and accelerated mortar bar testing, it has been decided to focus the current investigation on the highly reactive and moderately reactive aggregates.

Normal and high strength concrete specimens were cast using highly reactive or moderately reactive aggregates. Specimens of both normal and high strength concrete were equally divided, and placed in either an 80 °C solution bath containing water (the control environment), or in a NaOH solution to accelerate the reaction. Specimens from both solution baths were tested at various intervals up to the end of a 12 week testing period.

In general, the effect of ASR on the mechanical properties of high and normal strength concrete can be summarised as follows. Normal strength concrete specimens containing highly reactive aggregate exposed to NaOH showed a reduction in compressive strength, modulus of elasticity, direct tension and modulus of rupture. For similar specimens containing the moderately reactive aggregate, the reduction in the mechanical properties was much less.

High strength concrete specimens containing highly reactive aggregate exposed to NaOH showed a much smaller reduction in compressive strength, modulus of elasticity, direct tension and modulus of rupture than normal strength concrete. This is attributed to the improved micro-structure of high strength concrete, as a result of the secondary pozzolanic reaction. Moreover, the improved grain refinement, and decreased permeability reduces the mobility of aggressive agents. In addition, the secondary calcium silicate hydrate, provided to the mix by the silica fume, chemically binds the alkalis that otherwise may be available to initiate AAR. The following specific conclusions can be derived from the experimental investigations:

1. The effects of AAR on the mechanical properties of high strength concrete were minimal. The superior performance of high strength concrete can be explained by the improved micro-structure and decreased permeability of the calcium silicate hydrate (C–S–H) gel that resulted from the pozzolanic reaction.
2. In general, normal strength concrete specimens containing the highly reactive aggregate experienced a greater loss of mechanical properties than did the normal strength concrete containing the moderately reactive aggregate.
3. The compressive strength of normal strength concrete containing the highly reactive aggregates decreased

by 28% while the modulus of elasticity decreased by 80%. For the normal strength concrete containing the moderately reactive aggregate, the ultimate compressive strength remained almost constant, while a decrease in modulus of elasticity of 20% was recorded.
4. The direct tensile strength of both the normal strength concrete containing the highly or the moderately reactive aggregate was found to be very sensitive to the effects of AAR. The tensile strength of the normal strength concrete containing the highly and moderately reactive aggregate decreased by 37%, and 31%, respectively.
5. The effect of AAR on the modulus of rupture of normal strength concrete specimens was negligible. The modulus of rupture of specimens containing the highly reactive and the moderately reactive aggregates experienced a small decrease.

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