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Effects of alkali addition on the mechanical properties and durability of concrete

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Abstract

Increasing the concrete alkali content from 0.6% to 1.25% of Na_2O_e of the cement mass by adding NaOH to the mixture water has harmful effects on most mechanical properties (compressive, splitting, direct tensile, and flexure strengths) of concrete made with a water-to-cement (w/c) ratio of 0.41 and limestone aggregates not susceptible to alkali–silica reaction (ASR), however not on the elasticity modulus measured under compression or direct tension. Shrinkage tests at 50% RH and 23 °C started after 7 days at 100% RH and 23 °C show that the low-alkali concrete shrinks more than the high-alkali one, despite similar water losses. Freeze–thaw tests performed on air-entrained concretes show that the two concretes resist well to freezing and thawing while showing similar air–void systems. When examined under the scanning electron microscope (SEM), the hydrates in the two concretes present similar microstructure; however, the high-alkali concrete shows a more reticular and porous microtexture, which could explain the reduction in strength.

Keywords: Alkalies; Concrete; Shrinkage; Freezing and thawing; Mechanical strengths

1. Introduction

The effects of alkalies on various properties of cement paste, mortar, and concrete, including early hydration and setting, bleeding, strength development and ultimate strength, drying shrinkage, susceptibility to cracking, microtexture of cement hydrates, and durability, have been a subject of concern since many decades. Reviews on the subject can be found in Burrows [1] and Jawed and Skalny [2]. From the literature then available, the latter [2] concluded that significant proportions of alkalies in clinker can cause a quick setting, reduce the ultimate strength of concrete, and increase expansion under water and shrinkage under drying conditions. As discussed hereafter, based on limited or conflicting information in many respects, the present paper addresses the effects of alkalies on strength development, drying shrinkage, freeze–thaw durability, and microstructure of concrete.

1.1. Effects of alkalies on cracking and drying shrinkage

Burrows [1] participated in a long-term test program that consisted in the fabrication of 104 concrete panels made with 27 different cements and that were placed in 1943 at Green Mountain dam in Colorado. Fifty-three years later, he found that the amount of cracking observed on these panels was directly proportional to the alkali content in the cements used, thus suggesting that high-alkali cements are more susceptible to drying shrinkage. Blaine et al. [3] performed shrinkage tests on cement pastes made with 199 different cements. They found that cement pastes containing more alkalies were undergoing more shrinkage; however, they did not observe any correlation between the alkali content and the amount of drying shrinkage for their companion concrete specimens. Based on the work by Carlson [4], Burrows [1] attributes this behaviour to the development of micro-

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cracking within the concrete subjected to drying, which decreases the bulk shrinkage (since the measurements account for combined effects of contraction due to shrinkage and expansion due to microcracking).

So, it has been well demonstrated that a higher cement alkali content tends to increase the susceptibility to shrinkage under drying conditions in the case of cement pastes and mortars. However, this effect is not so clear in the case of concrete.

1.2. Effects of alkalies on strength development and ultimate strength

A number of experimental studies showed that the higher the alkali content in the cement, the lower the ultimate strength of the corresponding test specimens [2,5]. From their study with 199 commercial portland cements, Blaine et al. [3] concluded that a higher cement alkali content statistically resulted in a higher dynamic modulus of elasticity measured on corresponding concrete specimens after 14 days. Osbaeck [6] concluded that a higher alkali content in cement accelerates the strength development in the short term but decreases the ultimate strength. From their literature review, Jawed and Skalny [2] also concluded that a high alkali content in cement generally results in a higher strength at early age, but to a lower strength after 28 days. Gouda [7] observed a similar trend for concrete specimens made with low-alkali (0.58% Na_2O_e) and very high-alkali (1.76% Na_2O_e) cement except that the turning point was at 7 days.

A very low cement alkali content can result in abnormally low strength developments at early ages [8], which was also noted by other researchers [9,10]. On the other hand, Odler and Wonnemann [11] observed that the alkalies incorporated into the cement clinker did not affect the compressive strength, whereas an external addition of alkali sulfate considerably reduces the strength at any age up to 28 days [10]. Alexander and Davies [12] observed that the higher the alkali increase, the lower the compressive strength of cement pastes; however, intermediate alkali additions increased the modulus of rupture whereas smaller and larger additions decreased it.

In the case of concrete specimens placed outdoor by Burrows [1] at the Green Mountain dam, the least cracked of all the 104 concrete panels made after 53 years of field exposure was the one made with a very low alkali cement (0.23% Na_2O_e) [1]. On the other hand, the same concrete was also presenting the lowest 7-day compressive strength of all ASTM Type I cements investigated, which is coherent with a lower early rate of hydration.

Vivian [13] subjected to flexure tests mortar specimens containing alkali–silica reactive and nonreactive aggregates. The mortars were made with a cement containing 0.59% Na_2O_e, and NaOH additions of 0%, 0.5%, 2%, and 4.5% (by mass of cement), which correspond to total alkali contents of 0.59%, 0.98%, 2.14%, and 4.08% Na_2O_e, respectively (by mass of cement). The author observed that the addition of NaOH did not reduce the tensile strength of the mortars containing nonreactive aggregates, except for mixtures containing 4.08% Na_2O_e, which content is, however, unrealistic. It must be mentioned that all mortars with a lower alkali content were made with a water-to-cement (w/c) ratio of 0.50 or 0.52, whereas a higher ratio (0.60) was used for the 4.08% Na_2O_e mixture, which could explain the decrease in strength by itself. Moreover, the study was limited to mortar specimens.

Shayan and Ivanusec [9] studied the changes in the mechanical properties (compressive strength and modulus of rupture) and microstructural characteristics of cement pastes and mortars of various alkali contents. The two cementitious systems were made with w/c ratios of 0.4 and 0.6, a cement containing 0.84% Na_2O_e, with and without reactive aggregates (in the case of mortars). The alkali content of the different systems was adjusted to the level desired by using mixture waters made of 0, 0.5, 1.0, 2.0, and 4.5 M NaOH solutions. The corresponding total alkali contents (by mass of cement) were 0.84%, 1.9%, 3.0%, 5.1%, and 10.5% Na_2O_e for the pastes or mortars with a w/c of 0.6; they were 0.84, 1.6, 2.3, 3.8, and 7.4% Na_2O_e for those with a w/c of 0.4. The authors found that the higher the alkali content, the lower the compressive strength and modulus of rupture at any age (i.e., 7, 28, and 90 days); however, the highest reduction in strength was obtained for alkali contents comprised between the minimum tested and about 3% Na_2O_e. Unfortunately, just one of all alkali contents investigated by the authors falls between the range of 0.5% to 1.3% Na_2O_e (by mass of cement) used for most field concretes. Moreover, the study was limited to cement pastes and mortar specimens.

Unfortunately, most studies on the effect of alkalies on the mechanical properties of hydraulic systems were performed on cement pastes and/or mortar specimens. Moreover, the alkali content was adjusted to various levels by using different cements of different alkali contents; consequently, the alkali content was not the single parameter involved, except maybe in a few studies [9,13], also on cement pastes and/or mortars, for which the results are conflicting, at least within a realistic range of alkali content. In addition, in most studies, the mechanical properties involved were usually limited to compressive strength.

1.3. Effects of alkalies on freeze–thaw durability

Burrows [1] reports that in the case of the concrete specimens placed at the Green Mountain dam, the least cracked concrete panel after 53 years, made with a very low alkali cement (0.23% Na_2O_e), was also presenting the lowest resistance in the ASTM C 666 freezing–thawing test; it must be mentioned that no panel was undergoing alkali–silica reaction (ASR). Backstrom and Burrows [14] measured the number of freezing–thawing cycles to reach 0.1% expansion for concretes exposed outside and made with five cements of different alkali contents (0.25%, 0.41%, 0.60%, 0.74%, and

0.93% Na_2O_e), each ground at five different finenesses. For each cement, they observed that the finer the grind, the less durable the concrete. Moreover, for a given cement fineness, the cement with the lowest alkali content (0.25% Na_2O_e) always gave the most resistant concrete, followed far behind by the one with 0.41% Na_2O_e. Burrows [1] suggested that the better performance in the freezing–thawing test (conducted outside) of low-alkali, coarse ground cements, is attributed to less microcracking from drying and weathering.

However, the effect of alkalies on freeze–thaw durability was not so clear for the three other alkali contents investigated by Backstrom and Burrows [14]. Indeed, a reverse trend was observed, with the cement of 0.93% Na_2O_e resulting in the best durability (just a little worse than the cement with 0.41%), followed by the cement with 0.74%, then by the one with 0.60%. Moreover, the results by Plante et al. [15] suggest that a higher alkali content in concrete could be positive for the stability of the air–void spacing factor, which could then improve the freezing–thawing durability of concrete made with a higher alkali content.

Thus, the effect of alkalies on freezing–thawing durability is still not clear at least within the range of cement alkali contents normally used in field concrete (i.e., 0.5% to 1.3% Na_2O_e).

1.4. Effects of alkalies on microtexture

According to Jawed and Skalny [2], "when alkali-containing cement is mixed with water, the alkali metal ions readily go into the liquid phase of the hydrating system and influence the rate of cement hydration and the morphology of the hydration products. This, in turn, affects the strength and other engineering properties of the concrete." The effect of alkali on microstructure is reviewed by Burrows [1] and Jawed and Skalny [2]. The second authors report from the literature that the microstructure of CSH becomes coarser and heterogeneous in alkali solutions and the lower strength development at later age is due to this heterogeneous structure. Moreover, the shape of hydrates formed depends of the alkali anion (i.e., sulfate or carbonate or hydroxide). Vivian [16] reported that in the presence of high alkali contents, the products of hydration tend to be gelatinous rather than crystalline; however, such changes in the microtexture of cement hydrates were observed only when the alkali content of the mortar tested exceeded 4.5% Na_2O_e, which is quite unrealistic.

Under the scanning electron microscope (SEM), Shayan and Ivanusec [9] observed that high-alkali cement pastes had a less dense microstructure compared to low-alkali pastes. From another study where they investigated the nature of solid phases formed during early hydration of a portland cement in solutions of various NaOH concentrations, Way and Shayan [17] did not observe any change for concentrations up to 1 M; however, for concentrations of 2 and 4.5 M, the CSH contained significant amounts of sodium and new phases were even formed. Shayan and Ivanusec [9] then attributed the cracking of cement pastes made with high NaOH concentrations to the formation of these new phases. It must be recalled that such alkali concentrations correspond to total alkali contents that are unrealistic. Since the sharpest decrease in strength observed by the authors arose at low levels of alkali addition, i.e., before new phases were formed, the authors then suggested that substitution of Na in CSH likely also occurs at lower alkali addition, which has a significant detrimental effect on the development of the mechanical properties of the hydrating cement phases. Suzuki et al. [18] also showed that sodium was incorporated into CSH in significant amounts in basic NaOH solution.

1.5. Research significance

The following statement by Jawed and Skalny [2] still represents the present state of the knowledge about the effects of alkalies: "The effects of alkalies on the role of hydration and on the nature and morphology of hydration products influences the engineering properties of concrete such as setting time, strength development, shrinkage, volume expansion, etc. However, one finds conflicting reports in the literature regarding the effects of alkalies on these properties, this presumably reflecting the use of cements produced from different raw materials and of technical processes involving different parameters. The strength development of a given cement is controlled by several factors (e.g., clinker composition, cement fineness, gypsum content, and its degree of dehydration), and it may not be easy to single out one factor responsible for changes in strength of cement paste or concrete produced from a given cement".

In fact, the effects of alkalies on most properties of concrete are still not well understood, for the following reasons: (1) Most studies involved cement paste and/or mortar specimens. (2) The different alkali contents were usually achieved by using cements with different alkali contents, such as the alkali content is not the single parameter involved. (3) The compressive strength was often the only mechanical property investigated in most studies. The available information is also conflicting as concerns the effect of alkali on drying shrinkage (i.e., cement paste and mortar vs. concrete), whereas very limited as concerns freezing–thawing durability.

It is well known that concrete, in the presence of reactive aggregates and sufficient quantities of alkalies and moisture, can undergo deleterious expansion and cracking due to ASR. Testing for ASR commonly requires raising the alkali content of concrete to accelerate the reaction/expansion processes. This may in itself significantly affect the mechanical properties of concrete, i.e., induce reduction in strength that is not due to ASR only. Some authors effectively pointed out that the strength reductions observed for concrete affected by ASR can be partly attributed to the alkalies present in significant amounts in the concrete.

As concerns cracking, ASR-affected concrete can also exhibit map cracking that may have originated from drying shrinkage and this may sometimes cause misleading in the diagnosis of the cause of cracking. In his review paper, Burrows [1] discusses a number of cases where drying shrinkage cracking due to high-alkali cement was incorrectly diagnosed as ASR.

1.6. Objectives of the study

With the main objective to better interpret the reduction in the mechanical and durability properties of field and laboratory concretes affected by ASR, which are usually alkali rich, this study was undertaken to isolate the effect of alkalies on a number of properties of “nonreactive” concrete, which includes strength development (compressive, indirect tension, direct traction, modulus of rupture, modulus of elasticity under compression and traction), drying shrinkage, air–void system, and freezing–thawing durability. All tests are performed on concrete specimens with two alkali contents (0.6% and 1.25% Na_2O_e with respect to the cement), which cover the range of alkali content used in most field concretes. All specimens are made with the same (low alkali) cement, however, adding NaOH to the mixture water in the case of the high-alkali concrete. This is not usual for field concrete; however, it is current practice when testing aggregates for potential alkali reactivity or when investigating in the laboratory the effect of ASR on the mechanical properties of concrete, while being the only way to isolate the effect of alkalies.

2. Materials and characteristics of concrete mixtures

Low-alkali (0.6% Na_2O_e by mass of cement) and high-alkali (1.25% Na_2O_e) concrete mixtures were made with nonreactive coarse (limestone) and fine (granitic sand) aggregates, with and without air entrainment. The basic cement used was a 50–50 blend of two normal (CSA Type 10 or ASTM Type I) cements with alkali contents of 0.4% and 0.8% Na_2O_e, respectively (Table 1). The high-alkali concrete was obtained by adding reagent-grade NaOH pellets dissolved in the mixture water to raise the alkali level of the system to 1.25% Na_2O_e by mass of cement.

The concrete mixture proportioning generally followed the recommendations of the CSA A23.2-14 A (or ASTM C 1293) Concrete Prism Test Method used for evaluating aggregates for potential ASR. A nominal cement content of 420 kg/m^3 was used, with fine-to-coarse aggregate ratio of 40:60 and a w/c ratio of 0.41 (Table 2). With the exception of the test prisms subjected to freezing and thawing testing, all concrete specimens were non-air-entrained. The properties of the freshly mixed concretes are given in Table 2.

Table 2
Concrete mixture proportioning and properties of freshly mixed concrete

Type of concrete	Concrete characteristics	Low-alkali concrete	High-alkali concrete
All	Water (kg/m^3)	172	172
	Cement (kg/m^3)	420	420
	Water/cement	0.41	0.41
	Cement Na_2O_e content (%)	0.63	0.63
	NaOH addition (kg/m^3)	–	3.52
	Total Na_2O_e (% of cement)	0.63	1.25
	Total Na_2O_e (kg/m^3)	2.65	5.25
	Fine aggregate (kg/m^3)	755	755
	Coarse aggregate (kg/m^3)	1080	1080
Non-air-entrained	Slump (mm)	75	95
	Air in fresh concrete (%)	2.0	2.3
	Unit weight (kg/m^3)	2404	2398
Air-entrained	Air-entraining admixture (ml/kg of cement)	0.4	0.4
	Slump (mm)	85	100
	Air in fresh concrete (%)	6.1	6.2
	Unit weight (kg/m^3)	2395	2390

3. Making, curing, and testing of concrete specimens

A series of concrete prisms, 50 × 75 × 350 mm in size, and cylinders, 100 × 200 mm in size, were made from the concrete mixtures described before and subjected to various mechanical tests at different ages. All the test specimens were stored in a moist curing room at 23 °C and 100% RH until due for testing. Considering the small size of the specimens, attention was given to try minimizing the leaching of alkalies. Specimens were cured in boxes with no direct contact with water till the last testing date of 180 days. The mechanical testing performed in this study included the following tests: compressive strength, modulus of elasticity under compression, direct tensile strength, modulus of elasticity under tension, splitting tensile strength, and modulus of rupture. In addition to the above series of specimens, concrete prisms, 50 × 100 × 350 mm in size, were made from the concrete mixtures described before

Table 1
Chemical composition of the normal (CSA Type 10) Portland cements used in the study (percent by mass)

Cement	Oxide (%)									LOI (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Na_2O_e	
A—Type 10	19.8	5.20	2.30	62.1	2.75	3.02	0.26	0.86	0.83	2.63
B—Type 10	20.2	4.72	3.60	63.8	1.32	2.85	0.18	0.40	0.44	2.98
50:50 Blend	20.0	4.96	3.45	63.0	2.04	2.94	0.22	0.63	0.63	2.81

and kept in a moist curing room at 23 °C for 7 days. The prisms were then stored in a cabinet at 23 °C and 50% RH and their length changes monitored regularly over a 100-day period for establishing the susceptibility of the concretes to drying shrinkage.

4. Results of mechanical testing

The results of the mechanical tests performed in this study are given in Table 3. All results presented are the mean for three specimens.

4.1. Compressive strength and modulus of elasticity under compression

The results show that raising the alkali content in concrete resulted in significant reductions in the compressive strength. The main reduction with respect to the low-alkali system was obtained at 3 days and the differences remained somewhat similar afterwards, i.e., up to 180 days (Fig. 1A). When maintained in the moist curing room at 23 °C, the two concretes showed continuous strength gains during the 180-day testing period (Fig. 1A).

Table 3
results of mechanical testing

Property	Age (days)	Low-alkali concrete	High-alkali concrete	Difference[a] (%)
Compressive strength (MPa)	3	42.6	31.4	– 26
	7	43.6	34.9	– 20
	28	49.9	41.6	– 17
	90	57.4	46.8	– 18
	180	58.5	51.7	– 12
Average		–	–	– 19
Modulus of elasticity under compression (GPa)	3	35.6	33.8	– 5
	7	39.7	35.3	– 11
	28	39.4	35.7	– 9
	90	38.8	41.0	+ 1
	180	39.9	38.7	– 3
Average		–	–	– 5
Direct tensile strength (MPa)	3	2.82	2.28	– 19
	7	2.93	2.63	– 10
	28	3.14	2.72	– 13
	90	3.33	3.10	– 7
	180	4.12	3.49	– 15
Average		–	–	– 13
Modulus of elasticity under compression (GPa)	3	34.7	32.4	– 7
	7	35.3	33.3	– 6
	28	35.8	37.8	+ 1
	90	39.0	40.1	+ 1
	180	44.1	41.1	– 7
Average		–	–	– 4
Splitting tensile strength (MPa)	3	2.98	2.79	– 6
	7	3.38	3.04	– 10
	28	4.57	3.84	– 16
	90	4.20	4.00	– 5
	180	4.90	4.20	– 14
Average		–	–	– 10
Modulus of rupture (MPa)	3	5.08	4.64	– 9
	7	5.44	5.04	– 7
	28	5.93	5.44	– 8
	90	6.19	6.07	– 2
	180	7.04	6.82	– 3
Average		–	–	– 6

[a] High-alkali concrete with respect to the low-alkali concrete.

Table 3 gives the results of the modulus of elasticity testing under compression. The modulus is lower for the high-alkali concrete up to 28 days, whereas both concretes gave similar modulus values in the long term (Fig. 2A).

4.2. Tensile strength and modulus of elasticity under tension

As observed previously under compression, the addition of alkalies to concrete resulted in a noticeable reduction in the tensile strength (Fig. 1B). Again, the main reduction was observed at 3 days, while the difference remained about the same afterwards. On the other hand, the modulus of elasticity under tension was not significantly affected by the increase in the alkali content with differences generally within ± 2 GPa (Fig. 2B).

Despite some scattering in the test results, the addition of alkalies to the concrete mixture resulted in reduction in the splitting tensile strength from 5% to 16% over the 180-day testing period (Fig. 1C).

4.3. Modulus of rupture

Fig. 1D shows that increasing the alkali content in concrete resulted in reductions of about 8% in the modulus of rupture up to 28 days; afterwards, both high- and low-alkali concretes showed similar values.

5. Results of drying shrinkage testing

Fig. 3 illustrates the average mass loss and drying shrinkage of test prisms cast from the low- and high-alkali concretes and subjected to drying shrinkage. Fig. 3A shows that both low- and high-alkali specimens suffered quite similar mass losses over time; however, the test specimens cast from the high-alkali concrete mixture showed slightly less drying shrinkage compared to those cast from the low-alkali mixture (Fig. 3B). Picket [19] found that adding external alkalies as potassium sulphate (compared with NaOH in our case) decreases shrinkage compared to cement pastes made with clinkers that are already rich in alkalies. This may be due to the development of more significant microcracking in the case of the high-alkali concrete caused by a paste of lower strength and which would hide the bulk shrinkage, as suggested by Carlson [4] and Burrows [1]. Nevertheless, the amount of shrinkage remains quite low for both concretes tested. Let us recall that Blaine et al. [3] showed that a higher cement alkali content increases the amount of drying shrinkage of cement pastes and mortars but usually not of concretes, probably due

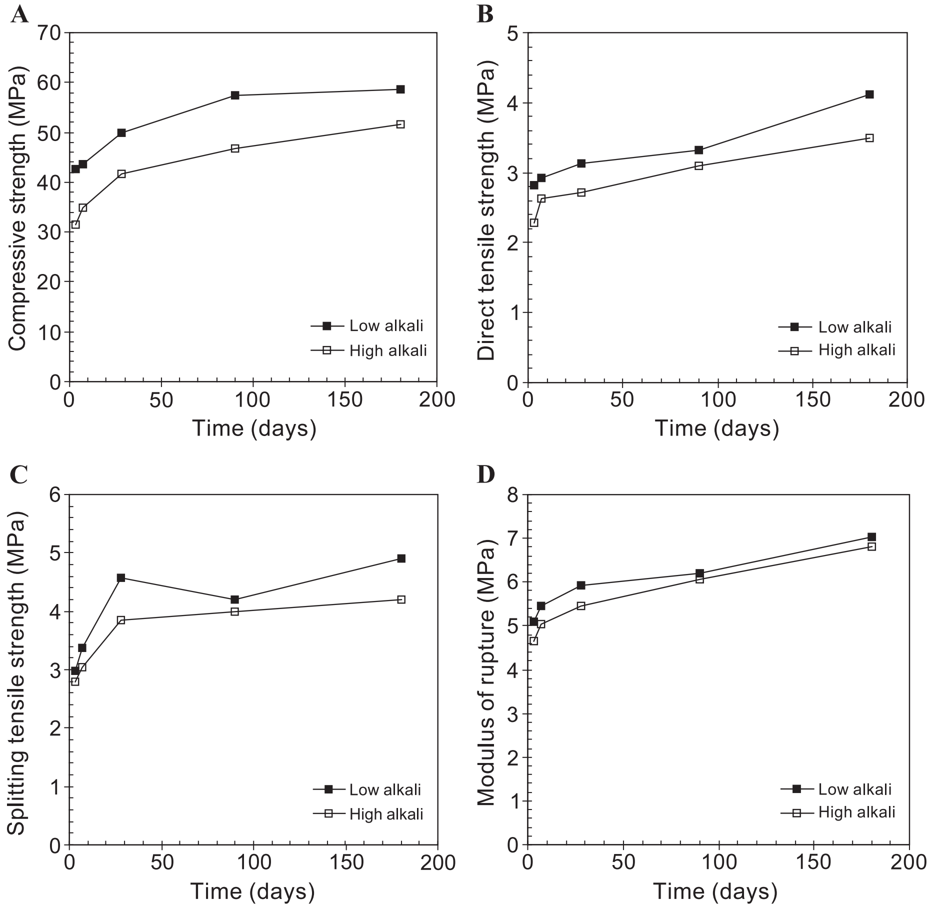

Fig. 1. Results of mechanical testing as a function of time: (A) compressive strength, (B) direct tensile strength, (C) splitting tensile strength, (D) modulus of rupture.

to more microcracking within concrete, as suggested by Carlson [4] and Burrows [1].

6. Results of freezing and thawing testing

Backstrom and Burrows [14] found that a very low alkali concrete can perform badly in the ASTM C 666 durability test without suffering major deterioration in the field. On the other hand, Plante et al. [15] observed that the use of high-alkali cements could improve the stability of the air–void system of air-entrained concrete. However, since the high-alkali concrete tested in our investigation shows relatively lower tensile strength and modulus of rupture, it could potentially be less resistant to freezing and thawing cycles.

Table 4 gives the parameters of the air–void system in the air-entrained and non-air-entrained concretes, both made with the same dosage of air-entraining admixture. One can note that additional alkalies have no significant effects on air distribution. Moreover, Fig. 4 shows that the two air-entrained concretes resisted similarly well to freezing–thawing cycles. Consequently, the addition of alkalies in the form of soluble NaOH did not significantly affect the

Table 4
Parameters of the air–void system in the air-entrained and non-air-entrained concretes

Type of concrete	Alkali content	Standard calculation			Without large bubbles		
		Air (%)	Specific surface (mm^{-1})	Spacing factor L bar (μm)	Air (%)	Specific surface (mm^{-1})	Spacing factor L bar (μm)
Non-air-entrained	Low	1.9	6.8	1203	0.7	15.3	803
	High	2.2	6.2	1268	1.1	10.5	995
Air-entrained	Low	6.7	29.2	156	5.1	37.8	136
	High	7.3	29.5	138	6.5	33.5	134

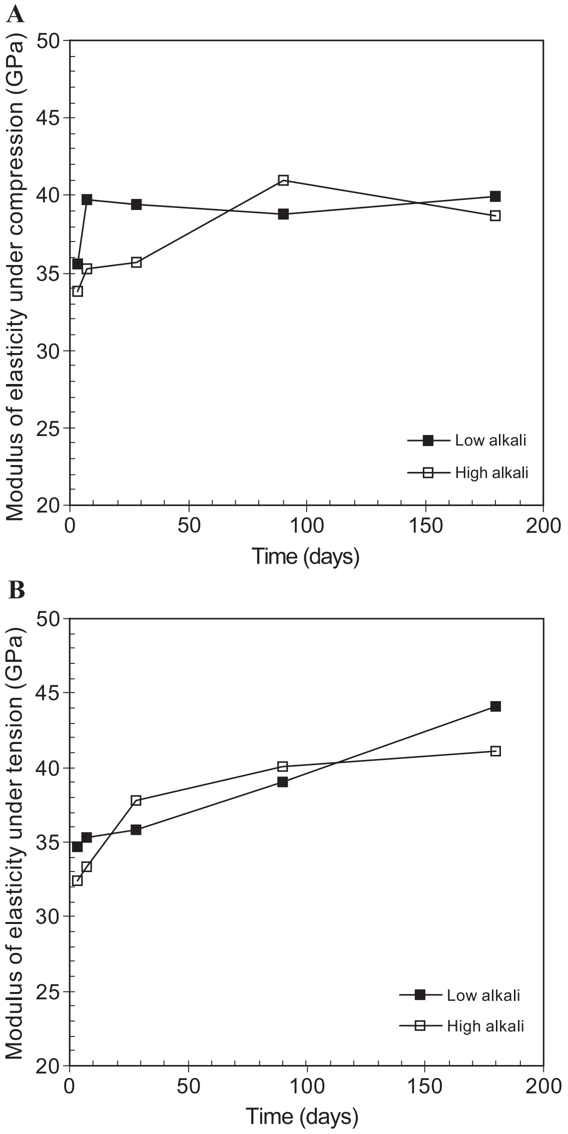

Fig. 2. Results of modulus of elasticity as a function of time: (A) under compression, (B) under direct tension.

durability of the corresponding concrete in the presence of freezing and thawing cycles.

7. Microstructure investigation

Cement pastes of w/c of 0.4 and 0.5 were cast at the 0.6% and 1.25% Na$_2$O$_e$ alkali levels. The paste specimens were cast and stored at 23 °C and 100% RH. They were analyzed by X-ray diffraction and examined under the SEM at various ages to determine if the addition of alkalies caused differences in the nature and morphology of the cement hydrates.

X-ray diffraction showed the same peaks for the two systems with no indication of different phases formed. However, SEM observations showed that the high- and low-alkali pastes have fairly different microtextural characteristics. The high-alkali paste has a more reticular (like “sea

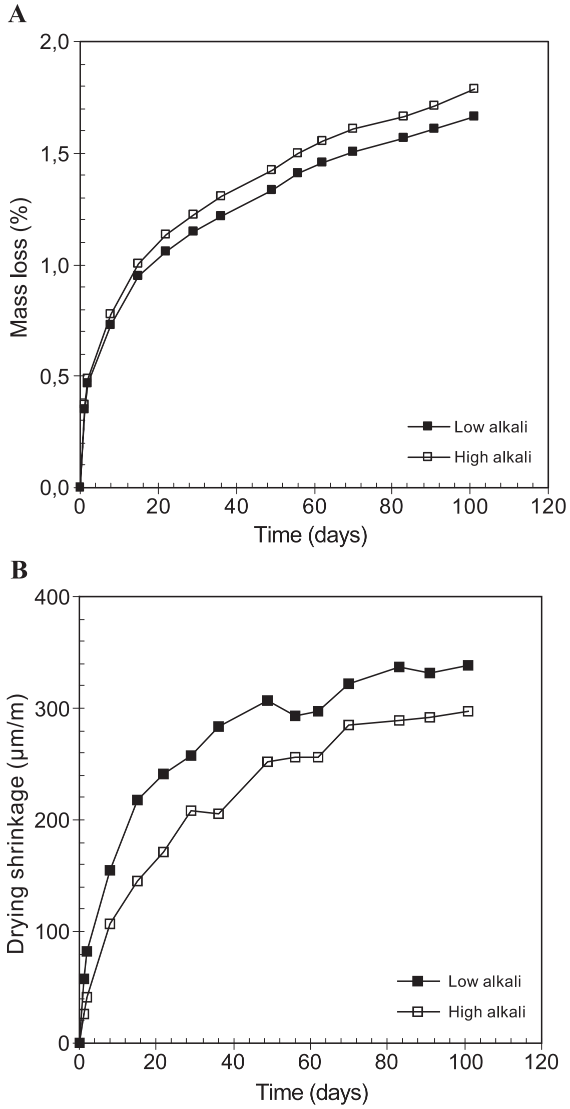

Fig. 3. Results of drying shrinkage testing as a function of time: (A) mass loss of test prisms subjected to drying, (B) shrinkage.

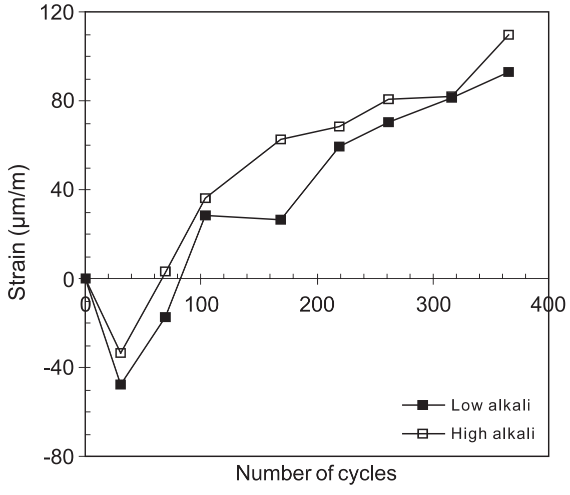

Fig. 4. Deformations against time for the air-entrained test specimens subjected to freezing and thawing cycles.

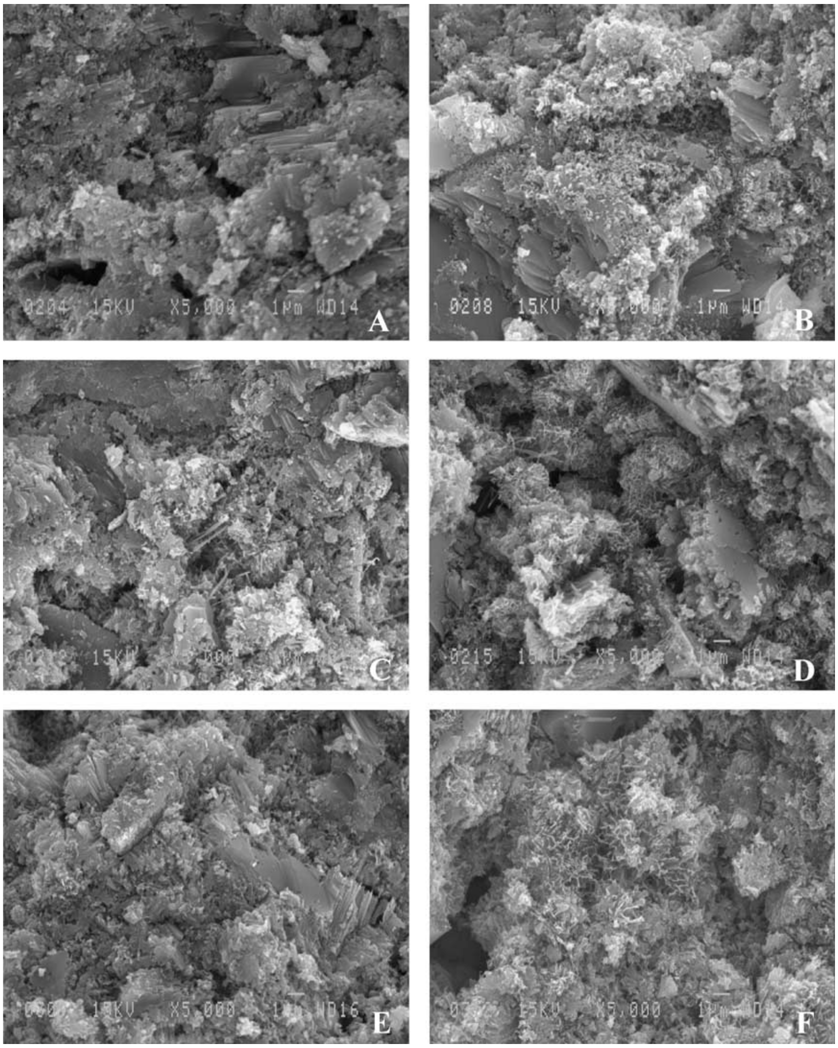

Fig. 5. Microstructural characteristics, as observed under the SEM, of low- and high-alkali cement pastes: (A) low-alkali paste with w/c of 0.4 (7 days), (B) high-alkali paste with w/c of 0.4 (7 days), (C) low-alkali paste with w/c of 0.5 (7 days), (D) high-alkali paste with w/c of 0.5 (7 days), (E) low-alkali paste with w/c of 0.5 (56 days), (F) high-alkali paste with w/c of 0.5 (56 days).

urchins'') and porous microtexture compared to the low-alkali paste. The same morphological differences were observed at all ages from 3 to 90 days (Fig. 5). The relatively more porous appearance of the high-alkali system and the reticular microtexture of hydrates formed could possibly explain the reduction in strength of the high-alkali system examined. Shayan and Ivanusec [9] also observed that high-alkali cement pastes had a less dense microstructure compared to low-alkali pastes.

8. Discussion

The various tests performed in this study indicate that the addition of alkalies in the form of NaOH, which is commonly done when evaluating aggregates for potential alkali–silica reactivity and the effect of ASR on the mechanical properties of concrete, can cause reductions in compressive, tensile, splitting, and flexure (modulus of rupture) strengths. SEM observations suggest that this could be related to the formation of hydration products with a weaker (reticular) microtexture and a globally more porous cement paste resulting from the addition of alkali hydroxide to the mixture water of concrete. On average over time (from 3 to 180 days), the reduction in strength was 19% under compression, 13% under tension, 10% under splitting, and 6% under flexure. On the other hand, the modulus of elasticity measured during compressive and tensile tests did not show any noticeable difference between the two concretes.

Test results have shown that the compressive strength is more affected by adding alkalies than the modulus of elasticity under compression. The latter is the slope of the curvature of stress vs. strain between 0% and 40% of the ultimate strength. It is well accepted that compressive strength is related to the growth and propagation of cracks.

As indicated by Nemati et al. [20], from 0% to 40% of the compressive strength, the only cracks observed are interfacial cracks (around the aggregates). These cracks grow until 70% of the ultimate strength and then begin to extend in the cement paste. During the modulus of elasticity test, the number of cracks in the paste remains limited. This could explain why the modulus for the two concretes (low- and high-alkali concretes) is about the same.

From this study, it is obvious that an alkali addition in the form of NaOH to concrete cause significant reduction in early and ultimate strengths, whereas the modulus of elasticity and the susceptibility to drying (bulk) shrinkage and freezing–thawing are not significantly affected. The available information on the effect of alkalies on concrete properties, which is reviewed by Burrows [1] and Jawed and Skalny [2], suggests that the higher the alkali content in the concrete, the lower the ultimate strength, irrespective of the manner the higher content is achieved, i.e., by using cement with a higher alkali content or by adding external alkalies in the form of sulphate, carbonate, or hydroxide. Unless it is clearly demonstrated that added alkalies are more deleterious than cement alkalies, this remark should be considered.

In the particular case of concretes affected by ASR, which are mostly alkali rich, the possibility that the high alkali content may explain by itself some reduction in the mechanical strength obtained must be considered.

The most important remark concerns, however, the experimental studies performed for evaluating the effect of ASR on the mechanical properties of concrete. Often, high-alkali reactive/expansive and low-alkali nonreactive/nonexpansive concretes are compared that contained the same reactive aggregates but where NaOH is added to the concrete mixture to obtain the high-alkali expansive concrete. The reduction in strength due to the higher alkali content by itself must be taken into account.

9. Conclusion

The present study on the effect of alkalies on a number of concrete properties was undertaken due to limited or conflicting information in the literature in many respects, particularly as concerns strength development, ultimate strength, drying shrinkage, and durability against freezing and thawing. We can conclude the following from the results obtained:

- The addition of alkali in the form of NaOH causes significant reductions in the compressive, splitting, direct tensile, and flexure (modulus of rupture) strengths of concrete at all ages, which is attributed to a more reticular and more porous cement paste, as observed under the SEM; however, for the two alkali contents investigated (0.6% and 1.25% of Na_2O_e by mass of cement), XRD did not show any difference in the nature of hydrates formed.
- The modulus of elasticity as measured during compressive and direct tensile tests (i.e., between 0% and 40% of the ultimate strength) is not significantly modified by the NaOH addition, likely because the number of cracks in the cement paste remains limited for both low- and high-alkali concretes tested within 0 and 40% of the ultimate strength.
- Drying shrinkage tests show that the low-alkali concrete shrinks a little more than the high-alkali one, although the two concretes lost the same amount of water.
- The two concretes resist well to freeze–thaw tests; moreover, additional alkalies do not modify the characteristics of the air–void system (L_{bar}).
- The existing literature suggests that a higher concrete alkali content decreases the strength, whatever the manner this content is achieved (i.e., high-alkali clinkers or external addition of alkali sulphate, carbonate, or hydroxide); the results obtained in this study thus likely apply when the alkali content is increased as a result of the use of a cement with a higher alkali content.
- In the particular case of field concretes affected by ASR, usually alkali rich, a certain part of the observed reductions in strength are likely due to the high alkali content by itself.
- Where the effect of ASR on concrete strength is investigated in the laboratory by comparison between low-alkali/nonexpansive and high-alkali/expansive concretes made with the same reactive aggregates but where the high-alkali/expansive concrete is obtained by adding NaOH to the mixture water, which is quite common, it must be recalled that the observed reductions of strength are partly due to the higher alkali content by itself.

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