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Quantitative measurements of curing methods for concrete bridge decks

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HIGHLIGHTS

- Resistance of microstructure to lime water and chloride penetration is investigated.
- Drying rate is higher in lithium cured spans of bridge decks than in wet cured ones.
- Lithium cured samples have higher chloride concentration than wet cured samples.

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ABSTRACT

This paper gives a quantitative comparison of how different curing methods impact the rate of drying and subsequent penetration of lime water and chloride penetration of concrete. Laboratory work is used to investigate a bridge deck concrete mixture cured by two different curing compounds, wet curing of different lengths, and then no curing. The results confirm that wet curing methods reduce the ingress of external chemicals more effectively. The wet curing for even one day provided significant improvement over both curing compounds and no curing. To confirm the findings in the field eight bridge decks were investigated that were cured with a curing compound and wet curing. The field investigation confirms the findings of the laboratory testing and emphasizes the importance of wet curing for long term durability of concrete. This paper provides important quantitative data that can be used to compare these methods and help with making decisions about different curing practices and the impact on the service life of concrete.

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1. Introduction

After casting concrete it is typically necessary to maintain sufficient moisture content on the surface to sustain hydration [1]. This process is called curing [2]. Maintaining the moisture in concrete promotes reaction of the binder to develop a torturous and strong microstructure [1–3]. A torturous microstructure will reduce the drying rate and the ingress of fluids and external ions. This means that curing can improve the long-term durability of concrete [4–6].

Wet curing continuously supplies moisture to the surface of the concrete [1,2]. However, there are challenges in curing concrete elements that dry from one side, such as pavements [2,7,8]. For example, concrete pavement in a dry environment can suffer from large differential drying shrinkage after the termination of wet curing which can lead to dimensional instability, called curling [9–13].

Some have suggested that a possible alternative could be to use curing compounds instead of wet curing. While wet curing must be removed from the surface to allow traffic on the structure, curing compounds can stay in place until they are worn off the concrete surface [14,15]. Curing compounds have their own challenges. For example, the amount of curing compound needed depends on the ambient conditions, surface texture, and product being used [16]. Therefore, it has been suggested to apply them in two layers to ensure a uniform coverage [17–20].

Two recently developed curing compounds are investigated in this paper. The first is based on Poly(alpha-methylstyrene) or PAMS, which has been reported to be very effective in reducing the moisture loss and drying shrinkage induced curling [16,21]. This work also investigates a lithium silicate curing compound that has been reported to cure concrete and reduce the cracking in bridge decks [22]. The lithium silicates are reported to react with calcium hydroxide to generate calcium silicate hydrates and cause a densification near the surface [23,24]. Some researchers reported a potential benefit in using lithium-based curing for airport

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pavements [25–27]. It should be pointed that there is a lack of knowledge in the literature about the performance of different curing practices. This work aims to quantitatively compare the different performance in drying, subsequent moisture uptake, and then chloride penetration of concrete cured with different curing methods in laboratory testing. Therefore, the moisture loss, moisture gain on rewetting, and chloride penetration for concrete cured with curing compounds, no curing, and wet curing of different durations will be compared. To verify the findings, chloride profiles from eight bridge decks cured with a lithium silicate curing compound and wet curing are compared.

2. Experimental methods

2.1. Materials, mixture proportion, and procedures

The cement used for laboratory concrete samples was type I, according to ASTM C150 [28], and its chemical analysis is shown in the Table 1. Samples were made with dolomitic limestone aggregate and natural river sand used commercially in concrete. An ASTM C618 [29] class C fly ash with chemical analysis shown in Table 1 was also used.

All of the aggregate, both coarse and fine, were brought into the temperature controlled mixing facility at least a day before and their batch weights were corrected based on the moisture content of the aggregates. The aggregates were charged into the mixer along with approximately two-thirds of the mixing water. The combination was mixed for three minutes. Next any clumped fine aggregate was removed from the walls of the mixer. Then the cement and fly ash were loaded into the mixer, followed by the remaining mixing water. The mixer was turned on for three minutes. Once this mixing period was complete, the mixture was left to “rest” for the following two minutes while the buildup of material along the walls was removed. Next the mixer was allowed to run for three minutes and the water reducer was added as well. The mixture proportion used is presented in Table 2 for a cubic meter. The mixtures had a water to binder ratio (w/b) of 0.40 and 20% of the mass of cement was replaced by the class C fly ash. The slump, unit weight and the air content were measured according to ASTM C143 [30], ASTM C138 [31], and ASTM C231 [32] respectively. The results are presented in Table 2.

2.2. Sample Preparation, Casting, and curing

Three samples were used for each curing method. Each sample was cast in plastic containers with area of about 10.2 cm × 10.2 cm and a height of about 7.6 cm. Samples were filled with concrete in two layers and were rodded 25 times with a 9.5 mm rod at each

Table 2

The mixture proportions (kg/m³) and fresh concrete properties (assuming SSD condition).

Cement	Fly ash	Coarse aggregate	Fine aggregate	Water
290.1	72.4	1110	733.3	145.4
			Water reducer 9.7 (mL/kg)	
Unit weight (kg/m ³)		Slump (cm)		Air (%)
2234.6		10.2		2.5

layer and then the side was tapped to consolidate the concrete. The samples were finished with a wood float. After finishing the specimens were either wet cured, covered with a curing compound, or not cured. Details are provided in the following respective sections.

2.2.1. Wet curing and no curing

Samples were covered in wet burlap and a plastic tarp for 3, 7, and 14 days inside an environmental chamber room at 23 °C and 40% relative humidity. The burlap was wetted every day to ensure that it remained saturated until the curing was terminated. The sample that was not cured was placed directly in the environmental chamber.

2.2.2. Curing compounds

In addition to the wet cured samples, specimens were also cured with two curing compounds. A cart was constructed that held the application nozzle at a controlled height as shown in Fig. 1. The cart was moved across the sample at a constant velocity by placing marks on the track at set distances. A metronome was used to help the cart operator move at the desired velocity. For this testing the velocity of the cart was kept constant and the application rate was adjusted by changing the height of the spray nozzle. A pump pressure of 40 psi was used to produce a spray angle of 80° and a flow of 1.36 kg/min through a commercially available curing compound flat nozzle. To check the uniformity of the coverage, tests were done using steel plates of known areas placed at the same height as the specimen. These plates were weighed before and after applying curing compounds. By using the area of the plate and the weight of the curing compound the coverage was calculated. This equipment and procedure has been used successfully in other publications [21].

The suggested application rate by the manufacturer was 4.9 m²/L with a double layer of application. Therefore, a double layer of curing compound was applied in two equal layers with the application of each layer to be equal or close to 9.8 m²/L. The second layer was applied after a few minutes after the first one at the same rate and in the same direction. The results are shown in Table 3.

Table 1

Oxide analyses reported on the mill sheets.

Chemical test results (%) of the cement						
SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	CaO	SO ₃	
20.77	4.57	2.37	2.62	62.27	3.18	
Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	SrO	BaO	
0.19	0.32	0.34	0.14	0.22	0.07	
Phase concentrations (%) of the cement						
C ₃ S		C ₂ S		C ₃ A	C ₄ AF	
52.13		20.22		7.68	7.97	
Chemical test results (%) of the fly ash						
K ₂ O	BaO	MgO	SrO	CaO	SO ₃	Na ₂ O
0.58	0.72	5.55	0.39	23.12	1.27	1.78
SiO ₂	Al ₂ O ₃	MnO ₂	P ₂ O ₅	Fe ₂ O ₃	TiO ₂	
38.71	18.82	0.02	1.46	5.88	1.35	

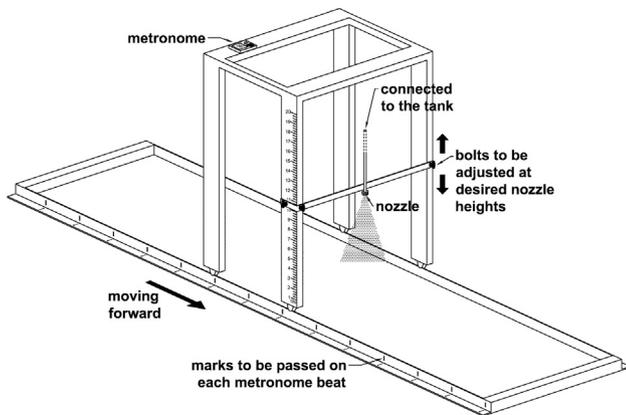


Fig. 1. The cart used to control the consistency of the application rate.

Table 3
Curing compound application rates.

Curing material	Application rate (m ² /L)
Lithium silicate	4.81
PAMS	5.14

2.3. Weight loss measurement

The loss of moisture of the sample was measured through the weight loss over time with 0.1 g accuracy. To ensure that drying only occurred from the top surface the samples were not demolded. After finishing each measurement, the specimen was returned to the chamber room. The weight loss measurements were continued for 22 days for all curing methods. Samples with the lowest mass loss are the best to resist drying and so are expected to have the most torturous microstructure. The time period was chosen based on previous testing that showed 22 days was enough time to find statistical differences in the different curing methods [9–11,21].

2.4. Storage in limewater

The samples were then removed from the environmental chamber and placed in limewater. This was done to measure the initial water uptake or sorption of the sample and also to condition the sample for bulk diffusion testing according to ASTM C 1556. The edges of the samples were sealed with wax before putting them in the limewater to force the water uptake to occur at finished surface. All samples were submerged upside down about 2.5 cm deep in 3 g/L saturated lime solution for 5 days. The weight before and after placing in the lime water solution was measured.

2.5. Storage in NaCl solution

Next, samples were ponded in 165 g/L aqueous NaCl solution according to ASTM C1556 [33] for 35 days at 23 °C. After ponding, samples were removed from the solution and stored for 24 h in laboratory conditions. The weight before and after ponding was measured. Then, samples were cut and the exposed cross section was polished on a sanding belt for 5 mins with 120 grit sandpaper to create a flat surface for μ XRF and optical microscopy. Ethanol was used to remove dirt and residue from the polished surface.

2.6. μ XRF

A μ XRF (Orbis by EDAX) was used to measure the Cl profile on the polished surface. The instrument uses an 80 mm² Silicon Drift

Detector Energy Dispersive Spectrometer (SDD-EDS) and a capillary optic that produces a 50 μ m diameter beam. Images are created by moving the sample under the stationary X-ray beam. The X-ray beam causes characteristic X-rays to be fluoresced at each spot, the intensity of these characteristic X-rays are measured by the SDD-EDS and stored in a database for later processing and analysis. Table 4 summarizes the settings used by the μ XRF in this work. More details can be found in other publications [34–36].

Reference standards were used to develop a calibration curve to change the count data to Cl concentration. This was done by making concrete samples with known amounts of NaCl.

The μ XRF data was used to make the compositional maps were analyzed with an image processing software package called Lispix [33]. Regions of unique chemical composition were defined as shown in Fig. 2. An image analysis code developed in Matlab was used to find Cl concentration over depth of the sample with 0.50 mm layers of equal thickness. Additional details and validation of the method can be found in previous publications [34–36].

A nonlinear regression is then conducted on Cl profiles with simplified solution of Fick's second law as shown in Eq. (1) [37], the values of apparent diffusion coefficient and surface concentration were determined. The highest Cl concentration within the sample is assumed as the surface concentration for samples that showed a reduction in Cl content at the surface:

$$C_{(x,t)} = C_s \left(1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_c t}} \right) \right) \quad (1)$$

$$C_{(x,0)} = 0 \text{ for } x > 0, C_{(0,t)} = C_s \text{ for } t \geq 0$$

where x is the distance from sample surface; t denotes time; D_c is diffusion coefficient; C_s is surface Cl concentration; $C_{(x,t)}$ represents Cl concentration at the depth of x from the surface after time t ; and erf is the error function.

2.7. Field sample acquisition and testing

Cores that were approximately 2 cm in diameter by 3 cm in height, as shown in Fig. 3, were taken from ten spans of a bridge deck in Oklahoma. The spans were either cured by 7 days of wet curing with wet burlaps that was applied within 30 mins according to Oklahoma Department of Transportation (ODOT) requirements, or with a lithium silicate curing compound with 4.9 m²/L application rate in double layers. The concrete mixture designs were similar with a water to binder ratio of 0.42, a minimum binder content of 335 kg/m³ with a 20% replacement of class C fly ash. All concrete had been in service for approximately two years at testing.

One insightful project was the Bristow Bridge carrying State Highway 66, located in Tulsa, Oklahoma. For this bridge, all spans were cast on the same day by the same contractor and materials supplier. Two spans of the bridge were wet cured for 7 days with wet burlaps and one of them was cured with lithium silicate curing compound with 4.9 m²/L application rate in double layers. This allowed a direct comparison between the two methods to be made.

Six cores were taken from each span. Cores were taken from areas that were clear of debris, cracks, and oil. These cores were

Table 4
Summary of μ XRF settings used.

Counts per second	Minimum of 20,000
Current	1 mA
Dead time	Maximum of 20%
Dwell time	400 ms/pixel
Filter	25 μ m Al
Vacuum	1 Torr
Voltage	40 keV

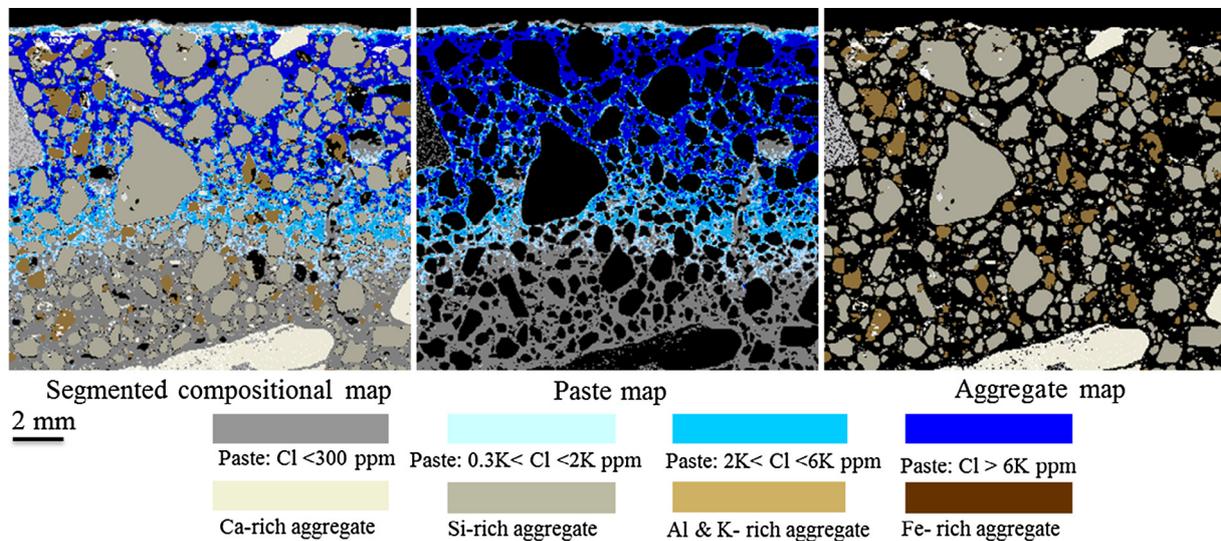


Fig. 2. An example of a compositional map showing the aggregate and paste: Compositional map (left), aggregate (middle), and cement paste (right), (K is an abbreviation for one thousand).

collected with a cordless drill. Since the cores were small, this minimized damage and patching to the bridges [38].

A cross section of each core was then exposed by polishing with 120 grit sandpaper for 5 mins. Next, the polished surface was cleaned with ethanol to remove any dirt and residue. A new piece of sand paper was used for each sample. Each sample was investigated with μ XRF to determine the initial Cl concentration profile from field exposure. While this value it useful it will depend on the amount of Cl that is placed on the structure and so the results can be subjective to local salting practices. However, more insights can be determined with additional laboratory testing.

Next, samples were conditioned in an environmental chamber at 23 °C and 50% RH for 72 days and the weight of samples were monitored. After conditioning, samples were sealed with wax on all surfaces but the finished surface. Next, the samples were exposed to saturated limewater for 5 days and then NaCl solution for 35 days. The samples were then polished and analyzed with μ XRF to find the resulting Cl profile.

The final Cl profile is the summation of the Cl introduced to the bridge before the core was taken and from the Cl added in the laboratory. However, since a Cl profile was measured before the labo-

ratory testing, the initial Cl profile can be subtracted from the final results of the laboratory testing. By subtracting the two profiles, the Cl introduced from the laboratory testing can be isolated. This allows a useful way to compare the effective Cl penetration for these different samples.

3. Results and discussion

3.1. Laboratory experiments

3.1.1. Mass change from drying

Fig. 4 shows the mass change in the samples after casting, the error bars show one standard deviation. The wet cured samples increase in mass and the others decrease in mass immediately. The mass gain for the wet cured samples is caused by the penetration of the curing water into the concrete. The error bars for the different wet curing lengths are so small and overlap which shows the consistency of the wet curing.

Because water penetrates into the wet cured samples this means that they contain more water than the other samples. Despite the wet cured samples containing more water, these samples showed a lower mass loss when the wet curing was removed. This lower evaporation rate of the wet cured samples is likely due to a more torturous pore structure for these materials. This decrease in evaporation rate improved as the wet curing was extended. Therefore, the 14-day wet cured specimen had the lowest mass change from drying. Both of the curing compounds show improvements over not curing – with PAMS showing the best performance of the curing compounds investigated.

3.1.2. Mass change from limewater

After the 22 days of drying, the samples were submerged in the limewater for 5 days. The mass increase after this period is presented in Fig. 5. One standard deviation is shown with error bars.

The mass change represents the amount of limewater absorbed into the sample. A smaller amount of mass change represents a lower amount of absorption and therefore a more torturous microstructure. The lowest mass gain was for the 14-day wet cured samples followed by 7 and 3 day wet cured specimens. However, the mass changes of 7 day and 14 day wet curing were only slightly different.



Fig. 3. Example of cores were taken from bridge deck.

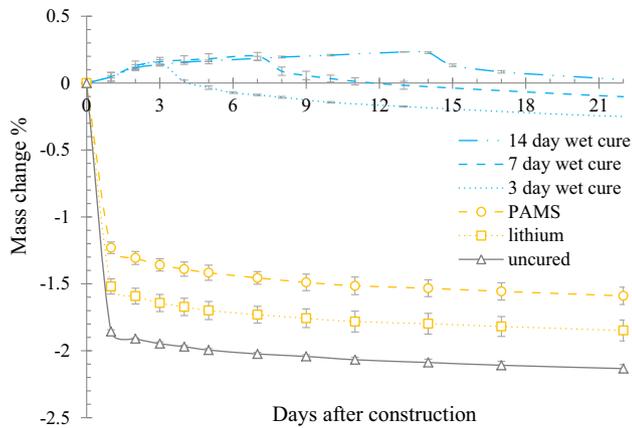


Fig. 4. Comparison between the mass changes over the time from curing and also storing samples in 40% RH and 23 °C after casting.

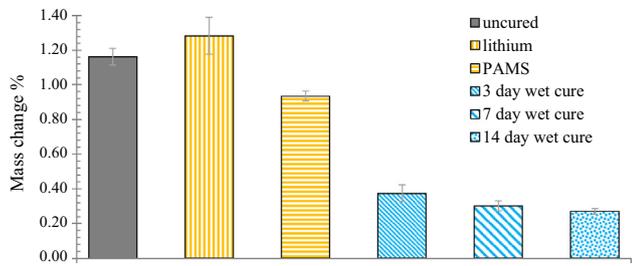


Fig. 5. Comparison between the mass changes after a 5-day limewater ponding.

Also, there was more limewater absorption in the lithium cured samples compared to PAMS specimens. This suggests that the PAMS curing compound creates a more impermeable microstructure at the surface among the two curing sealants. The uncured samples and lithium silicate curing compounds had statistically similar amount of surface absorption as there is overlap in their error bars. The investigated lithium cure sealant in this study has a poor performance and so more work is needed with other sealants to provide greater insights.

3.1.3. Mass change from NaCl solution

Next, the samples were ponded in NaCl solution for 35 days. The percentage of mass change is presented in Fig. 6. One standard deviation is shown with error bars.

The results of ponding in NaCl solution has a similar trend to the limewater absorption shown in Fig. 5. The wet cured samples showed the lowest Cl penetration. The 14-day wet curing specimens had the least mass change followed by 3 and 7-day wet curing. This is likely due to the higher penetration at the surface of the

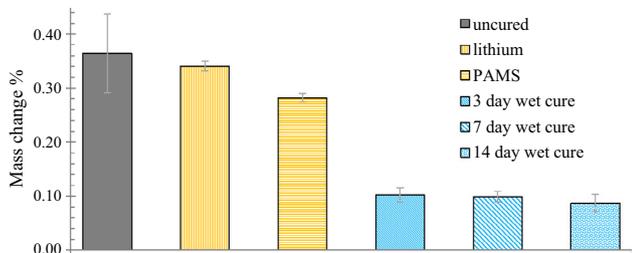


Fig. 6. Comparison between the mass changes from ponding in NaCl solution for 35 days.

sample because of the shorter duration of wet curing. Figs. 5 and 6 both show that wet curing of any length can have a huge impact on the penetration of outside fluids and ions at the surface of the concrete. This reduction in penetration can improve the expected life-time of the concrete.

Similar to the limewater ponding from Fig. 5, the PAMS specimens had less NaCl solution penetrate into the top layers compared to the lithium cured specimens. This is also caused by PAMS promoting a higher amount of hydration at the surface and this more torturous pore structure being more resistant to these solutions. Finally, the lithium cured samples showed almost the same amount of Cl penetration as the samples that were not cured. The standard deviation of the uncured samples was larger than all the other samples. This may be caused by an increase in surface cracking for the uncured samples.

3.1.4. Cl concentration profiles from μ XRF

Fig. 7 shows Cl concentration profiles for the samples with different curing methods as determined by μ XRF.

In addition, the total Cl content from the surface to 10 mm depth (this is the area under the Cl profile) is presented in Fig. 8 and calculated diffusion coefficients and surface chloride concentrations of varying samples based on Eq. (1) are summarized in Table 5.

The total Cl content is helpful to normalize some of the anomalies that may occur in the Cl profiles from local voids, cracks, or non-uniform aggregate distribution. Based on these results, the lowest Cl penetration and diffusion coefficient were for 7-day wet cured sample; however, the results are similar to the 14-day data set. This suggests that there is a little difference in the performance of Cl penetration after 7 days of wet curing but this should be investigated in more detail for a wider range of materials.

The uncured sample and a sample with lithium curing compound showed the highest Cl penetration and diffusion coefficient compared to other curing methods. The sample with PAMS curing compound showed an abnormal decrease in Cl concentration at the surface and then a sudden increase in Cl concentration between 2 mm and 6 mm in-depth. More research is needed to investigate this phenomenon. However, PAMS reduced the Cl diffusion coefficient by 27% when compared to uncured sample. In general, the wet cured samples showed better performance against Cl penetration (a 44% reduction in the diffusion coefficient of 7-day wet cure sample) than the samples with curing compounds or not cured. This was especially true for the measurements made over the first 4 mm of the sample and may reflect the benefits of wet curing. Furthermore, the wet cured samples reduced the surface Cl concentra-

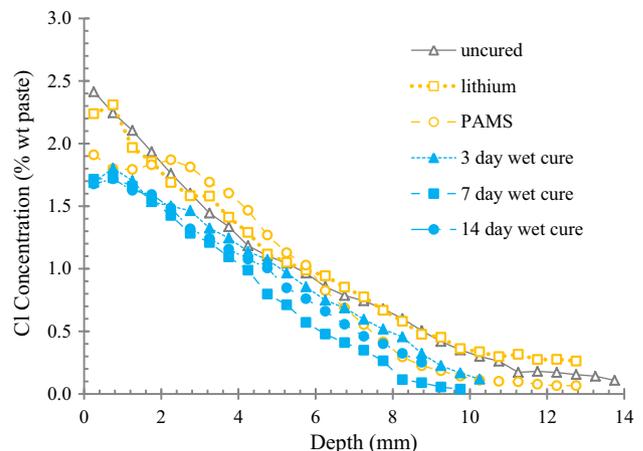


Fig. 7. Cl concentration profiles of samples with different curing regimes.

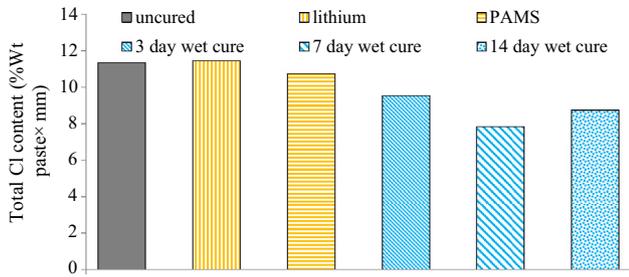


Fig. 8. Total Cl content of samples up to 10 mm depth (area under Cl profiles).

Table 5 Diffusion coefficient and surface chloride concentration of samples.

Sample	$D_c \times 10^{-12}$ (m ² /s)	C_s (% Wt paste)	% decrease of D_c	% decrease of C_s
Uncured	7.5	2.4	0	0
Lithium	8.7	2.3	-16.7	4.1
PAMS	5.5	2.2	26.8	9
3-day wet cure	7	2	6.9	20.4
7-day wet cure	4.2	2	43.9	20.3
14-day wet cure	6.3	1.9	16.2	23

tion about 20–23% compared to uncured and lithium cured samples.

3.2. Field samples

3.2.1. Mass change for Bristow Bridge

The mass change results of field samples from the Bristow Bridge from different curing conditions stored in 50% RH and 23 °C are presented in Fig. 9.

Based on Fig. 9, the lithium silicate cured samples showed higher mass gain over time compared to the wet cured samples (i.e., mass gain of 0.91% and 0.62% for lithium silicate and wet cured samples respectively after 72 days of conditioning). This suggests that the drying rate in the field was higher for the lithium cured span of the bridge compared to the wet cured spans of the investigated bridge. This suggests that the wet cured sample had a more torturous microstructure. This result is consistent with the results of laboratory experiments.

3.2.2. Cl concentration profiles from μXRF for Bristow Bridge

Fig. 10 shows the Cl concentration profiles of field samples with different curing conditions.

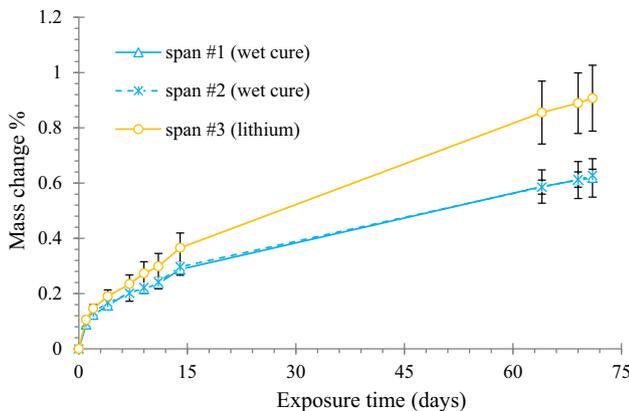


Fig. 9. Comparison between the mass changes over the time from storing field samples from Bristow Bridge in 50% RH and 23 °C.

According to Fig. 10, the lithium cured samples from span #3 showed higher concentration of Cl over the sample depth and also higher depth of Cl penetration compared to wet cured samples from spans #1 & 2. The Cl concentration is about 0.75% by weight of paste at depth of 10 mm of lithium cured sample compared to the 0.12% at the same depth in wet cured samples. With assumption of Cl threshold value of 0.21% by weight of paste (≈0.05% weight of concrete) [39], the Cl concentration at depth of 10 mm of lithium cured sample is 3.5× of the assumed Cl threshold value. This suggests that the lithium cured span did not produce a surface that was as impermeable as the wet cured sample spans.

3.2.3. Cl concentration profiles from μXRF for other bridges

Seven other spans were investigated that used lithium silicate curing compound or water cured and the results are shown in Fig. 11. In most of cases, the lithium silicate curing compound showed a higher Cl value at a comparable depth to the cores from water cured spans. This again supports all other findings in this paper and shows that similar results were obtained with a wide range of materials, contractors, and field conditions.

3.3. Practical considerations

This work has shown that based on laboratory and field testing that the curing method used on concrete has a profound impact on the ability to resist drying, moisture penetration, and Cl penetration. All of these measurements are an indicator of the durability of concrete and so this data provides comparative insights into how curing practices impact concrete durability. This work shows that even wet curing concrete for 3-day showed a significant improvement over the two curing compounds investigated and

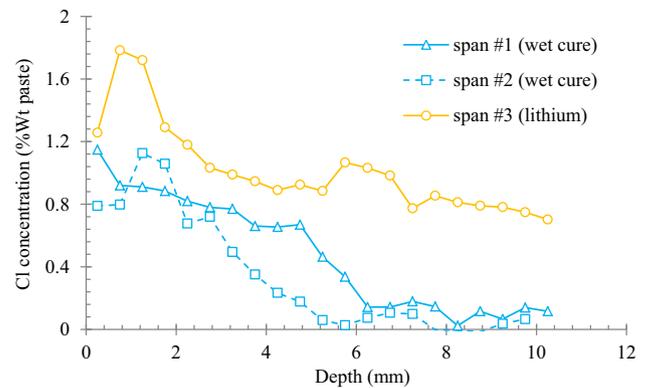


Fig. 10. Cl concentration profiles of field samples from Bristow Bridge.

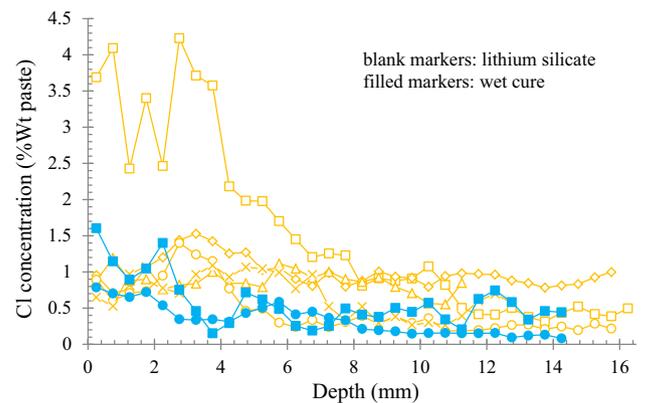


Fig. 11. Cl concentration profiles of field samples from seven bridges.

not curing. The work also shows that after wet curing for 3 days that there was only minimal improvement in the performance of the concrete. While this suggests that extended wet curing may not be necessary, these experiments were only done with limited materials. However, because there is uncertainty in the weather and field practices, additional wet curing beyond these limits are needed to ensure the necessary concrete properties are obtained.

While many practitioners have complained of the increased cost and effort to wet cure concrete, the results show that it reduced the Cl diffusivity by 44% in the laboratory testing and 6 times in the field testing while also reducing drying rate and moisture uptake. This suggests that using a wet cure for concrete will increase the time-to-corrosion initiation of rebars and subsequently service life of the bridge decks. These results are based on both laboratory and field testing. These quantitative differences allow a specifier to compare the cost of two practices to the resulting benefit and determine if this is an economical choice. While it is unrealistic to think that all concrete should be wet cured, these results suggest that concrete that desires long life – such as a bridge deck – then there seems to be strong justification to wet cure concrete over using the curing compounds investigated.

4. Conclusions

This work provides quantitative comparisons of the impact of different curing methods on the evaporation rate during drying, subsequent moisture uptake, and Cl penetration that can help practitioners decide how their construction practices impacts the durability of their concrete.

The following conclusive remarks can be made:

- The samples that were uncured showed the worst performance of the investigated samples.
- Wet curing significantly reduced the mass loss during drying, mass gain from sorption, and the penetration of NaCl solution.
- As the wet curing was increased then so was the durability performance in these tests; however, there was a little improvement after 7 days of wet curing with these materials and in this testing. This finding should be investigated with a wider range of materials before changes in practice are made.
- PAMS curing compound performed better than the lithium silicate curing compound in water retention during drying, and then the subsequent resistance of the microstructure to lime-water and NaCl penetration.
- The drying rate in the field was higher for the lithium cured span of the bridge compared to the wet cured spans of the investigated bridge.
- The lithium silicate cured samples from the field showed higher Cl concentration and penetration depth compared to the wet cured samples for all seven bridges investigated.

This work concludes that wet curing is preferable over curing compounds for concrete if decreases in rate of drying, moisture penetration, and external chemicals are desirable. The reader should be careful in interpreting the results for the effectiveness of wet curing for different durations. Wet curing for longer durations is helpful to ensure that a minimum curing length is provided for a wide range of materials, construction practices, and weather.

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