

# INFLUENCE OF LITHIUM IONS ON THE CHEMISTRY OF PORE SOLUTIONS IN PASTES AND MORTARS WITH INERT AGGREGATES

Taehwan Kim<sup>1\*</sup>, Jan Olek<sup>1</sup>

<sup>1</sup>Purdue University, West Lafayette, IN, USA

## Abstract

This paper presents the results of the investigation of the chemistry of pore solutions in cement slurries and mortars containing various dosages of lithium nitrate. Specifically, the effects of the following parameters on the chemistry of pore solutions were investigated: a) timing of lithium nitrate ( $\text{LiNO}_3$ ) introduction, b) the dosage of lithium nitrate, c) water-to-cement ratio, d) length of curing time, and e) curing temperature.

The focus of the cement slurry studies was on determining whether the removal of the lithium ions from the pore solution takes place during the actual hydration process or if the lithium ions are adsorbed on the existing particles of C-S-H gel. It was hypothesized that the information regarding the timing of the lithium ions removal will be helpful in developing potential methods of lithium nitrate treatments which will minimize the loss of the admixture. The analysis of the composition of pore solution in cement slurries indicated that the removal of the lithium ions takes place during the actual hydration process.

Mortar specimens prepared using the non-reactive aggregate were tested to study the influence of lithium ions on the chemistry of pore solution. It was established that a linear correlation exists between the initial concentration of the lithium and the concentration of lithium ions remaining in the pore solution.

**Keywords:** Alkali silica reaction, lithium nitrate, pore solution analysis

## 1 INTRODUCTION

The deterioration caused by alkali-silica reaction (ASR) was first described over 70 years ago in the paper by Thomas E. Stanton [1] and has been extensively researched ever since. The main factors controlling both, the occurrence and the severity of ASR, include the presence of reactive aggregate, the alkali content of concrete and the availability of moisture. In addition, the presence of the calcium ions ( $\text{Ca}^{2+}$ ) has been reported to have significant influence on the observed level of expansion of the gel [2-5].

The use of lithium based chemical admixtures for the purposes of ASR mitigation has been extensively studied for more than 50 years. One of the first to report on the beneficial effects of lithium ions on ASR expansion were McCoy and Caldwell [6]. Subsequent studies by numerous researchers resulted in several proposed mechanisms by which lithium ions ( $\text{Li}^+$ ) allegedly control ASR. These include: a) formation of physical barrier by insoluble Si-Li reaction products [7-9], b) formation of less expansive Si-Li reaction products [10-12], c) decreased repolymerization of ASR gel due to high repulsive forces between the colloidal particles [13] and d) increased chemical stability of reactive silica exposed to pore solution [7,14-16]. However, none of these mechanisms fully explains the role of lithium in controlling ASR.

Among different lithium compounds that can be potentially used as admixtures to control the ASR, lithium nitrate ( $\text{LiNO}_3$ ) is considered to be the most effective. A primary advantage of  $\text{LiNO}_3$  over the other

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\* Correspondence to: kim312@purdue.edu

lithium compounds is that it does not increase the concentration of hydroxyl ions ( $\text{OH}^-$ ) in the pore solution, and thus eliminates the pessimum effect of other lithium compounds [17,18]. In addition,  $\text{LiNO}_3$  is compatible with other chemical admixtures and does not significantly affect such properties of concrete as strength, electrical resistance, drying shrinkage and resistance to freezing and thawing [19,20].

One of the interesting properties of  $\text{Li}^+$  ions is that they tend to be incorporated into the cement hydrates to much greater extent than sodium ions ( $\text{Na}^+$ ) and potassium ions ( $\text{K}^+$ ) ions [21]. In general, about half of originally added lithium is lost during early hydration, presumably sorbed by the hydrating cement [18]. Diamond and Ong [11] reported that even in nonreactive aggregate mortars, more than 40% of added  $\text{Li}^+$  ions were removed from the pore solution after only 1 day. These authors also suggested that, presumably,  $\text{Li}^+$  ions removed from pore solution are not available for suppressing ASR.

The current paper concentrates on phenomenon of the substantial loss of  $\text{Li}^+$  ions during early stages of hydration and on the interaction between  $\text{Li}^+$  ions and hydration products in the cement slurries and nonreactive aggregate (NR) mortars. Specifically, the effects of following parameters on the loss of  $\text{Li}^+$  ions are described: a) timing of lithium introduction into cement slurry system (at 0, 1 and 2 days after mixing of cement and water), and (for the mortar systems): b) dosage of lithium nitrate (from 0 to 1.48 of lithium to alkali molar ratio), c) water-to-cement ratio (0.42, 0.47, 0.49 and 0.55), d) curing temperature (23°C, 38°C and 55°C) and e) length of curing time (up to 40 days).

## 2 MATERIALS AND METHODS

### 2.1 Materials

Two Type I high-alkali portland cements (C1 and C2) were used during the current study. The compositions of these cements were as follows: a) C1 cement: 61.1%  $\text{CaO}$ , 19.1%  $\text{SiO}_2$ , 4.8%  $\text{Al}_2\text{O}_3$ , 3.3%  $\text{Fe}_2\text{O}_3$ , 3.8%  $\text{MgO}$ , 3.6%  $\text{SO}_3$ , 0.86%  $\text{Na}_2\text{O}_{\text{eq}}$ , 1.5%  $\text{CO}_2$ , 3.6% limestone, 2.5% LOI (loss of ignition) and b) C2 cement: 61.8%  $\text{CaO}$ , 20.1%  $\text{SiO}_2$ , 5.2%  $\text{Al}_2\text{O}_3$ , 2.1%  $\text{Fe}_2\text{O}_3$ , 3.7%  $\text{MgO}$ , 3.6%  $\text{SO}_3$ , 1.04%  $\text{Na}_2\text{O}_{\text{eq}}$ , 1.2% LOI. One non-reactive aggregate (ASTM C 778 standard Ottawa graded sand) was used to prepare the mortar specimens. The specific gravity of the Ottawa sand was 2.65 and its water absorption was 0.0%. The reagent grade lithium nitrate ( $\text{LiNO}_3$ ) was used as the source of  $\text{Li}^+$  ions.

### 2.2 Experimental Methods

#### *Cement slurry experiments*

The cement slurry experiments were designed to investigate the effect of timing of the addition of  $\text{LiNO}_3$  on the concentration of lithium ions in the pore solution during the early hydration period. Cement slurries were prepared by mixing C1 cement and deionized water at two different water-to-cement ratios: 1.0 and 2.0 (see Table 1). Two specific amounts of  $\text{LiNO}_3$  were selected for preparation of the slurries: 1.034 g of  $\text{LiNO}_3$  for slurries with  $w/c=1.0$  and 1.723 g of  $\text{LiNO}_3$  for slurries with  $w/c=2.0$ . These amounts of  $\text{LiNO}_3$  were specifically selected to yield 0.5 molar (M) concentrations of  $\text{Li}^+$  ions in the solutions containing the original amount of the mix water (i.e. immediately after combining water and cement). The  $\text{LiNO}_3$  was introduced to the slurry at three different times: a) with the mixing water (0 days), b) after 1 day of continuous mixing of the slurry and c) after 2 days of continuous mixing of the slurry.

Table 1 summarizes the test matrix used in the cement slurry experiment. When preparing the slurries, a constant amount of cement was mixed thoroughly with deionized water in the ointment jars (50 mm in diameter, 63 mm in length). For these cement slurries in which the required quantity of lithium admixture was introduced at the time of initial mixing ( $t=0$  days), the  $\text{LiNO}_3$  was dissolved in the mixing water before combining the water with the cement. Delayed addition of lithium admixture was achieved by adding crystalline  $\text{LiNO}_3$  to the slurries at 1 or 2 days after initial mixing of cement with water. In order to limit the

extent of hydration in slurries used for delayed addition of lithium experiment, they were continuously mixed (using a magnetic stirrer) until the pre-designated time (1 or 2 days) for  $\text{LiNO}_3$  introduction was reached. Once one of these pre-designated times was reached, the required amount of  $\text{LiNO}_3$  was added to each of the slurries and stirring process continued for two additional minutes. Magnetic stirrers were then removed and the slurries were stored in sealed jars under the laboratory conditions ( $23^\circ\text{C}$  and 50% RH) until they were 5 days old. At that time, the slurries were either filtered (in case of  $w/c = 2.0$ ) or squeezed in the die-and-piston device [22] (in the case of  $w/c=1.0$ ).

The pore solutions were chemically analyzed for  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Li}^+$  ions using the atomic absorption/emission spectrophotometer (Varian® SpectrAA – 20). The concentrations of  $\text{OH}^-$  ions in the solutions were determined by titration with a standardized hydrochloric acid using methyl red indicator.

#### *Mortar experiments*

The experiments with mortar specimens used eight different lithium-to-alkali molar ratios (0, 0.185, 0.261, 0.370, 0.522, 0.740, 1.110 and 0.480) and were designed to quantify the effects of water-to-cement ratio,  $\text{LiNO}_3$  dosage and curing temperature on the loss of lithium ions during the early hydration period. Previous research by Lumley [23] indicated that the dosage of lithium required to inhibit the ASR expansion depended on the alkali content of the cement used. Furthermore, the work by numerous other researchers revealed that ensuring a molar ratio of lithium to alkali (expressed as  $[\text{Li}]/[\text{Na}+\text{K}]$ ) of at least 0.74 is generally sufficient for the effective control of the ASR expansion [19,24,25]. However, this molar ratio is not always effective in mitigation of the ASR. For example, Tremblay et al. [26] reported that using 0.74 molar ratio of lithium to alkali was able to control ASR in only 6 out of 12 aggregates used in their research.

In the present paper, to simplify the naming scheme for individual series of mortars, the amount of  $\text{LiNO}_3$  needed to ensure 0.74 molar ratio of lithium to alkali at a given  $w/c$  is referred to “100% dosage of  $\text{LiNO}_3$ ”, with other percentages corresponding to, respectively, lower or higher ratios (see Table 2). All mortar specimens were prepared using the non-reactive (NR) Ottawa sand as the aggregate. Four water-to-cement ratios were used: 0.42, 0.47, 0.49 and 0.55. The C1 cement was used for mortars with  $w/c$  of 0.42, 0.47 and 0.49 and the C2 cement was used for mortars with  $w/c$  of 0.55. The total aggregate content in the mortars with  $w/c$  levels of 0.42 and 0.47 was 55% by volume of the mixture and the volumes of aggregate in the set of mortars with  $w/c$  of 0.49 and 0.55 were, respectively, 51% and 50% by volume of the mixture. These differences in the volumes of the aggregates were due to the fact that the same mortars were also used in other sets of experiments.

$\text{LiNO}_3$  admixture was introduced to mortar mixtures by dissolving it in the mix water. All mortars were prepared and mixed in accordance with the provisions of ASTM C 305. Once mixed, all mortars were placed in the small ointment jars (50 mm in diameter and 63 mm in length), which were then sealed and placed on the shelves in the curing room ( $23^\circ\text{C}$ , 100% RH). The jars were then transferred to the air-tight container, the interior of which was kept in a saturated condition by placing a thin layer of deionized water at the bottom of the container. Mortar specimens prepared with the C1 cement were stored in the curing room ( $23^\circ\text{C}$ , 100% RH) for prescribed curing period (1, 2, 7 and 14 days). The mortar specimens prepared with the C2 cement were stored at three different temperatures ( $23^\circ\text{C}$ ,  $38^\circ\text{C}$  and  $55^\circ\text{C}$ ) for up to 40 days.

When the prescribed curing period was completed, the mortar specimens were removed from the jars, weighted and placed in the die and piston squeezing device [22] to extract the pore solution. Once the pore solution extraction process was completed, the remnants of the specimen were immediately removed from the die and weighed. They were then broken up into several pieces, flushed with acetone (to stop hydration and to reduce the carbonation) and dried at  $105^\circ\text{C}$  to a constant weight. The difference between the initial weight of the specimen (as removed from the ointment jar) and its dried weight was then calculated and

assumed to represent the amount of evaporable water in the specimen. That calculated quantity of the evaporable water was used to adjust the measured concentrations of ions in the pore solutions to compensate for chemically bound water. Adjusted concentrations were calculated using the Eq. (1)

$$M_a = (w_{\text{eva}} / w_{\text{initial}}) \cdot M_m \quad (1)$$

where,  $M_a$  and  $M_m$  are the adjusted concentration (M) and the measured concentration (M), respectively.  $w_{\text{eva}}$  and  $w_{\text{initial}}$  are, respectively, the amount of evaporable water (g) and the amount of the initial mix water (g) in the mortar sample. This adjustment normalizes the concentration of ions in the solution with respect to the initial water content of the mix and thus allows for the direct comparison of specimens at various degrees of hydration.

The concentrations of  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{OH}^-$  ions in the pore solutions were determined using the same methods as those used in the cement slurry experiments.

### 3 RESULTS AND DISCUSSION

#### 3.1 Effects of timing of $\text{LiNO}_3$ introduction on $\text{Li}^+$ ions concentration in pore solutions of cement slurries

As shown in Table 3, the delayed addition of  $\text{LiNO}_3$  increased the concentration of  $\text{Li}^+$  ions retained in the pore solution of cement slurries. In other words, the later edition of  $\text{LiNO}_3$ , the smaller the amount of  $\text{Li}^+$  removed from the pore solution.

As already mentioned in section 2.2, the amount of  $\text{LiNO}_3$  added to both Groups of cement slurries was designed to provide 0.5 M concentration of  $\text{Li}^+$  ions when dissolved in the initial amount of the mix water. At the first glance, the measured concentrations of  $\text{Li}^+$  ions shown in Table 3 which are higher than 0.5 M seem to be incorrect. However, it must be noted that the reported “measured concentrations” represent a “compromise” between the relative concentration “increase” (due to the reduction in the amount of free water due to hydration) and the relative concentration “decrease” (due to incorporation of  $\text{Li}^+$  ions into the cement hydrates, presumably C-S-H). Therefore, the measured concentrations of  $\text{Li}^+$  ion higher than 0.5 M are simply indicative of the fact that lower amounts of  $\text{Li}^+$  ions were incorporated into the C-S-H gel.

For the slurries in which  $\text{LiNO}_3$  was added directly with the mix water, the observed relative decrease of  $\text{Li}^+$  ion concentration indicates that the amount of lithium incorporated into the cement hydrates was high enough to “mask” any apparent concentration increase due to the loss of the free water. As seen in Table 3, those slurries showed concentrations of  $\text{Li}^+$  ions of 0.428 M ( $w/c = 1.0$ ) and 0.488 M ( $w/c = 2.0$ ) both lower than 0.5 M initial concentration. For all other slurries, in which the  $\text{LiNO}_3$  was added at the latter ages, the  $\text{Li}^+$  ion concentrations were higher than 0.5 M, indicating that the degree of incorporation of  $\text{Li}^+$  ions into cement hydrates was reduced when the lithium admixture was introduced 1 day or 2 days after initial mixing of the cement and water.

The results of the cement slurry tests confirm that delayed addition of  $\text{LiNO}_3$  reduced the loss of  $\text{Li}^+$  ions. In addition, these results also indicate that the loss of  $\text{Li}^+$  ions from the pore solution takes place during the early stages of hydration (at the time of actual formation of the hydrates) and it is therefore not the result of delayed adsorption by the existing (mature) hydration products. If the reduction in the concentration of  $\text{Li}^+$  ions was primary due to their adsorption by the “mature hydrates”, then one would expect that identical amounts of  $\text{Li}^+$  ions will be lost after the same curing period, irrespective of the time of addition of  $\text{LiNO}_3$ .

On the other hand, if  $\text{Li}^+$  ions are predominantly removed from the pore solution during the formation of the hydrates (i.e. they are “captured” by the “immature hydrates”), one would expect (as

observed in the present experiment) that the amount of  $\text{Li}^+$  ions incorporated into the cement hydrates would decrease with the increase in time of  $\text{LiNO}_3$  addition. This is because the formation of “immature hydrates” would be more or less proportional to the rate of hydration, which decreases over time.

Delaying the addition of  $\text{LiNO}_3$  typically resulted in slightly higher concentration of  $\text{Na}^+$  and  $\text{K}^+$  ions for mixtures prepared at the same w/c. In addition, at each w/c level, the delayed addition of  $\text{LiNO}_3$  resulted in slight decrease of  $\text{OH}^-$  concentration. These results are consistent with the results of Bérubé et al. [21], who showed the increase in the concentration of  $\text{Li}^+$  ions in the pore solution increases in the concentration of  $\text{Na}^+$  and  $\text{K}^+$  ions and decreases  $\text{OH}^-$  ion concentration slightly.

### 3.2 Analysis of pore solution of mortars

Pore solutions extracted from mortars with non-reactive aggregate (Ottawa sand) were used to evaluate the influence of: (a) w/c, (b) molar ratio of lithium to alkalis, (c) temperature on the concentrations of various species in an attempt to determine how the loss of  $\text{Li}^+$  ions affects the overall levels of other ions. All measured concentrations of various ions ( $\text{OH}^-$ ,  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Li}^+$ ) were adjusted to account for the loss of free water and thus to allow the direct comparison of specimens at various degree of hydration.

#### *Concentration of $\text{OH}^-$ ions in pore solution*

As shown in Figure 1, the adjusted concentrations of  $\text{OH}^-$  ions in pore solution of NR0.47 mortar mixture increased during the first 7 days but it stabilized at an approximately constant value after that. These constant concentrations were computed for each mixture in order to determine how they were affected by changes in the  $\text{LiNO}_3$  dosages (and thus  $[\text{Li}]/[\text{Na}+\text{K}]$ ) and water-to-cement ratio. In general, at every w/c level, the increase in  $\text{LiNO}_3$  dosage resulted in slight decrease of  $\text{OH}^-$  ion concentration (Figure 1). These results confirm the previous finding by Diamond who reported that  $\text{LiNO}_3$  does not increase  $\text{OH}^-$  in the pore solution [18].

Although not shown in this paper due to the space limitation, a comparison of the adjusted concentrations of  $\text{OH}^-$  ion from the different water-to-cement ratios at the same dosage of  $\text{LiNO}_3$  showed that increasing the water-to-cement ratio resulted in only slight decrease of  $\text{OH}^-$  concentration. This result simply indicates the dilution effect of increased free water in mortars.

#### *Concentration of $\text{Na}^+$ and $\text{K}^+$ ions in pore solutions*

The adjusted concentrations of  $\text{Na}^+$  and  $\text{K}^+$  ions in pore solutions of mortars prepared at two different w/c ratios (0.42 and 0.47) are shown in Figure 2. Again, a slight gradual increase in concentrations during the first 7 days of hydration but the rate of increase slows down considerably during the next 7 days. In fact some mixes showed slight decrease in concentration. In addition, within the mixtures prepared at the same w/c, higher concentrations of  $\text{Na}^+$  and  $\text{K}^+$  ions were typically associated with the higher dosages of  $\text{LiNO}_3$ . The overall average concentrations of  $\text{Na}^+$  and  $\text{K}^+$  ions decreased with the increase in the w/c. These observations are consistent with the fact that  $\text{Li}^+$  ions were reported to be more preferentially incorporated into cement hydrates than  $\text{K}^+$  and  $\text{Na}^+$  ions [21]. As a result, increased levels of  $\text{Na}^+$  and  $\text{K}^+$  ions remain in the pore solution of mixtures with higher dosage of  $\text{LiNO}_3$ .

#### *Concentration of $\text{Li}^+$ ions in pore solutions*

As expected, the higher initial levels of addition of  $\text{LiNO}_3$  resulted in the higher adjusted concentrations of  $\text{Li}^+$  ions in the pore solution (Figures 3(a) and 4(a)). The adjusted concentration of  $\text{Li}^+$  ions in each mixture decreased significantly during the early stages of hydration (about the first 2 days) and then remained relatively constant. As already mentioned during the discussion of the results for cement slurries,

this can be attributed to the fact that  $\text{Li}^+$  ions are incorporated into the “immature hydrates” during the early stages of hydration. Since it has been suggested that only the  $\text{Li}^+$  ions that remain in the pore solution are effective with respect to preventing the expansion induced by ASR,  $\text{Li}^+$  ions removed from the pore solution due to incorporation with the cement hydrates represent a net loss of the admixture.

When comparing the initial (0 days) and the final (after 2 weeks) concentrations of  $\text{Li}^+$  ions at each w/c ratio, it can be observed that higher initial concentration of  $\text{Li}^+$  ions resulted in higher losses (Figures 3(a) and 4(a)) For example, the concentration of  $\text{Li}^+$  ions in NR0.42+50% Li mixture decreased only by 0.153 M (from 0.244 M to 0.091 M) but that of NR0.42+150% Li mixture decreased by 0.419 M (from 0.733 M to 0.314 M). These results suggest that the amount of lithium incorporated into cement hydrates is highly (and linearly) correlated with the initial  $\text{Li}^+$  concentration in the pore solution.

This strong, linear correlation can be readily observed in Figure 3(b) and 4(b). For the NR0.42 mixtures, the slope of the linear regression line was 0.4148, which indicates that practically the same percentage (41.5%) of  $\text{Li}^+$  ions remained in the pore solution, regardless of the initial different  $\text{LiNO}_3$  dosages. Similarly, for the NR0.47 mixtures, 48.2% of the initial amount of  $\text{Li}^+$  ions remained in the pore solutions. Thus, these results clearly show that (for the same w/c mortars), at any given age, an identical fraction of the  $\text{Li}^+$  ions would be removed from the pore solution, regardless of the initial amount of the admixture used.

In order to study the effect of w/c ratio on the loss of  $\text{Li}^+$  ions from pore solution, the mixtures having different w/c ratios but the same dosage of  $\text{LiNO}_3$  (NR0.42+100% Li, NR0.47+100% Li and NR0.55+100%) and cured at the same temperature (23 °C) were compared. The percentages of  $\text{Li}^+$  remaining in the pore solution after 14 days were, respectively, 39.5%, 44.2% and 51.3% of the percentage of the initial amount. These results indicate that, when using the same dosage of  $\text{LiNO}_3$ , higher water-to-cement ratio resulted in larger amount of  $\text{Li}^+$  ions remaining in the pore solution.

The effect of temperatures were also investigated by comparing NR0.55+100% Li mixtures which were exposed at 3 different temperatures (23°C, 38°C and 55°C). As shown in Figure 5, higher temperatures resulted in slightly increased adjusted concentrations of  $\text{Li}^+$  ions (from 0.232 at 23°C to 0.252 at 55°C). In general, however, the differences in the adjusted concentrations of  $\text{Li}^+$  ions were not significant, and thus the temperature does not seem to have a significant effect on the loss of lithium in the pore solution. These results are not surprising as all specimens were cured for the first day at in the curing room at 23°C and thus the significant amount of  $\text{Li}^+$  ions was already removed from the pore solution during that time.

#### 4 CONCLUSIONS

Pore solutions obtained from numerous mixtures were analyzed to develop the better understanding of the interaction between lithium ions and other ions present in the pore solution. The following conclusions can be drawn from the results obtained during this study.

- It has been shown that the early age loss of  $\text{Li}^+$  ions from pore solution is the result of their incorporation in the forming hydration products and not the results of sorption by the existing hydrates.
- About half (50~60%) of the originally added  $\text{Li}^+$  ions are removed from the pore solution after about two days of hydration, regardless of the initial amount added. Furthermore, the percent of  $\text{Li}^+$  lost remains constant in mixtures prepared at the same w/c. However, that percentage will decrease with the increase in the w/c value.
- The adjusted concentrations of  $\text{OH}^-$  ions in the pore solutions tend to decrease slightly when  $\text{LiNO}_3$  are added to the mixtures. In addition, adjusted concentration of both  $\text{Na}^+$  and  $\text{K}^+$  ions increase slightly with an increase in the dosage of  $\text{LiNO}_3$ . However, the overall effects of  $\text{LiNO}_3$  on the pore solution composition ( $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{OH}^-$ ) do not appear to be significant.

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TABLE 1: Paste slurry mixtures, LiNO<sub>3</sub> dosages and the addition time of LiNO<sub>3</sub>

Paste slurries	w/c	Cement (g)	Deionized water (g)	LiNO <sub>3</sub> (g)	Addition time of LiNO <sub>3</sub> (days)
Group 1	1.0	30	30	1.034	0, 1 and 2 days
Group 2	2.0	25	50	1.723	0, 1 and 2 days

TABLE 2: Mortar mixtures, LiNO<sub>3</sub> dosages and storage temperature

Mortar specimens	Cement	W/C	Vol. % of Ottawa sand	Weight ratio (sand / cement)	LiNO <sub>3</sub> dosage (%)	Molar ratio [Li] / [Na+K]	Initial conc. of Li <sup>+</sup> in mix water (m*)	Temp. (°C)
NR0.42+0% Li	C1	0.42	55	2.389	0	0	0	23
NR 0.42+50% Li	C1	0.42	55	2.389	50	0.370	0.244	23
NR 0.42+100%** Li	C1	0.42	55	2.389	100	0.740	0.489	23
NR 0.42+150% Li	C1	0.42	55	2.389	150	1.110	0.733	23
NR0.47+25% Li	C1	0.47	55	2.550	25	0.185	0.109	23
NR0.47+50% Li	C1	0.47	55	2.550	50	0.370	0.218	23
NR0.47+100% Li	C1	0.47	55	2.550	100	0.740	0.437	23
NR0.47+150% Li	C1	0.47	55	2.550	150	1.110	0.655	23
NR0.47+200% Li	C1	0.47	55	2.550	200	1.480	0.874	23
NR0.49+35% Li	C1	0.49	51	2.250	35	0.261	0.148	23
NR0.49+70% Li	C1	0.49	51	2.250	70	0.522	0.296	23
NR0.55+100% Li	C2	0.55	50	2.299	100	0.740	0.452	23, 38, 55

\* Due to overall low level of initial concentrations the molality (m) and molarity (M) of the solutions will be assumed to be approximately equal

NR: non-reactive aggregate

\*\* 100% LiNO<sub>3</sub> corresponds to 0.74 of [Li]/[Na+K] molar ratio

Paste slurries.	W/C	Addition time of $\text{LiNO}_3$ (days)	Measured concentration at 5 days (M)			
			$\text{Li}^+$	$\text{K}^+$	$\text{Na}^+$	$\text{OH}^-$
Group 1	1.0	0	0.428	0.171	0.073	0.393
		1	0.517	0.182	0.079	0.367
		2	0.527	0.181	0.080	0.352
Group 2	2.0	0	0.488	0.093	0.033	0.243
		1	0.524	0.098	0.035	0.233
		2	0.529	0.099	0.038	0.212

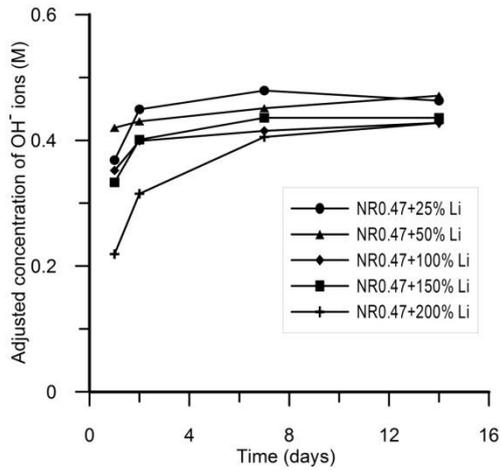


FIGURE 1: Adjusted concentration of  $\text{OH}^-$  ions in pore solutions of NR0.47 mortar mixtures

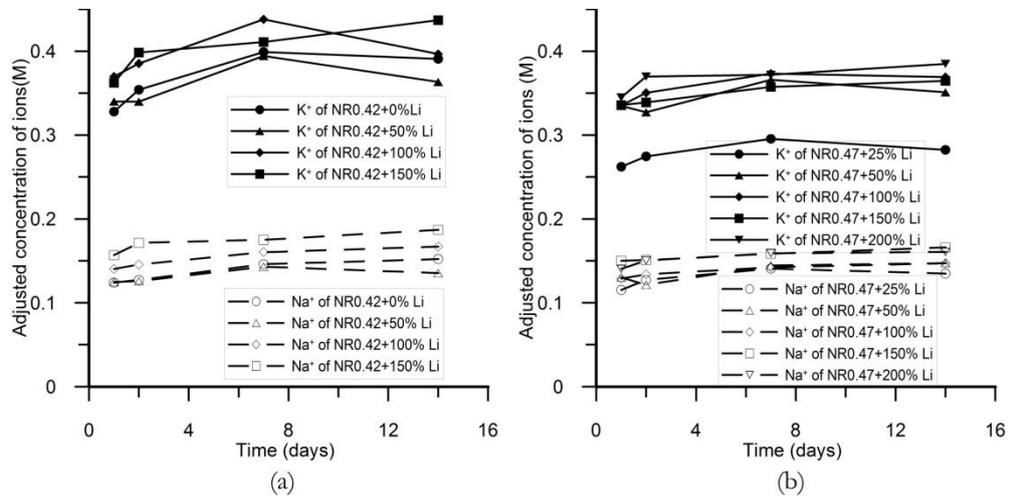


FIGURE 2: Adjusted concentrations of  $\text{Na}^+$  and  $\text{K}^+$  ions in pore solutions of NR0.42 and NR0.47 mortar mixtures

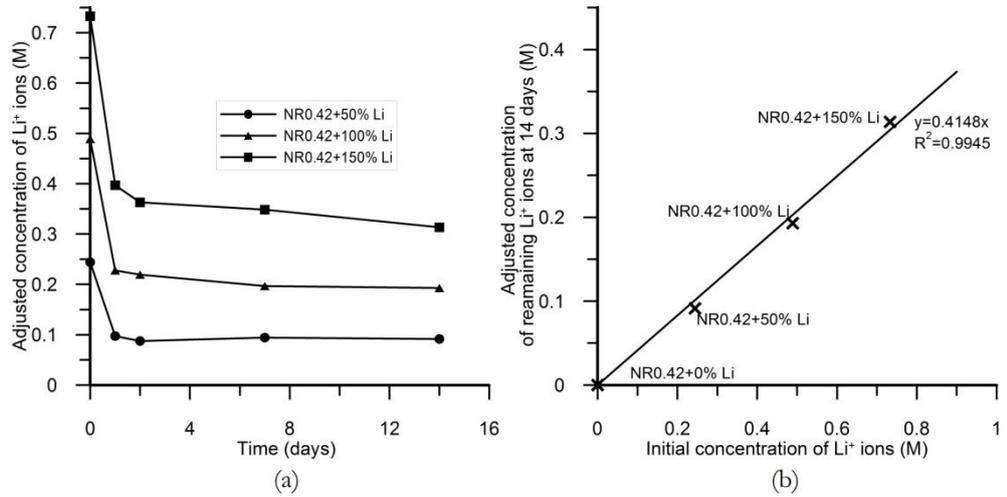


FIGURE 3: Adjusted concentrations of Li<sup>+</sup> ions in pore solutions of NR0.42 mortar mixtures

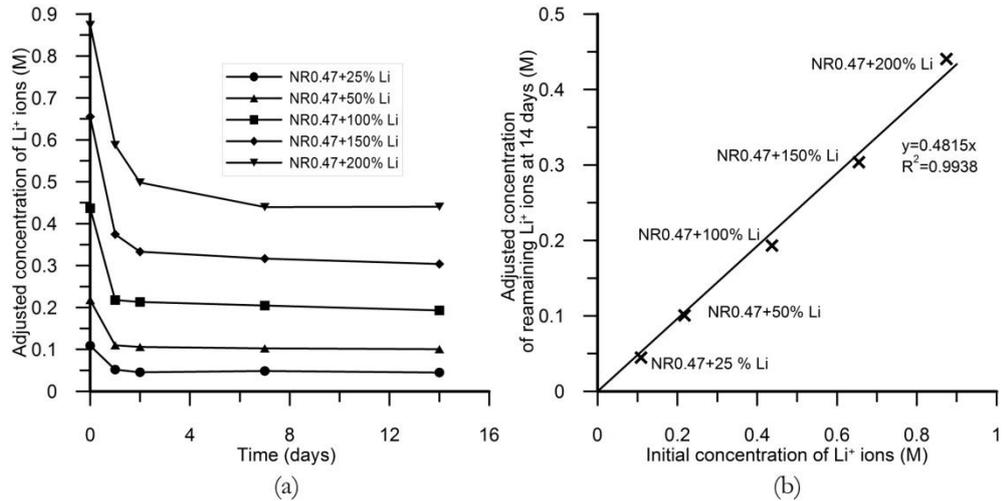


FIGURE 4: Adjusted concentrations of Li<sup>+</sup> ions in pore solutions of NR0.47 mortar mixtures

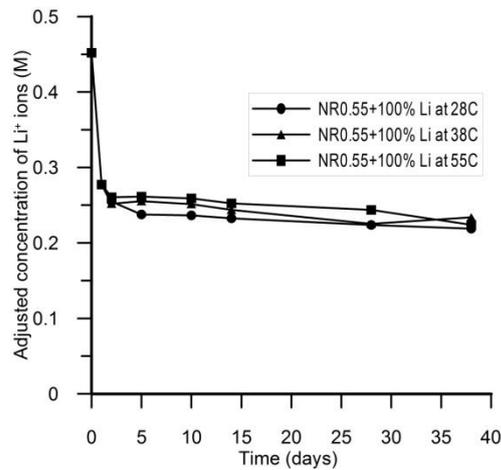


FIGURE 5: Adjusted concentrations of Li<sup>+</sup> ions in pore solutions of NR0.55+100% Li mortar mixtures cured at different temperatures