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Influence of fly ash fineness on water requirement and shrinkage of blended cement mortars

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Abstract

In this paper, the influence of fly ash fineness on water requirement and shrinkage of blended cement mortar was studied. The results indicate that the water requirement and shrinkage characteristic of the blended cement mortar are dependent on fly ash fineness and replacement level. The use of coarse fly ash slightly reduces the water requirement but greatly reduced the drying and the autogenous shrinkage of the blended cement mortars and the reduction is more with an increase in the fly ash replacement level. The finer fly ashes further reduce the water requirement, but increase the drying and the autogenous shrinkages as compared with coarser fly ash. The incorporation of superplasticizer drastically reduces the water requirement, but the effect on the drying and autogenous shrinkages of the normal Portland cement mortar is small. However, for the fly ash mortar, the use of superplasticizer results in a decrease in drying shrinkage and in a substantial increase in the autogenous shrinkage particularly for the fine fly ash at a high replacement level.

Keywords: Fineness, Fly ash, Drying shrinkage, Autogenous shrinkage, Mortar

1. Introduction

It is known that shrinkage is important to the performance of structural concrete. Shrinkage among other things could induce cracking, and hence decreases the service life of the structure. The use of certain pozzolans such as some fly ashes increases the durability through the pore refinement and the reduction in the calcium hydroxide of the cement paste matrix. The other properties including the shrinkage characteristics of the mortar and concrete are also affected.

Different behaviors of shrinkage of fly ash blended cement concrete have been reported [1-2]. Drying shrinkage of fly ash blended cement concretes of similar strength grade varies quite widely with the source of fly ash. This is due primarily to the differences in chemical as well as physical properties of fly ash used. For paste and mortar, there is a tendency that the incorporation of fly ashes reduced the drying shrinkage in comparison with those of normal Portland cement [3-4].

In normal circumstances, the major part of shrinkage can be attributed to drying shrinkage. For high strength concrete with high cementitious content and low water to binder ratio, autogenous shrinkage becomes significant [5-6]. The incorporation of fly ash is found to reduce the autogenous shrinkages [7].

It is generally agreed that the use of fine fly ash improves the properties of mortar and concrete [8-10]. Limited work dealing with the influence of fly ash fineness on shrinkage has been done. For drying shrinkage, there is no definite trend on the effect of fly ash fineness level except that fly ash generally reduces the shrinkage of fly ash mortar. The reduction is mainly related to the reduction in water content of the mix [3]. For autogenous shrinkages, there is an indication that the autogenous shrinkage of paste is related to the hydration of fly ash [11]. This suggests that the fine fly ash with higher degree of hydration increases the autogenous shrinkage of the mixture in comparison with that of the coarse fly ash.

The use of superplasticizer also affects the shrinkages of the blended cement fly ash paste and concrete [12]. When a large amount of superplasticizer is used, the hydration and the autogenous shrinkage are usually delayed [11]. However, the final shrinkage could still be high. The interaction of the effect of fly ash fineness and the action of superplasticizer is, therefore, of considerable interest.

The knowledge of influence of fly ash of different finenesses on the drying and the autogenous shrinkage of mortar would, therefore, be beneficial to the understanding of the mechanisms of shrinkage as well as for the future applications of these materials for controlling the shrinkage and to increase the service life of the structure.

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2. Experimental details

2.1 Materials

The Portland cement (PC) used in this work was a type I cement (as per ASTM C150). In this experiment, one lot of fly ash was used to eliminate the effect of the variation in chemical composition. The fly ash was lignite fly ash from Mae Moh power station in the north of Thailand and was classified into three lots:

1. OFA: original fly ash complying with ASTM C618, class F.
2. 45FA: 45% fine portion fly ash obtained from air classification.
3. 10FA: 10% fine portion fly ash obtained from air classification.

The 45FA and 10FA fly ashes were obtained by air classifying of original fly ash and the unwanted coarse portions discarded. River sand with the specific gravity of 2.63 and fineness modulus of 2.85 was used. A type F superplasticizer (SP) complying with ASTM C494 at the dosage of 3% by weight of binder was incorporated to a series of the mixes.

2.1 Experimental procedures

The compressive strength test was determined at the age of 3, 7, 28 and 90 days in accordance with the ASTM C109 using 50x50x50 mm cube specimen with sand-to-binder ratio of 2.75. For normal mortar without SP, water content was adjusted to give a flow of 110±5% and the fly ash replacements were varied at 0, 20, and 40% by weight of binder. For the mixes containing SP, 3% of superplasticizer by weight of binder and water content to give a flow of 110±5% were employed and the fly ash replacements were varied at 0 and 20% by weight of binder. The reported results were the average of three samples.

The shrinkage test was done following the procedures given in the ASTM C596 using 25x25x285 mm mortar bar with sand-to-binder ratio of 2.0. For normal mortar without SP, water content was adjusted to give a flow of 110±5%. For the mixes containing SP, 3% of superplasticizer by weight of binder and water content to give a flow of 110±5% were employed. The cast specimens were covered with polyurethane sheet and damped cloth in a 23±2°C chamber. They were demoulded at the age of 23½ hours and the first measurements of length were recorded within the age of 24 hours. The drying shrinkage test was performed in the 50% R.H. chamber at 23±2°C and four specimens were used. The other four specimens were used for the companion autogenous shrinkage test.

For the companion autogenous shrinkage test, the specimens were sealed immediately after the demoulding at the age of 23½ hours. The specimens were wrapped with thin polyurethane sheet and adhesive aluminium foil tape and the ends were sealed with adhesive. The wrapping and sealing of the specimens was adapted from the technique used by Tazawa and Miyazawa [5]. To monitor the tightness of the wrap such that there would be no moisture transfer from the test specimens, the weights of the wrapped bar were monitored against the dummy steel tube specimen wrapped in the similar way. The autogenous shrinkage test was performed in the 23±2°C chamber. The first measurements were also recorded within the age of 24 hours.

3. Results and discussion

3.1 Characteristics of fly ash

The physical properties of PC and fly ashes are summarized in Table 1. The fineness of the OFA is 2700 cm^2/g, which is a little coarser than that of the Portland cement. The Blaine finenesses of the classified 45FA and 10FA are 3900 and 4500 cm^2/g respectively. The specific gravity of the OFA, 45FA and 10FA are 2.21, 2.38 and 2.41 respectively.

Table 1 Physical properties of fly ash and Portland cement

Materials	Specific Gravity	Average Particle Size (micron)	Blaine Fineness (cm^2/g)
PC	3.12	17	3300
OFA	2.21	25	2700
45FA	2.38	16	3900
10FA	2.41	9	4500

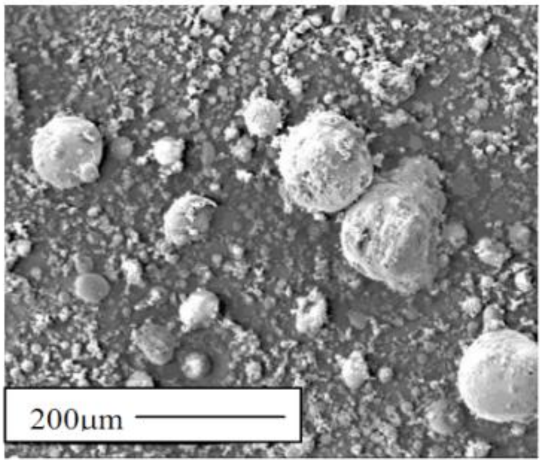
The chemical constituents of PC and the fly ashes are given in Table 2. There is no significant difference in chemical analyses of fly ash of different finenesses. The calcium oxides content of the Mae Moh fly ashes are higher than 10%, which is usual for lignite fly ash. As shown in Figure 1, the fine fly ash is more spherical and its surface is smoother in comparison with the coarser original fly ash. With regard to the chemical constituents, there is no significant difference in chemical compositions of fly ash of different finenesses.

3.2 Water demand and strength development

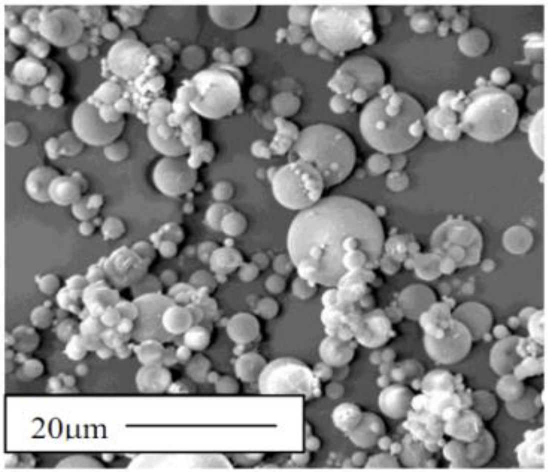
Table 3 shows the influence of fly ashes on water demand and strength development of mortar for similar flow (110±5%). The sand-to-binder ratio is 2.75 by weight. The results indicates that the incorporation of fly ash as cement replacement reduces the water demand, expressed as water-to-binder ratio (W/B) of mortar for similar flow. The reduction in water demand consistently increases with high replacement percentage. In the case of original fly ash, the reduction in water demand is noticeable but not as significant as in the case of 45FA and 10FA. The fineness of the fly ash clearly has a pronounced effect on the water demand of the mortar as expected.

Table 2 Chemical analysis of Portland cement and fly ashes

Oxides	PC	OFA	45FA	10FA
SiO_2	20.9	45.0	44.4	44.4
Al_2O_3	5.3	24.0	23.4	23.7
Fe_2O_3	3.8	10.7	10.3	10.4
CaO	64.5	13.3	14.5	13.1
MgO	1.2	3.4	3.3	3.4
Na_2O	0.1	0.1	-	0.1
K_2O	0.4	2.4	2.7	2.7
SO_3	2.5	1.6	1.1	1.3
LOI	1.6	0.5	1.0	1.0



a. OFA sample



b. 10FA sample

Figure 1 SEM micrograph of OFA and 10FA sample

Table 3 Water demand and strength development of mortars with similar flow

Mix	W/B[1]	Compressive strength, MPa				W/B[2]
		3d	7d	28d	90d	
PC	0.515	27.0	39.0	53.5	63.5	0.405
20%OFA	0.470	22.0	31.0	50.5	67.5	0.380
40%OFA	0.440	19.0	26.5	49.5	63.0	0.350
20%45FA	0.450	23.0	34.0	60.5	80.5	0.370
40%45FA	0.425	22.0	33.0	62.0	82.5	0.340
20%10FA	0.455	26.5	37.0	58.5	81.5	0.370
40%10FA	0.420	23.5	34.5	68.0	83.5	0.340
PC-SP	0.380	54.0	62.5	71.0	75.5	0.275
20%OFA-SP	0.350	48.0	55.0	75.5	89.5	0.250
20%45FA-SP	0.315	54.5	61.0	78.5	100.0	0.235
20%10FA-SP	0.315	58.0	62.5	91.0	107.0	0.235

Note: 1 for strength test with sand-to-binder ratio of 2.75
2 for shrinkage test with sand-to-binder ratio of 2.0

After 90 days of curing, all fly ash mixes show strength comparable to or higher than that of Portland cement. This was due the pozzolanic reaction from fly ash at later age [13]. At early ages of 3 days and 7 days, all fly ash mixes show lower strength than the Portland cement. It is interesting to note that the difference in strength development between 20 and 40% fly ash replacement is not large.

Compared to SP freed normal mixes, the incorporation of SP at the dosage of 3% by weight of binder results in a large reduction in the water content of all mixes. The strength of the mortar with SP increases significantly especially at the early age. At 3 days the increase is more than 100%. The strength at the later age of 90 days is also high for all mixes. The strength of 100.0 and 107.0 MPa are obtained for the 20%45FA-SP and 20%10FA-SP mixes with W/B of 0.315 for both mortars.

3.3 Drying shrinkage

In this test, mortar bars with sand-to-binder ratio of 2.0 and water content to give a flow of 110±5% are used. The length of specimen at the age of 24 hours is used as the initial reading. The water-to-binder ratios (W/B) of theses mixes are consistently lower than those of the strength test series as a result of an increase in the paste content.

The results of the drying shrinkages are shown in Figures 2-4. To facilitate the interpretation of the results, the shrinkage at the age of 90 days is plotted against the W/B as shown in Figure 5. From Figures 2 and 5b, the shrinkage of the mortar containing rather coarse OFA is lower than that of PC mortar. The reduction in shrinkage is slightly more with an increase in the OFA content. The reduction is due primarily to the reduced water content and W/B of the mortar containing fly ash [3]. In addition, the replacement of PC by fly ash reduces the PC content and its hydration products [14]. This would reduce the shrinkage as it is related to the amount of the gel or hydration products.

For the fine fly ash as shown in Figures 3 and 5b, the incorporation of 20% of 45FA results in similar shrinkage to that of the PC mortar despite a decrease in the W/B, whereas the incorporation of 20% of 10FA results in a measurable increase in the shrinkage. It should be noted here that the W/B's of mortars with the same amount of fly ash replacement level are not very different between 0.37-0.38 and 0.34-0.35 for the 20% and 40% replacement levels, respectively. At 20% replacement level with similar W/B ratios between 0.37-0.38, the drying shrinkage increases with an increase in the fly ash fineness. For the low replacement level of fly ash, the hydration of PC is a dominant factor. The increase in shrinkage for the low replacement level of fine fly ash is due to multiple factors viz., an increase CSH gel owing to the dispersing effect and the increased nucleation and precipitation sites as compared to that of the coarser fly ash [11, 15], the higher degree of hydration of the finer fly ash [7], and a decrease in the average pore size of the cement paste as compared to the coarser OFA [16]. The incorporation of 40% of 45FA and 10FA results in a lower drying shrinkage of mortar as compared to that with 20% fine fly ash mortar. The general trend is that the 40% replacement shows lower drying shrinkage than the 20% replacement mixes. At the 40% replacement level, again with similar W/B ratios between 0.34-0.35, the trend of the result is still the same as that of 20% replacement level. An increase in the replacement level of fly ash causes a reduction in the Portland cement content and a decrease in the CSH gel, which would lead to a reduction in shrinkage. Furthermore, the unreact fly ash would also restrain the shrinkage. The reduction of drying shrinkage with the incorporation of fly ash has been reported by other researchers [1-2, 17-18].

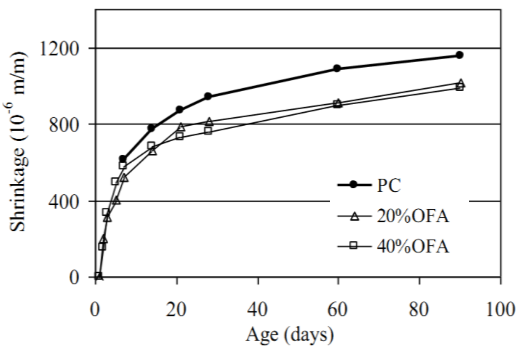


Figure 2 Drying shrinkage of PC and OFA mortars

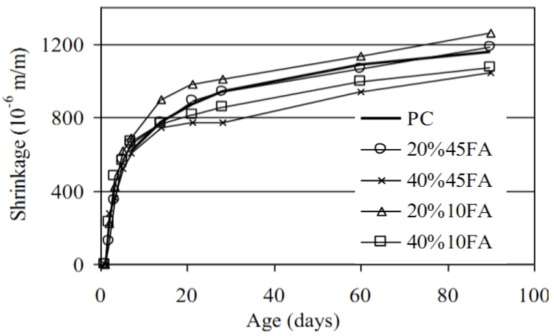


Figure 3 Drying shrinkage of PC, 45FA, and 10FA mortars

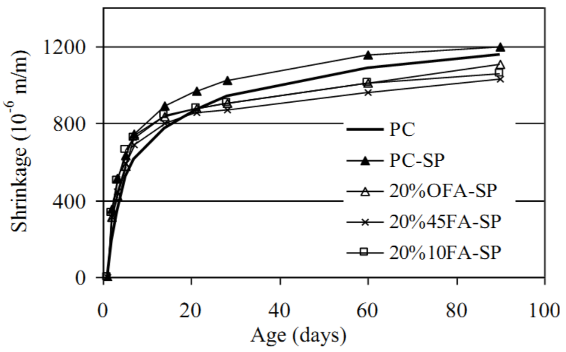


Figure 4 Drying shrinkage of mortars containing SP

For the mixes with SP, the results show that an incorporation of SP affects the shrinkage characteristics of the mortar as shown in Figures 4 and 5a. The effect of SP on the shrinkage of the PC mortar was small. The shrinkage of the PC-SP mortar is only slightly higher than that of the normal PC mortar in spite of the much lower W/B ratio. The drying shrinkage at 90 days of the PC and PC-SP mortar are 1153 and 1197 x10^{-6} m/m, respectively. The relatively high shrinkage of the PC-SP mix may be the result of an improvement in the cement dispersion and hydration [16]. The effect of the SP on the fly ash mortar is more significant in comparison to the PC-SP mortar. The decrease in shrinkage is more with an increase in the fly ash fineness owing to the reduction in the W/B as suggested by the straight line in Figure 5a. For the fine fly ash mixes, the shrinkage of both 20%45FA-SP and 20%10FA-SP mixes decrease as compared to those without SP and that of PC. The results indicate that the influence of the fly ash fineness on the SP mixes is different from the SP freed mixes. It appears that the incorporation of SP lower the shrinkage of the fine fly ash mixes more than that of the OFA mix as a result of the combined effect of the SP and the fine fly ash in reducing the water content. For the SP freed mixes as shown in Figure 5b, the difference in the graphs of different fly ash fineness indicates the effect of its fineness with different degree of hydration. The graph of the fine fly ash is higher than the others indicating the higher reaction, and thus the higher shrinkage.

It is of interest to note that the rate of the early shrinkage development is quite different for the mix with and without SP as shown in Figure 4. The incorporation of SP increases the early drying shrinkage quite significantly for all mixes. It can also be seen that the early drying shrinkage of mortar increases with an increase in the fly ash fineness. The drying shrinkages at the age of 2 days (one day drying) of the mortars with SP are between 312-358 x10^{-6} m/m while that of the PC mortar is only 186 x10^{-6} m/m. This is important, as the high early shrinkage is associated with the higher risk of having the shrinkage crack.

3.4 Companion autogenous shrinkage

The autogenous shrinkage of the companion mortar bars is shown in Figures 5c, 5d, and 6-8. The W/B ratios of the mixes ranges from 0.235 to 0.405, which are lower than the suggested value of 0.42 for the substantial amount of autogenous shrinkage to occur [19]. It can be seen that an incoporation of coarse OFA marginally reduces the autogenous shrinkage and the reduction was slightly more with an increase in the fly ash replacement level. The autogenous shrinkage at the age of 90 days of the normal PC mortar without SP was 334 x10^{-6} m/m and those of the 20%OFA and 40%OFA are reduced to 289 and 265 x10^{-6} m/m. A similar reduction in the autogenous shrinkage has been reported with the high level of fly ash replacement [7]. The reduction is due to the reduced CSH gel and the restraining effect of the fly ash particles.

The fine fly ash, as shown in Figures 5d and 7, however, increases the autogenous shrinkage of mortar in comparison to those of the OFA mortar. The autogenous shrinkages of the mortar containing fine fly ash are not reduced in comparison to that of the PC mortar and in fact the shrinkage of the mortar with high replacement level of 10FA is substantially increased. The graphs of the fine fly ash are higher than that of the coarser original fly ash indicating the effect of the higher reaction of the finer fly ash. The incorporation of fine fly ash decreases the average pore size of the cement paste [16] and increases the degree of reaction [7, 20] in comparison to that of the coarser fly ash. This would lead to a larger capillary pressure in the matrix when water is consumed and results in an increase in the autogenous shrinkage of the mortar containing finer fly ash.

For the mixes with SP, the autogenous shrinkage of the PC mortar with SP is similar to that without SP in spite of the large difference in the W/B. For the fly ash mortars, the autogenous shrinkages of all fly ash mixes with SP are significantly larger than those without SP. It has been shown that SP increases the autogenous shrinkage of PC mortar owing to the improved cement dispersion and hydration [16]. It is apparent that the incorporation of SP increases the autogenous shrinkage of the fly ash mortars and the increase is slightly more with the finer fly ash. The increase is due primarily to the reduction in the water demand as suggested by the graph in Figure 5c. The effect of higher degree of hydration of fine fly ash was not observed in this case.

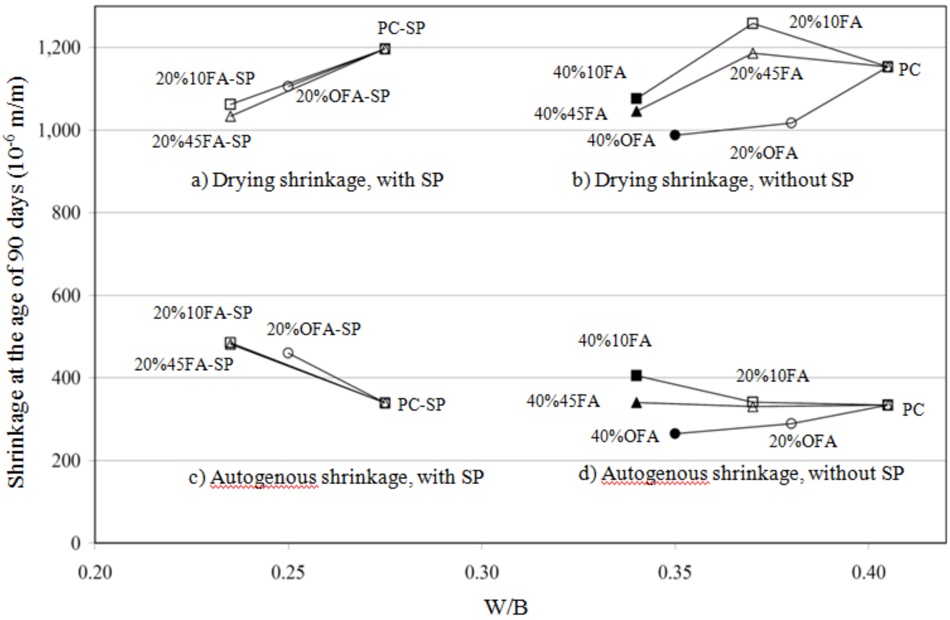


Figure 5 Shrinkage at the age of 90 days versus W/B

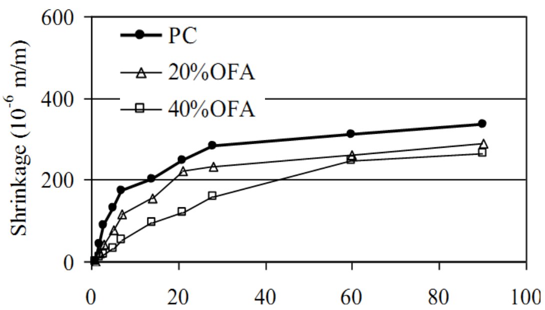


Figure 6 Autogenous shrinkage of PC and OFA mortars

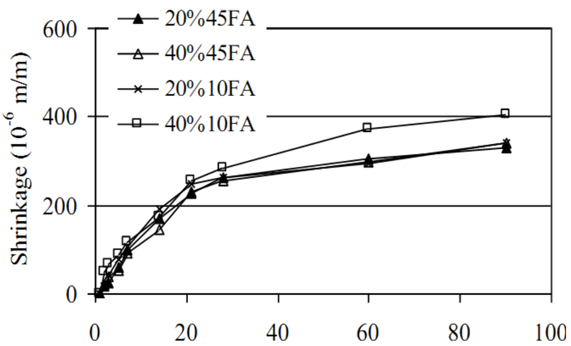


Figure 7 Autogenous shrinkage of PC, 45FA, and 10FA mortars

4. Conclusions

The results indicate that the differences in the chemical composition of the fly ash of different fineness from the same batch are small. The main difference is in the shape and the texture of the surface of the fly ash particles. The fine fly ash being more spherical and smoother in the surface reduces the

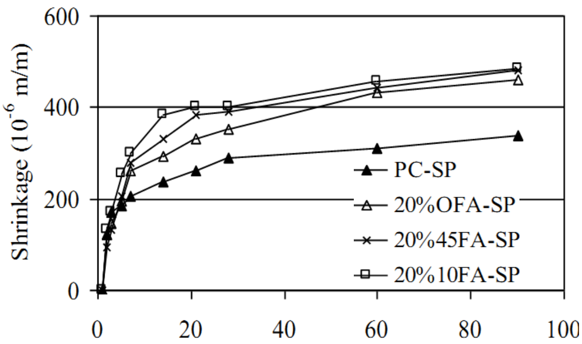


Figure 8 Autogenous shrinkage of mortars containing SP

water demand and improves the strength of the mortar as compared to the coarse original fly ash. The level of replacement and the fineness of fly ashes affect the shrinkages. The incorporation of original coarse fly ash reduces the drying and autogenous shrinkage. For the finer fly ashes, the drying shrinkage increases with the 20% fly ash replacement level and reduces with the 40% fly ash replacement level. For the low replacement level, the hydration of the PC is a dominant factor. For the large replacement level, the restraining effect of the fly ash particles becomes dominant and results in the reduction in the drying shrinkage. The autogenous shrinkage is, however, increased with the use of the fine fly ash especially at the 40% replacement level.

The incorporation of superplasticizer results in a reduction in water content and an increase in strength of the blended cement mortar. The drying shrinkage of the fly ash mortar is generally reduced and the autogenous shrinkage is significantly increased especially for the fine fly ash mortars. The substantial increase in the autogenous shrinkage is due to the combined effect from fly ash and superplasticizer. The incorporation of SP also results in significant increases in the early drying shrinkage for all mixes; thus, increasing the risk of shrinkage cracking at the early age.

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