Journal of Metals, Materials and Minerals, Vol.21 No.1 pp.9-17, 2011

Self-Crack Closing Ability of Mortar with Different Additives

Dechkhachorn JAROENRATANAPIROM[1] and Raktipong SAHAMITMONGKOL[2*]

[1]*Graduate Student, Asian Institute of Technology (AIT), Thailand*
[2]*Researcher, Construction & Maintenance Technology Research Center (CONTEC), Sirindhorn International Institute of Technology (SIIT), Thammasat University, Thailand*

Abstract

Self-crack closing ability of cementitious materials has been studied in various aspects. However, most studies focus mainly on the cementitious material with only cement as a binder (without mineral additives), although many additives are commonly used at present. This research thus aims to investigate the effect of additives on this self-crack closing ability by observing and measuring crack width on the mortar specimens. Cracks were created on mortar specimens by splitting method at the age of 3 and 28 days. As most reports show that the best self-crack closing performance was achieved when a plenty of water was supplied, the cracked specimens were thus cured in water for investigation of the self-crack closing ability.

According to the results, it was observed that all mortars showed self-crack closing ability to some extent, even the control mortar which had no additive. In addition, the results indicate that adding some types of additive improved the self-crack closing ability of mortar. For the range of 0 - 0.05 mm crack width, mortar with crystalline admixture showed the best performance to close its cracks at both cracking ages (3 and 28 days). However, for larger cracks, mortar with silica fume was more outstanding in terms of self-crack closing ability, especially when the crack was generated at the age of 28 days. Fly ash was found to be the worst additive to promote self-crack closing ability of mortar in most cases.

Key words: Additives, Crack width, Crystalline admixture, Expansive additive, Fly ash, Limestone powder, Self-crack closing, Silica fume

Introduction

Cracking is considered as an inherent feature of reinforced concrete structures. Cracks can be caused by loading of a structure itself or other mechanisms, e.g. drying shrinkage, thermal effect and freeze-thaw cycles. Cracking is also related to durability of a reinforced concrete structure because cracks act like openings that allow water penetration and ingression of some aggressive chemicals into concrete. They are the main causes of corrosion of reinforcing steels inside the concrete resulting in the decrease of strength and certain serviceability problems.

Concrete cracks were, however, found to be closed autonomously under certain conditions. The most classical experiment of this phenomenon was done by cutting parts of cement-lined pipe with cracks and immersing them in water [(1)]. It was found that those cracks closed themselves within a certain period of time. Moreover, other researchers performed the durability tests on cracked concrete as well; they indicated the ability of concrete to close its crack. The concrete specimens were cracked and installed in the special device to measure water flow through crack for 20 weeks [(2)]. Evidenced by water flow reduction with time, it was concluded that concrete cracks were able to heal themselves. The reduction of chloride migration through cracked concrete was also reported after the specimens were cracked by freeze/thaw and subsequently cured in lime saturated water for 3 months [(3)]. In addition, some researchers also studied favorable conditions for self-crack closing ability of the concrete. Water was found to be essential in the self-healing process of the concrete [(4, 5)]. It was also reported that the decrease of flow rate through the cracked concrete depends on crack width and temperature [(6)].

Self-crack closing mechanisms can be classified into 2 categories. The first is the artificial autonomic crack repairing in cases where small capsules with adhesive material are embedded in the concrete. The second is the natural ability of hydrates to heal crack over time. In case of the natural

*Corresponding author Tel: +66 2986 9009 ext. 3002; Fax: + 66 2986 9009 ext. 3001; E-mail: sahamit@siit.tu.ac.th

crack healing on which this research focuses, the most reliable assumptions are the continuity of hydration process (7, 8) and the formation of calcium carbonate, $CaCO_3$ (1,2, 5,9).

An ability of self-crack closing of cement mortar has been proved. It was also found that fly ash modifies microstructure and seals the crack after 28 days (8). A capability of the expansive agent to improve the self-crack closing ability of concrete as it provided additional expansion and precipitation of $CaCO_3$ to close the crack was also reported (10). Silica fume, crystalline admixture and limestone powder have never been studied for improvement of self-crack closing ability. However, silica fume is basically used to accelerate early strength. Crystalline admixture is used for water tightness improvement by crystal formation in concrete voids. Limestone powder is used to improve workability and allows more CSH precipitation at an early age. Therefore, these three additives are also interesting and were included in this study.

It can be seen that the self-crack closing ability of concrete was studied in various aspects. However, the effect from different types of additive on self-crack closing ability of the concrete has not been intensively investigated, although they are widely used to improve various properties of the concrete. Only some of them were studied, such as expansive agent that was found to improve self-crack closing ability of the concrete as it provided additional expansion and precipitation of $CaCO_3$ for crack closing (9). Under the assumption that aggregate is not involved in the crack-closing mechanism of the concrete, this research aims to investigate the self-crack closing ability of mortar with different additives by crack width observation and measurement.

Materials and Experimental Procedures

Specimens and Materials

50-mm mortar cubes with two reinforcing bars (DB10 with nominal diameter of 10 mm) were used as samples (see Figure 1). Different additives were added in different types of mortar by %weight of total binder. Their dosages are the normal dosages for each additive type in real practice. Six different mix proportions of mortars were investigated; i.e., cement type 1 (OPC) only, OPC + 30%fly ash (FA), OPC + 10%expansive additive (EA), OPC + 10%silica fume (SF), OPC + 1%crystalline admixture (CA) and OPC + 10%limestone powder (LP). Water-binder ratio and amount of cement paste in all mortars were controlled to be the same at 0.4 and 52.8% by volume, respectively.

Eight samples of each mix proportion were prepared. They were divided into two sets. Four of them were cracked at the age of 3 days while the others were cracked at the age of 28 days. Before creating cracks, those samples were sealed to prevent loss of moisture.

Chemical compositions and physical properties of the raw materials are given in Table 1. River sand with a specific gravity of 2.59 (at SSD), water absorption of 0.7, unit weight of 1.43 g/cm^3 and void ratio of 0.44, was used as fine aggregate.

Experimental Method

Cracks were created on mortar specimens by splitting method at two different ages (3 or 28 days after casting). Figure 2(a) shows the loading characteristic to form cracks. After cracking, all specimens were submerged in water. Specimens with different additives were kept in separate containers.

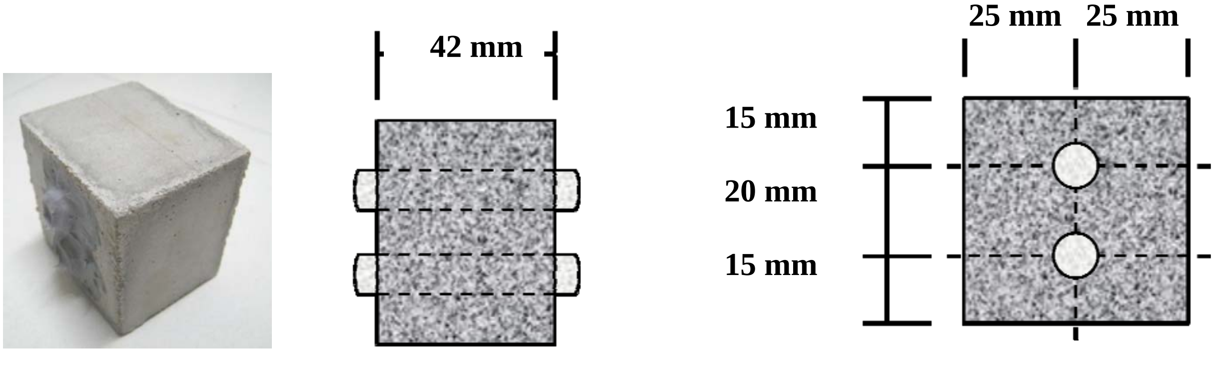
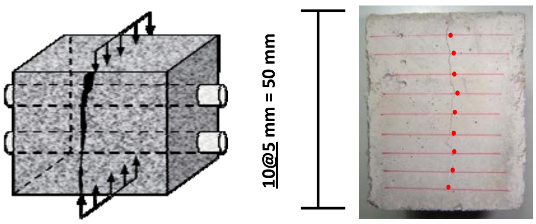


Figure 1. Mortar specimens.

Table 1. Chemical compositions and physical properties of cementitious materials.

	Material					
	OPC	**FA**	**EA**	**SF**	**CA**	**LP**
SiO_2 (%)	20.16	35.50	7.32	85.40	16.81	6.87
Al_2O_3 (%)	4.66	20.40	1.87	0.42	1.93	1.28
Fe_2O_3 (%)	3.49	13.83	1.50	2.76	1.98	0.33
CaO (%)	64.52	17.49	62.88	1.14	34.58	44.88
MgO (%)	0.64	2.74	0.51	2.15	1.29	4.78
SO_3 (%)	3.27	2.46	14.10	0.41	1.16	0.03
Na_2O (%)	0.02	1.46	0.02	0.02	15.22	0.02
K_2O (%)	0.41	2.20	0.12	2.39	0.16	0.24
TiO_2 (%)	0.25	0.38	0.10	< 0.01	0.11	0.09
P_2O_5 (%)	0.06	0.20	0.07	0.11	0.05	0.01
LOI (%)	2.10	2.81	11.29	4.94	26.43	41.27
Blaine fineness (cm^2/g)	4941	4790	6242	1151*	5765	6455
Specific gravity	3.15	2.15	3.04	2.20	2.90	2.72

*Condensed silica fume was used. The coarse silica balls broke into small silica particles during mixing.



(a) (b)

Figure 2. (a) Loading to form cracks and (b) positions for crack width measurement.

Measured crack width was used to indicate the damage degree. Digital microscope with computer software was used to observe and measure surface crack widths. The photos and widths of cracks were recorded from nine positions along the crack for each specimen. Distance between each position is 5 mm (see Figure 2(b)). Crack widths were measured and recorded just after cracking (as initial crack width) and then 3, 7, 12, 19, 29 and 44 days after cracking. Water in the containers was also renewed at each crack width measurement.

Since a width of cracks cannot be exactly controlled by loading, it was thus decided that cracks were created by varying from small to large crack widths among four samples of each mortar type. All results of these four samples were plotted together, and the effect of crack width on the self-closing ability was then observed by comparing the self-crack closing ability of three different ranges of crack widths.

Investigation Program

A summary of the investigation program is given in Table 2. Figure 3 illustrates curing periods and crack width measurement schedules.

Table 2. Summary of the investigation program**.**

Serial no.	**Ingredient**	**Specimen age at cracking**	**Number of mortar specimens**
OPC(3d/W)	OPC	3 days	4
OPC(28d/W)		28 days	4
FA(3d/W)	OPC + 30%FA	3 days	4
FA(28d/W)		28 days	4
EA(3d/W)	OPC + 10%EA	3 days	4
EA(28d/W)		28 days	4
SF(3d/W)	OPC + 10%SF	3 days	4
SF(28d/W)		28 days	4
CA(3d/W)	OPC + 1%CA	3 days	4
CA(28d/W)		28 days	4
LP(3d/W)	OPC + 10%LP	3 days	4
LP(28d/W)		28 days	4

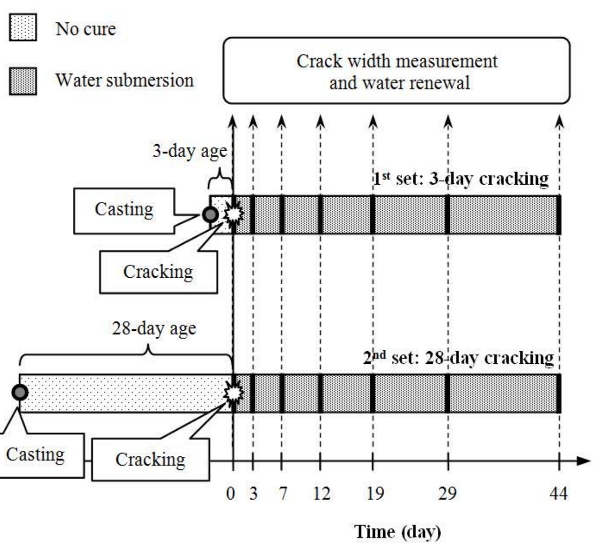


Figure 3. Illustration of curing periods and crack width measurement schedules.

Results and Discussion

Self-Crack Closing Ability and Evaluation Method

Figure 4 shows self-crack closing process of OPC mortar from initial day until crack-closing at 12 days (the mortar was cracked at the age of 3 days, initial crack width = 0.0564 mm). The curves between remaining crack widths before and after crack-closing at each observation day were plotted. Figure 5 shows the curves plotted between initial and remaining crack width at different ages of OPC mortar (cracked at the age of 3 days). At initial day, remaining and initial crack widths are equal so the graph plotted is diagonal. As remaining crack width is reduced by self-crack closing process, the graph moves down if the healing period is longer. The difference between initial line and the line at each crack-closing period is an indicator of self-crack closing ability. If the line lies on X-axis, the complete self-crack closing has been achieved.

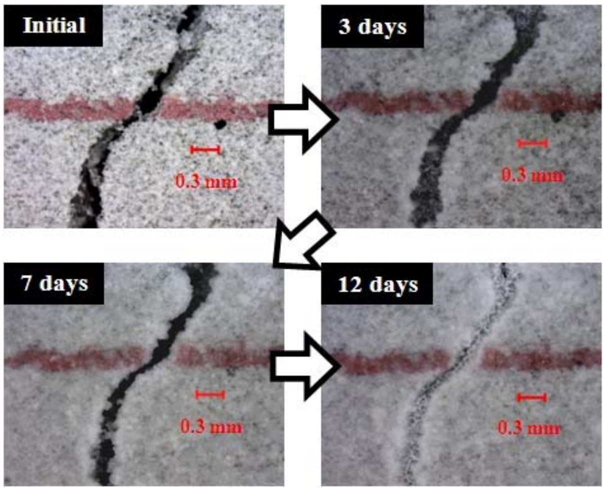


Figure 4. Crack-closing process of a crack on OPC mortar at initial, 3, 7 and 12 days (the mortar was cracked at an age of 3 days, initial crack width = 0.0564 mm).

In order to quantitatively evaluate self-crack closing ability of each mortar type, self-crack closing ratio (β) is introduced.

Self-crack closing ratio (β(t)) at specific time (t) was defined as:

$$\beta(t) = 1 - \frac{A(t)}{A_i} \quad (1)$$

where A_i is an initial area under graph between initial and remaining crack width and A(t) is an area under graph between initial and remaining crack width after t days of self-crack closing (see also Figure 5). Therefore, from Equation (1), β = 0 means that no crack-closing occurs while β = 1 means that complete crack-closing has been achieved. The evaluation of all mortars in this study was also done in this manner.

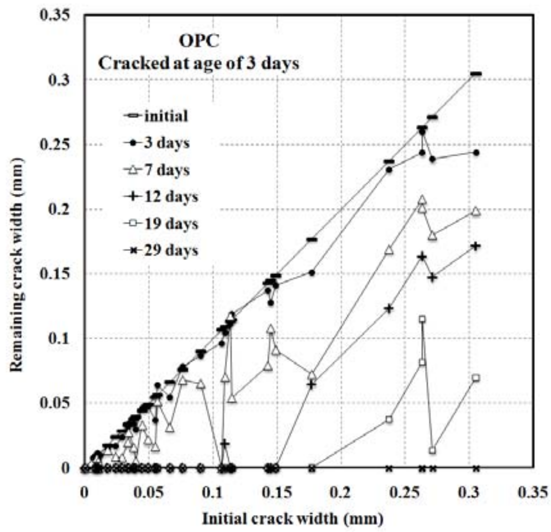


Figure 5. The curves plotted between initial and remaining crack width at each observation day of OPC mortar (cracked at an age of 3 days).

Influence of Different Additive Types on Self-Crack Closing Ability (Cracking at age of 3 days)

Figure 6 shows the graphs plotted between self-crack closing ratio (β) and time for the mortars with 6 different ingredients cracked at the age of 3 days. The crack width range of 0 - 0.05 mm is considered. The results show that all mortar types showed their performance to completely seal the crack within 12 days. However, the mortar which had the highest self-crack closing rate is the mortar with 1%crystalline admixture (CA mortar). The cracks of CA mortar were completely closed within 7 days only while the others, namely the control mortar (OPC mortar), the mortar with 30%fly ash (FA mortar), the mortar with 10%expansive additive (EA mortar), the mortar with 10%silica fume (SF mortar) and the mortar with 10%limestone powder (LP mortar) needed more than 7 days for complete sealing. OPC mortar had the lowest self-crack closing rate.

For wider crack (0.1 - 0.2 mm) in Figure 7, it is obvious that all mortars needed longer to close the crack when compared with the case of smaller crack. Moreover, it is interesting that the self-crack closing rate of CA mortar drastically decreased from the case of smaller crack. For the other mortars, their self-crack closing capabilities were found to follow a similar trend. However, the performance of EA and SF mortar seems to be more spectacular than the others in that their cracks were completely closed in 19 days only while the others needed longer period of time.

Even in the case that the size of cracks is large (0.2 - 0.3 mm) shown in Figure 8, the results still show the ability of all mortars to completely close the cracks. The time required to fully close the cracks was different for each mortar; within 19 days for EA and SF mortar, within 29 days for OPC and LP mortar, and within 44 days for FA and CA mortar. The self-crack closing capability of EA and LP mortar were somewhat outstanding since their self-crack closing rates were higher than the others during the first 19 days. Crystalline admixture and fly ash were not effective to improve self-crack closing ability in this case.

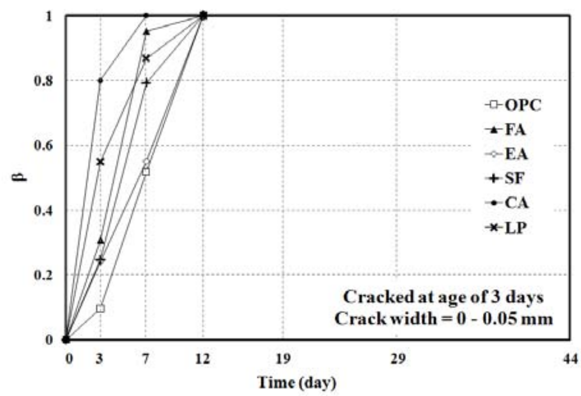


Figure 6. Self-crack closing ratio of each mortar type cracked at the age of 3 days, considered crack width range = 0 - 0.05 mm.

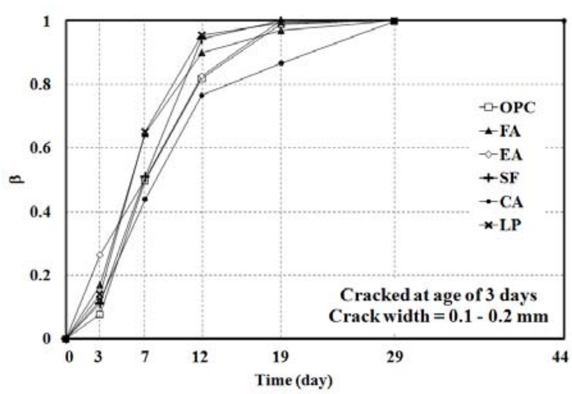


Figure 7. Self-crack closing ratio of each mortar type cracked at the age of 3 days, considered crack width range = 0.1 - 0.2 mm.

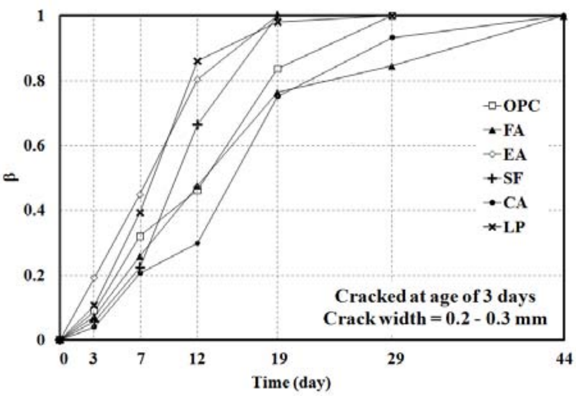


Figure 8. Self-crack closing ratio of each mortar type cracked at the age of 3 days, considered crack width range = 0.2 - 0.3 mm.

Influence of Different Additive Types on Self-Crack Closing Ability (Cracking at age of 28 days)

Figure 9 shows the graphs plotted between self-crack closing ratio (β) and time for the mortars with 6 different ingredients cracked at the age of 28 days. Although the mortars were cracked at a later age (28 days), CA mortar still had the highest self-crack closing rate for small crack (< 0.05 mm) in this case. However, its performance was not as spectacular as that observed when cracked at the age of 3 days. FA mortar had the lowest self-crack closing rate in this case (instead of OPC mortar as in case of cracking at 3 days).

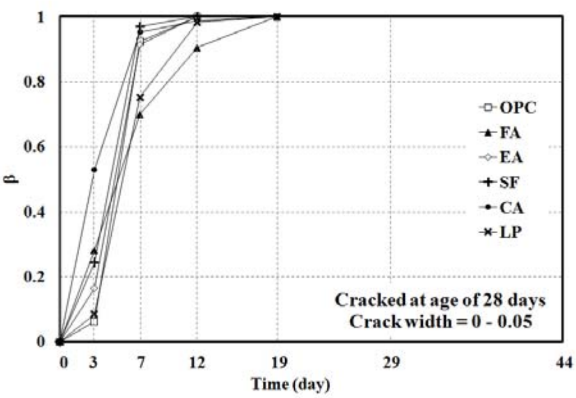


Figure 9. Self-crack closing ratio of each mortar type cracked at the age of 28 days, considered crack width range = 0 - 0.05 mm.

However, for larger cracks (0.1 - 0.2 mm), crystalline admixture became less efficient, as the self-crack closing rates of OPC and SF mortar were higher than CA mortar (Figure 10). Furthermore, SF mortar was the only type of mortar the cracks of which were completely closed within 19 days while the self-crack closing of the others stopped in incomplete condition after 19 days.

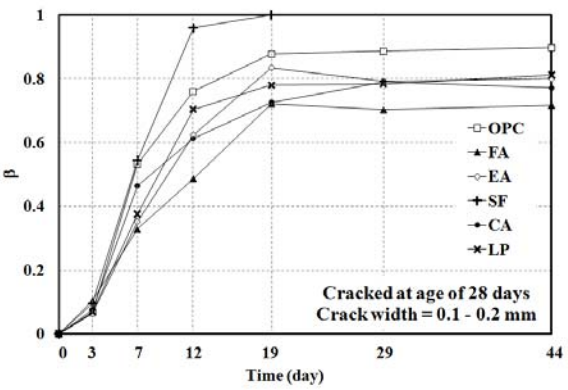


Figure 10. Self-crack closing ratio of each mortar type cracked at the age of 28 days, considered crack width range = 0.1 - 0.2 mm.

For the largest crack size (0.2 - 0.3 mm) in Figure 11, it can be seen that the self-crack closing ratios of all mortars became steady after 19 days except SF mortar for which the self-crack closing ratio still gradually increased. OPC seems to be the second best in both cases (0.1 - 0.2 mm and 0.2 - 0.3 crack width) while FA mortar had the lowest self-crack closing rate. However, it should be noted that there was no mortar which achieved complete crack closing in this case.

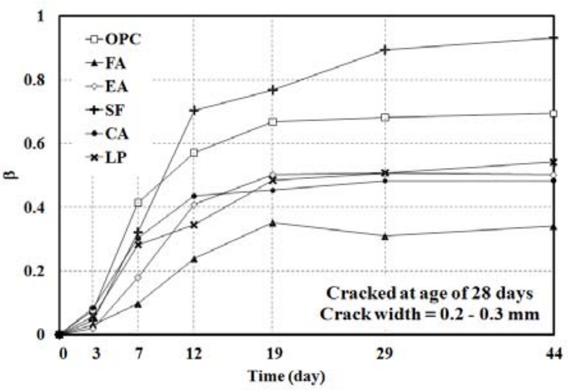


Figure 11. Self-crack closing ratio of each mortar type cracked at the age of 28 days, considered crack width range = 0.2 - 0.3 mm.

Characteristic of Self-Crack Closing Products

Figures 12 - 13 show microscopic observation of crack-closing products at a crack surface on different types of mortar. It is obvious that the products closing the cracks found in all mortars through the microscope were crystal-like materials. However, it is noticeable that the appearances of crack filling substances in each type of cracked mortar were different.

Figure 12 shows crack-closing products of small cracks (< 0.1 mm) on different mortars cracked at the age of 3 days. The crack-closing products in OPC, FA, SF and LP mortar look similar that there were crystals budding from two sides of the crack frank and bridging together. The crack-closing products of CA mortar look different from the other mortars. Its crack-closing products are composed of a huge number of tiny crystals filling the crack. This is probably the individual characteristic of the mortar incorporating crystalline admixture to seal small cracks faster than the other mortars. This kind of appearance was also observed in EA mortar, but the amount of tiny crystals looks smaller than in CA mortar. Moreover, its crystals were also formed slower than for CA mortar. Hence, the performance of EA mortar was not distinctly better than the other mortars in this case.

Figure 13 shows crack-closing products of large cracks (> 0.25 mm) on different mortars cracked at the age of 28 days. In this case, the characteristic of the product with many tiny crystals filling the crack was not observed. The healing products in all mortars including CA mortar look similar in that there were crystals budding from two sides of the crack frank and bridging together. However, it can be seen that the amount of the crystal product created from two sides at a crack surface was not large enough to bridge together and seal the cracks, except in SF mortar. SF mortar was the only type of mortar in which the crystals bridged together and completely closed the crack. Moreover, it should be noted that the shape of the crystals in SF mortar is different from the other mortars. The crystals in OPC, FA,EA, CA and LP mortar have quite smooth round edges while jagged edges crystals were observed in SF mortar which might be the individual characteristic of the mortar incorporating silica fume to seal large cracks faster than the other mortars in this case.

The experimental results shown in this article can well serve as an evidence of self-crack healing ability. It can be also observed that, with different types of additive, mortar behaves differently in terms of performance and mechanism of its self-crack closing performance. Types, shapes and growing mechanisms of crystals found in each case provide a clue to fully understand the real self-crack healing mechanisms of concrete with different additives. Further studies should be carried out in order to analyze the source of the crack-closing products and the reasons for which the observed crystals become different.

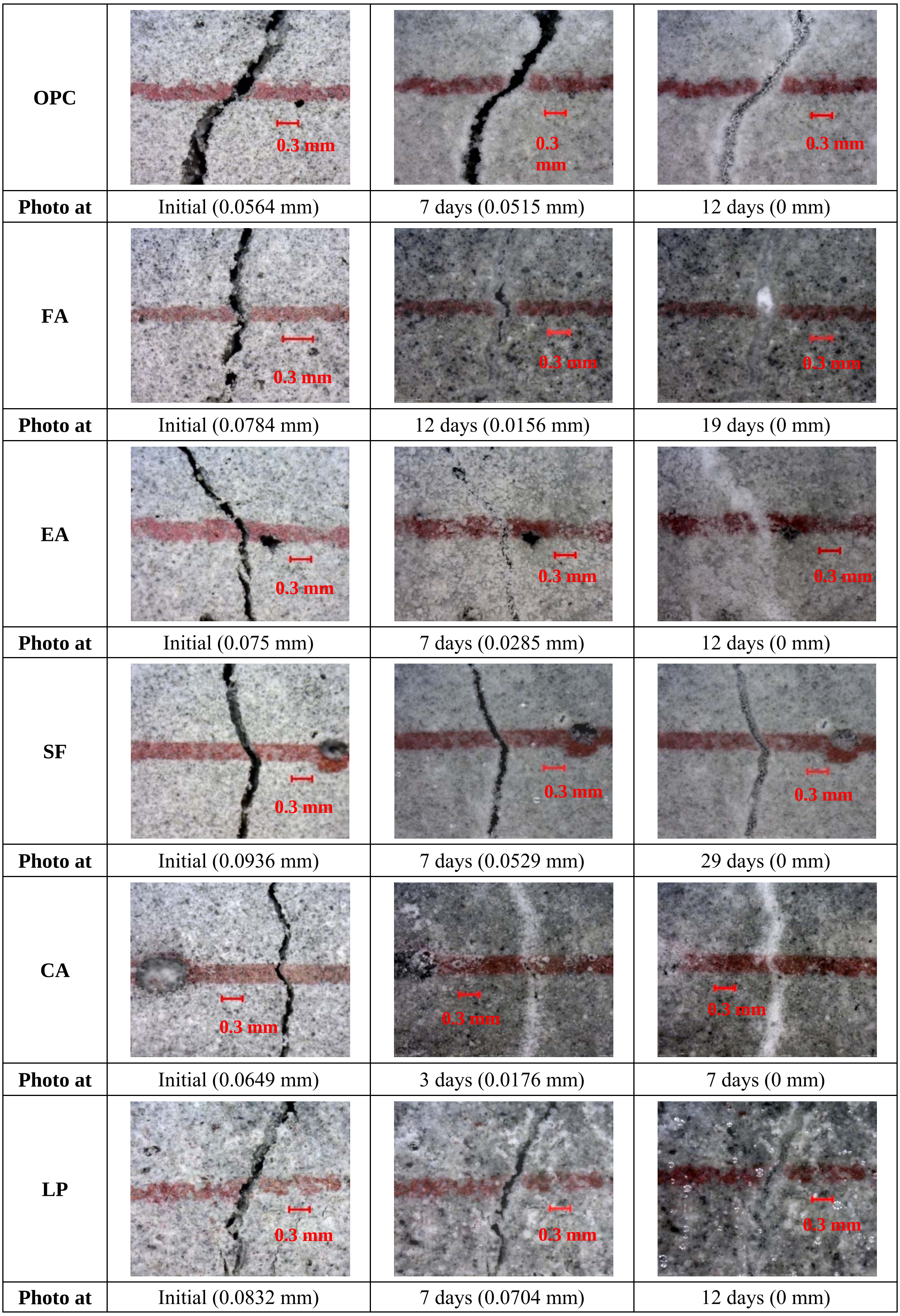


Figure 12. Crack-closing products at a crack surface on different mortars (cracked at an age of 3 days, initial crack width < 0.1mm).

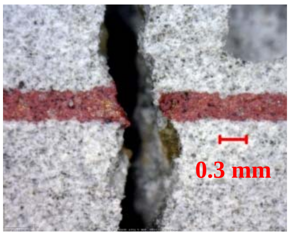
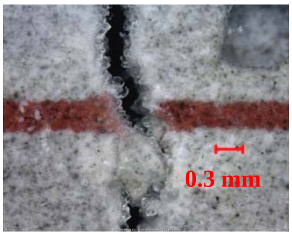
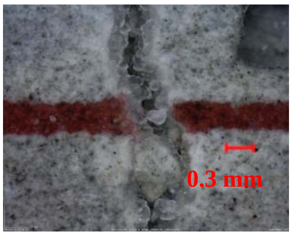
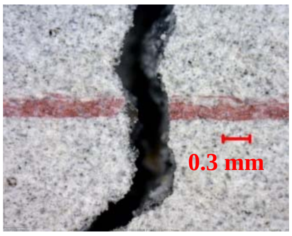
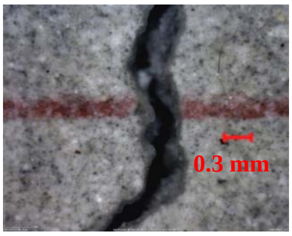
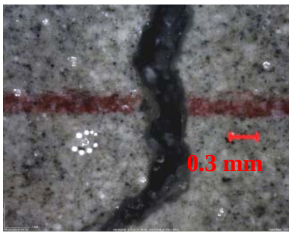
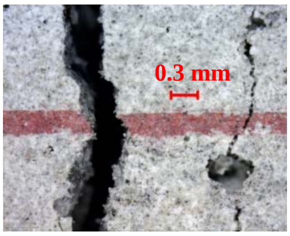
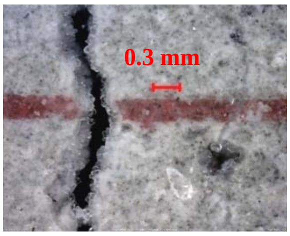
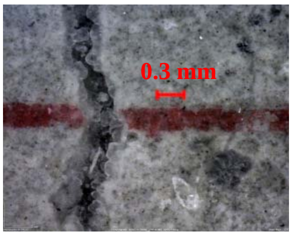
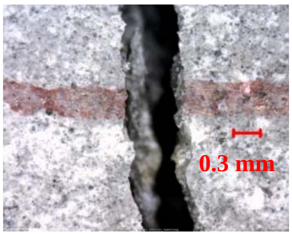
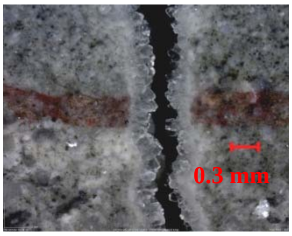
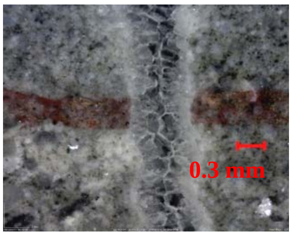
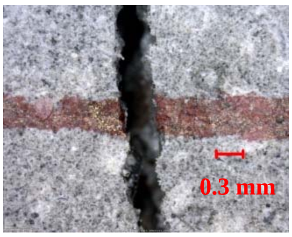
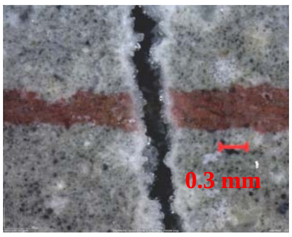
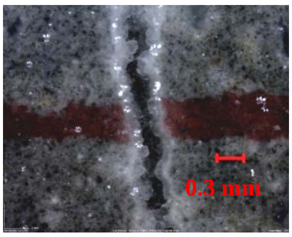
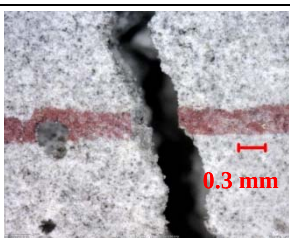
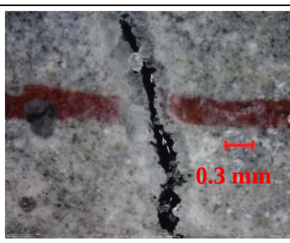
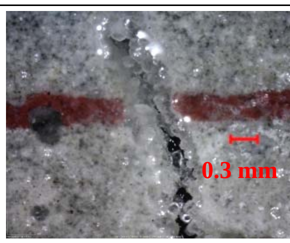
OPC			
Photo at	Initial (0.3032 mm)	12 days (0.1583 mm)	44 days (0.0912 mm)
FA			
Photo at	Initial (0.2548 mm)	19 days (0.1637 mm)	44 days (0.1663 mm)
EA			
Photo at	Initial (0.2763 mm)	12 days (0.1905 mm)	44 days (0.1797 mm)
SF			
Photo at	Initial (0.3916 mm)	12 days (0.1207 mm)	19 days (0 mm)
CA			
Photo at	Initial (0.2898 mm)	7 days (0.1558 mm)	44 days (0.1188 mm)
LP			
Photo at	Initial (0.2943 mm)	19 days (0.1494 mm)	44 days (0.1152 mm)

Figure 13. Crack-closing product at a crack surface on different mortars (cracked at an age of 28 days, initial crack width > 0.25 mm).

Conclusions

The following conclusions can be drawn from the results in this study.

1. All types of mortars show their self-healing performance to some extent. Each additive in each mortar has its own preferable conditions (mortar age at cracking and crack width) for performing its best self-crack closing ability.

2. Crystalline admixture (1% added) can improve self-crack closing ability of a mortar with small crack width (0 - 0.05 mm) at both cracking age of 3 and 28 days. However, for a wider crack, crystalline admixture became less effective while the mortar with silica fume (10% added) became more effective in self-crack closing, especially when a crack was generated at later age (28 days). Fly ash (30% added) was found to be ineffective to improve self-crack closing ability of mortar in most cases.

3. The products closing the cracks found in all mortars were crystal-like materials. However, the crystal forms are different in each type of binder. There are two possibilities to describe this occurrence, i.e. different crack-closing substances or same substances but different in forming process. Further investigation is needed to determine exact chemical compositions of these crack-closing products.

Acknowledgement

This work was supported by the National Research University Project of Thailand Office of Higher Education Commission

References

1. Wagner, E.F. (1974). Autogenous healing of cracks in cement-mortar linings for gray-iron and ductile-iron water pipe. *Journal of the American Water Works Association*. **66(6)**: 358-360.

2. Edvardsen, C. (1999). Water permeability and autogenous healing of cracks in concrete. *ACI Mater. J.* **96(4)**: 448-454.

3. Jacobsen, S., Marchand, J. & Boisvert, L. (1996). Effect of cracking and healing on chloride transport in OPC concrete. *Cement Concrete Res.* **26(6)**: 869-881.

4. Neville, A. (2002). Autogenous healing – A concrete miracle? *Concrete International.* **24(11)**: 76-82.

5. Qian, S., Zhou, J., De Rooji, M.R., Schlangen, E., Ye, G. & Breugel, K. (2009). Self-healing behavior of strain hardening cementitious composites incorporating local waste materials. *Cement Concrete Comp.* **31(9)**: 613-621.

6. Reinhardt, H.W. & Joose, M. (2003). Permeability and self-healing of cracked concrete as a function of temperature and crack width. *Cement Concrete Res.* **33(7):** 981-985.

7. Jacobsen, S., Marchand, J. & Hornain, H. (1995). SEM observations of the microstructure of frost deteriorated and self-healed concretes. *Cement Concrete Res.* **25(8)**: 1781-1790.

8. Sahmaran, M., Keskin, S.B., Ozerkan, G. & Yaman, I.O. (2008). Self-healing of mechanically-loaded self consolidating concretes with high volumes of fly ash. *Cement Concrete Comp.* **30(10)**: 872-879.

9. Yang, Y., Lepech, M.D., Yang, E.H. & Li, V.C. (2009). Autogenous healing of engineered cementitious composites under wet-dry cycles. *Cement Concrete Res.* **39(5)**: 382-390.

10. Yamada, K., Hosoda, A., Kishi, T. & Nozawa., S. (2007). Crack self healing properties of expansive concretes with various cements and admixtures. In: *Proceedings of the First International Conference on Self Healing Materials*. April 18-20, Noordwijk aan Zee, The Netherlands.