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Do crystalline water proofing admixtures affect restrained plastic shrinkage behavior of concrete?

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ABSTRACT

This paper describes the effect of crystalline water proofing admixtures on early-age cracking in concrete. The performance of three different types of these admixtures was compared to that of control. This study has been performed in two stages. Stage one was performed under ASTM specified conditions and a modified stage where more severe drying conditions than that described in the ASTM test standard were used. These modified conditions simulated inadequate curing under extreme exposure conditions as experienced by concrete in many parts of the world. The test results indicate that the water proofing admixtures can effectively reduce the early-age shrinkage cracking. The possible reasons for this secondary advantage of crystalline water proofing admixture is also hypothesized in this paper.

Keywords: restrained plastic shrinkage cracking; crystalline water proofing admixtures; crack reduction ratio; time to first crack.

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¿Los aditivos de impermeabilización cristalina afectan al comportamiento de retracción plástica restringida del concreto?

RESUMEN

Este artículo describe el efecto de las mezclas cristalinas de impermeabilización sobre el agrietamiento en concreto a temprana edad. El rendimiento de tres tipos diferentes de estos aditivos se comparó con el de control. Este estudio se ha realizado en dos etapas: la primera se realizó bajo condiciones especificadas por ASTM y la segunda fue una modificación de la primera, en la que se usaron condiciones de secado más severas que las descritas en la norma de ensayo ASTM. Estas condiciones modificadas simulaban un curado inadecuado en condiciones extremas de exposición como las experimentadas por el concreto en muchas partes del mundo. Los resultados de la prueba indican que los aditivos de impermeabilización cristalina pueden reducir eficazmente el agrietamiento por retracción a edad temprana. Las posibles razones de esta ventaja secundaria son también supuestas en este trabajo.

Palabras clave: agrietamiento por retracción plástica restringida; mezclas cristalinas de impermeabilización; relación de reducción de grietas; tiempo para la primera grieta.

As adições cristalinas impermeabilizantes afetam o comportamento da retração plástica do concreto?

RESUMO

Este artigo descreve o efeito de aditivos de impermeabilização cristalina na fissuração precoce em concreto. O desempenho de três diferentes tipos destas adições foi comparado com o de controle. Este estudo foi realizado em duas etapas. A fase 1 foi realizada sob as condições especificadas na ASTM e uma fase modificada onde foram utilizadas condições de secagem mais severas do que as descritas na norma de ensaio ASTM. Estas condições modificadas simulam uma cura inadequada em condições extremas de exposição, tal como experimentado pelo concreto em muitas partes do mundo. Os resultados do ensaio indicam que as adições impermeabilizantes podem efetivamente reduzir as fissuras de retração. As possíveis razões para esta vantagem secundária da adição impermeabilizante cristalina também são discutidas neste artigo.

Palavras-chave: fissuração por retração plástica; adições cristalinas impermeabilizantes; relação de redução de fissuras; tempo para a primeira fissura.

1. INTRODUCTION

The demand for cement around the world has continued to be strong over the last decade even though there have been major concerns about the CO_2 emissions associated with its production. To make concrete more sustainable, recent measures being taken include use of limestone blended cement (recently launched in the Canadian market (Holcim, 2011)), use of alternate fuels (Vaccaro, 2006) and improved energy management to fire kilns, and use of higher amounts of SCMs (supplementary cementing materials) in concrete. A complementary approach to make concrete a sustainable material is to improve its service life by improving its durability. One of the key parameters that affects durability of concrete structures is its permeability. Various commercial methods available to decrease permeability of concrete have been previously discussed by the authors (Biparva & Gupta, 2010). Even though the main motivation of such crystalline admixtures is to make concrete less permeable over time, it is well known that these admixtures also modify the early-age properties of concrete. Crystalline Admixtures are one of the Permeability Reducer

Admixtures (PRAs) type as described by the American Concrete Institute (ACI) Committee 212. Contrary to hydrophobic or water-repellent materials, these products are hydrophilic which makes them to react easily when moisture enters into the pores/cracks of concrete. After taking this reaction in place, the admixture forms water insoluble pores/cracks blocking crystals that create very low permeable concrete due to increase in density of Calcium Silicate Hydrate (CSH, main cement hydration product) and higher resistance to water penetration. The matrix component which reacts is tri-calcium silicate (C_3S) and presence of water is also essential for the reaction. Depending on crystalline promoter and a precipitate formed from calcium and water molecules, active chemicals contained in cement and sand form these products. As a result of crystalline depositions into concrete matrix, pressure resistance of modified matrix increases as high as 14 bars. In this previously published work, the authors have discussed the various advantages of using a hydrophilic crystalline water proofing admixtures in concrete over other methods to make concrete water proof. They mention that by using crystalline waterproofing not only can concrete permeability be reduced, but also other properties such as self-sealing and shrinkage will be affected. Some results are summarized in this published paper, but a more focused research is required to investigate the effects of different integral waterproofing admixtures on key properties such as self-sealing and shrinkage. Most of the available literature only describes the effects of these admixtures on the permeability of concrete (Geetha & Perumal 2011), but key properties such as self-sealing and shrinkage are still not understood.

The effect of various admixtures, mineral additives, and fibers on restrained plastic shrinkage has been studied by many researchers. This includes studying the effect of shrinkage reducing admixtures (Weiss and Shah, 2002; Lura et al, 2007; Bentur et al, 2001), silica fume (Bloom and Bentur, 1995), limestone (Corinaldesi & Moriconi, 2009), fly ash (Gupta et al 2010), and fibers (Soroushian et al, 1992; Soroushian & Ravanbakhsh, 1998; Corinaldesi & Moriconi, 2009; Gupta et al, 2010) on restrained plastic shrinkage of concrete. However, a literature search by the authors to identify the effect of crystalline waterproofing admixtures on restrained plastic shrinkage using the ASTM C1579 test method did not result in any articles. Moreover, no previous studies reporting the effect of these water proofing admixtures on drying shrinkage could also be identified. The research study presented in this paper was initiated due to the lack of understanding about the effect of these water proofing admixtures on restrained plastic shrinkage potential of concrete. Research was conducted according to ASTM C1579 to study the effect of three different types of admixtures on shrinkage cracking. The test conditions specified in the test standard were modified to simulate more severe curing conditions that concrete is exposed to in many parts of the world.

2. EXPERIMENTAL PROCEDURE

2.1. Mix design

A control mix with target strength commonly specified in practice of 40 MPa was chosen for this study. To study the effect of crystalline based waterproofing admixtures on plastic shrinkage, three commercially available products were used to modify the control mix. The admixtures chemically reacts with infiltrated water/moisture in the pores/cracks of concrete and results in growth of microscopic crystals that block the flow of moisture, hence making concrete more impermeable. Dosages recommended by the manufacturers were used to modify the control mix. Admixture K, P, and X were added at 2.0%, 0.8%, and 1% of the cement mass respectively in the control mix. A w/c ratio of 0.55 was chosen for all the mixes. Mix proportions can be seen on Table 1.

Table 1. Mix proportions

Ingredient	Quantity (kg/m^3)
Portland cement	340
Gravel	1120
Sand	820
Water	187

2.2. Test set-up

Molds were used according to ASTM C 1579-06, to induce a crack along the center of the slab. Slabs were 355 (± 10) mm x 560 (± 10) mm x 100 (± 5) mm and contained a metal stress riser plate that was bolted to the bottom of the mold. The stress risers were used to induce a crack in the concrete at an early age. For each mix, two specimens were tested in the environmental chamber shown in Figure 1.

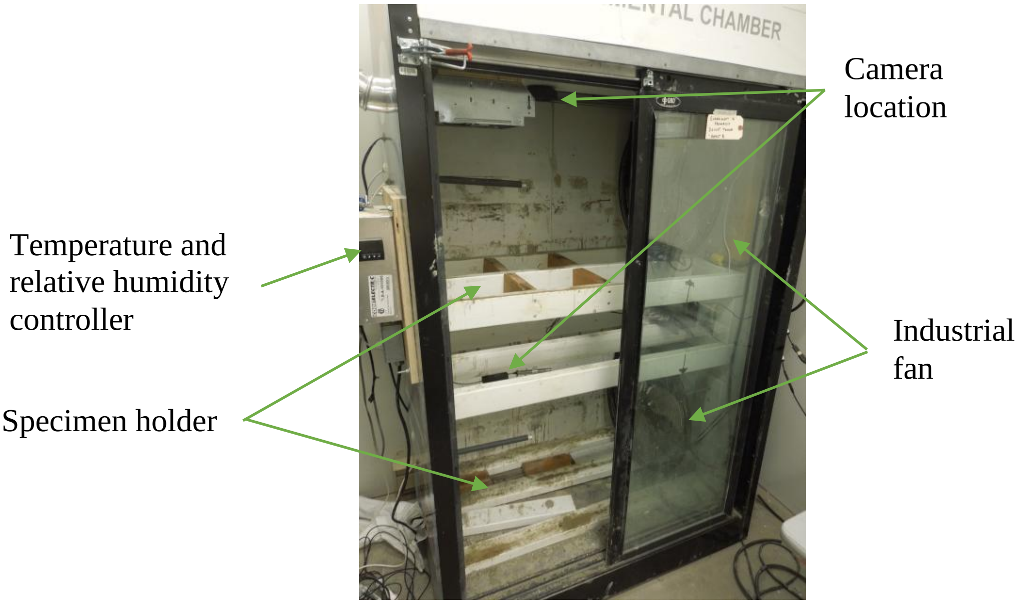


Figure 1. Instrumented environmental chamber for conducting restrained plastic shrinkage tests

Testing was done following ASTM C1579 standard in terms of materials, molds and specified environmental conditions. However, additional trials using higher temperatures and lower humidity were conducted to simulate conditions more severe than those specified by the test standard. According to the ASTM standard the temperature must be 36 ± 3 °C, the relative humidity 30 ± 10% and a minimum wind speed of 4.7 m/s over the center of the sample. The measured evaporation rate in the environmental chamber was greater than 1.0 kg/m^2/hr which is specified in the test standard.

2.3. Environmental Conditions

The conditions of the Environmental Chamber were regulated using a temperature and relative humidity controller. The temperature and relative humidity were recorded using a HOBOware data logger. A dual temperature and humidity sensor was placed above the center of each slab. Readings were taken by the logger every 10 seconds and the results were plotted using HOBOware software.

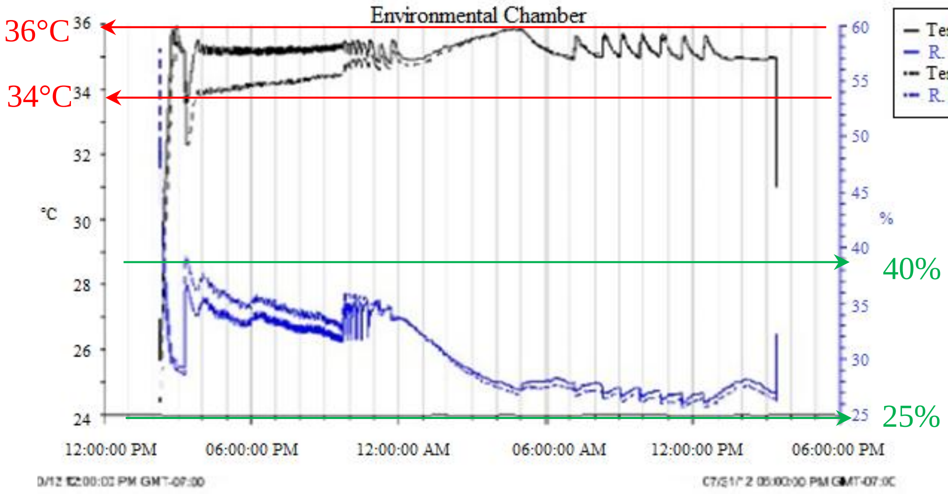


Figure 2. Typical screenshots of temperature and humidity vs. time (Standard conditions)

The graph above is a screen shot of the data and hence does not have very high resolution. This graph is however described below for clarity. Figure 2 shows a conditioning period of one hour when the temperature and relative humidity are brought up from ambient to standard test conditions. This is indicated by the first rise in temperature and drop in humidity. Later, there is a sharp increase in humidity and decrease in temperature, which indicates the slab being placed in the chamber. A few minutes after placing the specimens, both the temperature and humidity stabilize within the ASTM specified tolerances. The solid and dashed black curves represent the temperature at the top and bottom of the chamber respectively. Similarly, the two blue curves correspond to humidity values at the top and bottom of the chamber. Since the screen shots presented here have poor resolution, red lines and green lines have been added to allow reading the upper and lower bound temperature and humidity values respectively. Testing is conducted for 24 hours, after which the sample is removed and its crack size is measured. Once the specimens were placed in the environmental chamber the temperature was between 34°C and 36°C throughout the test (red lines), whereas the humidity was within a tight range of 25-40%. These values are within the limits allowed by ASTM.

2.3.1. Modified Condition

To study the behavior of the mixes tested previously under more severe drying conditions, the conditions in the environmental chamber were modified. As described earlier the solid red and blue lines have been added to read upper and lower bound temperature and humidity values respectively during the first 8 hours of the test. The dotted lines correspond to the modified conditions in the chamber after the first 8 hours.

As with the standard condition there is a conditioning period before placing the slab and a rebound period after. The modified condition was intended to expose specimens to more extreme temperature and humidity conditions. Conditions specified by the ASTM standard were used for the first 8 hours to emulate a work day were the concrete is monitored and maintained. After the 8 hour period the conditions were altered so that the temperature was gradually increased to 46±1°C. This resulted in the humidity to drop to a 15-27% range within 4 hours of these conditions being imposed. This approximately represented a 30% increase in the average temperature and a decrease of about 25% in the humidity. Testing under these conditios was also conducted for 24 hours, after which the cracks were measured.

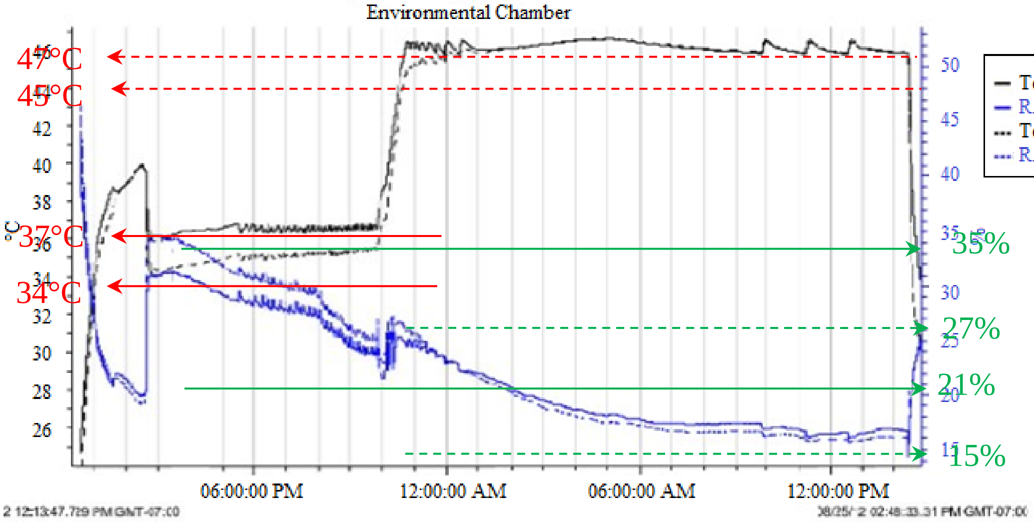


Figure 3. Typical screenshots of temperature and humidity vs. time (modified conditions)

2.4. Time to cracking

Even though not a requirement of the test standard, the time to first crack was measured using two HP AutoFocus 720i high definition video cameras. Video of the slab during the test was recorded to determine the time of cracking. This eliminated the need to manually observe the specimens for cracking.

3. RESULTS

3.1. Crack width

After 24 hrs, the test specimens were removed from the chamber and the cracks characterized. The crack size was measured using an optical handheld microscope at intervals of 10 mm along the length of the crack. The average of all the readings for the two specimens are presented in Table 2. Also, included in this table is the maximum crack width recorded in the specimens.

Table 2. Crack width measurements

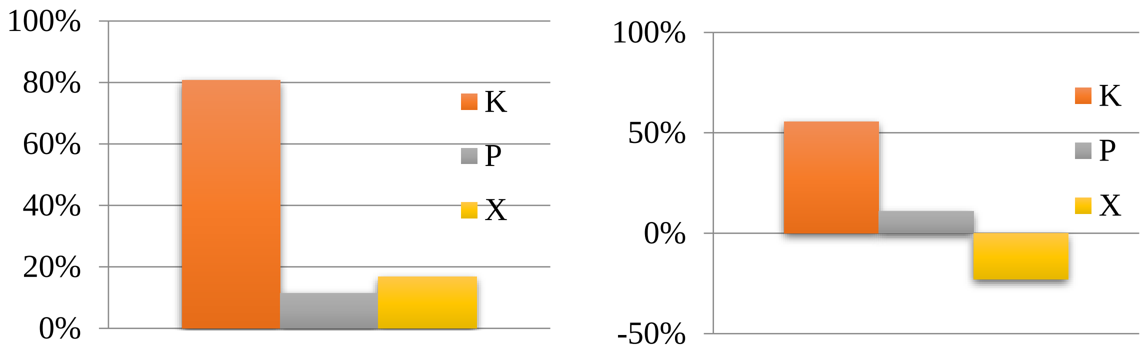
Mix	Average crack width (mm)		Maximum crack width (mm)	
	Standard conditions	Modified conditions	Standard conditions	Modified conditions
Control	0.57	0.50	1.3	1.0
K	0.11	0.22	0.6	0.62
P	0.50	0.45	1.02	0.98
X	0.47	0.62	1.0	1.2

The results in Table 2 clearly indicate that admixture K significantly reduces the average crack widths and maximum crack widths when compared to control under both standard and modified conditions. Similarly admixture P also shows some reduction in cracking when compared to control. Even though admixture X showed reduction in crack width under standard condition, it was higher than that measured for control under modified conditions. This indicates that some water proofing admixtures may be less effective at reducing shrinkage cracking under hotter and dryer conditions.

3.2. Crack reduction ratio

ASTM C1579-06 specifies that a crack reduction ratio (CRR) can be calculated using the following formula:

$$CRR = \left[1 - \frac{Average\ Crack\ Width\ of\ Modified\ Concrete}{Average\ Crack\ Width\ of\ Control\ Concrete}\right] \times 100\% \qquad (1)$$



a) Standard environmental conditions **b)** Modified environmental conditions

Figure 4. Crack reduction ratio over control

The graphs in Figure 4 compare the crack reduction ratio of each admixture when compared to control concrete mixture. It is evident that admixture K is the most effective in reducing the crack width. When admixture K was added at a dosage of 2% by mass of cement, the crack reduction ratio under standard conditions was about 80% and that under modified conditions was approximately 55% (shown in Figure 5). In comparison, the dosage for admixture X was only half of K, but this resulted in a CRR of only 15% under standard conditions and a negative CRR greater than -20% under modified conditions (meaning increasing the crack width). Admixture P at 0.8% by mass of cement had a modest CRR of about 10% under both environmental conditions.

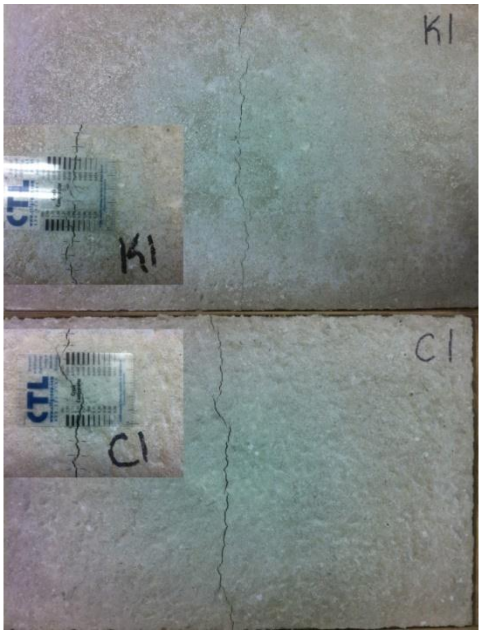
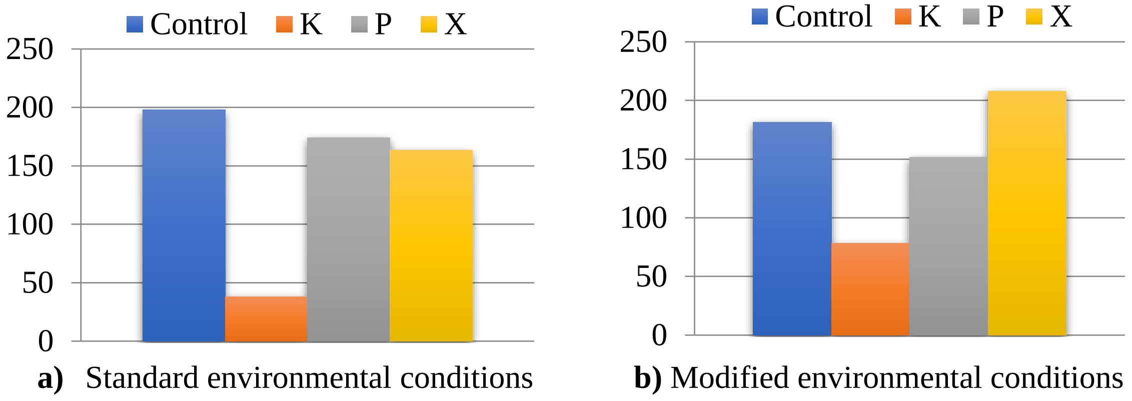


Figure 5. Crack widths of Control (C1) when compared with K1 (modified conditions)-indicating an approximate CRR of 55%.

3.3. Crack Area

Based on the crack width measurements, crack areas were calculated for all the specimens. The average crack areas for standard and modified conditions is shown in Figures 6a and 6b respectively. It is clear from the figures that the average crack area for the control was higher than 150mm2. All admixtures reduced the crack area under conditions specified by ASTM and under modified conditions. The only outlier was X that showed an increase in cracking under modified conditions. At the specified dosage, admixture K seems to be the most effective in reducing shrinkage induced cracking.



a) Standard environmental conditions **b)** Modified environmental conditions

Figure 6. Average crack area (mm^2)

3.4. Crack time and future scope of research

The following tables list out the time it took for each slab to crack. The time of cracking was observed visually from a video recording.

Table 3. Measured time to first crack.

Mix	**Time to first crack (h:min)**	
	Standard conditions	**Modified conditions**
Control	1:21	1:41
K	2:15	2:29
P	1:24	1:49
X	2:16	2:22

The time to first crack for the control specimens when compared to the mixes with admixtures is the lowest under both standard and modified conditions. This indicates that all the admixtures delay in formation of the first crack. Admxitures K and X delayed the time to first crack when compared to the control by an average of approximately 50mins considering both standard and modified conditions. The delay in time to first crack due to admixture P when compared to control was only an average of 5 mins.

It is also observed that the time to first crack increased under modified conditions not just for control but all specimens by an average of 16 mins. Under modified conditions, when the temperature is higher, the rate of strength gain would be faster. A delay in time to first crack under modified conditions for the control mix and the mix modified with admixture P translated into narrower cracks and slightly lower total crack area (refer to Table 2 and Fig. 6). However, for admixture K and X, larger crack areas were recorded under modified conditions. When compared to control, admixture K caused the largest delay in time to first crack and resulted in the highest CRR. Hence, no conclusive trends can be drawn from the available data and further research is warranted to confirm the relation between time to first crack and cracking. The influence of mixture proportion and additives such as fly-ash on evaporation rate has been described in a study by Banthia and Gupta (Banthia & Gupta, 2009). Future studies should focus on measuring the evaporation rate directly from the specimens as opposed to measuring the evaporation in the environmental chamber. Evaporation of moisture from the specimens is also a function of bleeding, hence measuring loss of moisture from the specimens directly can help capture the effect of bleeding as well. However, the large specimen size specified in ASTM poses challenges in accurately measuring the moisture loss from the specimens. The reduction in cracking observed in this study could be due to a faster rate of strength gain in at early-ages. To confirm this hypothesis future studies will focus on measuring the moisture loss of the specimens and also measuring the simultaneous increase in early-age strength gain of the material using dog-bone shape specimens as utilized in a study by Gupta (Gupta, 2008).

4. CONCLUSIONS

In this paper, the effects of crystalline waterproofing admixtures on restrained plastic shrinkage was examined under two environmental conditions, one specified by ASTM C1579 and the other modified. Three types of admixtures were used and added in concrete per the dosage prescribed by the manufacturers. Under both environmental conditions the samples with admixtures tended to resist cracking better than a control of the same mix proportions. Admixture K had a crack reduction ratio of approximately 80% and 55% under the standard and modified conditions respectively. The marked decrease proves that the admixture K resists plastic shrinkage effectively. The Admixture P maintained a 10% crack reduction ratio in both environmental conditions. Finally the Admixture X showed a small decrease in crack size in the standard condition. However, it performed poorly in the modified condition with it cracking more than the control. Overall, commercially available crystalline water proofing admixtures seem to offer the secondary benefit of serving as a shrinkage reducing admixture especially at early age.

5. ACKNOWLEDGEMENTS

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