CHAPTER II

LITERATURE REVIEW

2.1 Plastic Shrinkage Cracking of Concrete

ACI Committee 305 stated that the principal cause of plastic shrinkage cracking of Portland cement concrete is the excessive and rapid rate of evaporation and the inability or lack of bleed water to replace the evaporating water. ACI also suggests that precautions should be taken when the rate of evaporation is expected to approach 1.0 $kg/m^2 \cdot h$ at which plastic shrinkage cracking is likely to occur. The bleeding rate of water in concrete from previous studies say that it lies in the range of about 0.50 $kg/m^2 \cdot h$ to 1.50 $kg/m^2 \cdot h$. Thus, when evaporation rate exceeds the lower of these figures, trouble with plastic shrinkage cracking is potentially possible.

Plastic shrinkage cracking results from a volumetric change of the concrete while it is still in a semi fluid or fresh state. As explained by Wang, Shah, and Phuaksuk (2001), the volume change of concrete at a very early stage, before hardening, can be divided into four distinct phases:

Phase I: Plastic settlement

Prior to drying, the spaces in between the particles of freshly mixed concrete are completely water-filled. When the concrete is placed, the solid particles start to settle and water bleeds, forming a layer of surface water. The concrete volume change is very small and is mainly caused by plastic settlement.

Phase II: Primary plastic shrinkage or bleeding contraction

Concrete surface will evaporate in hot, windy weather. When the rate of evaporation exceeds the bleeding rate, the concrete mixture will begin to shrink. This shrinkage can occur before and/or during concrete setting, and is assumed to be attributed to the pressure that develops in the capillary pores of concrete during evaporation. During evaporation, water between the surface of cement and aggregate particles in the plastic concrete forms a complicated system of menisci due to capillary action. This in turn generates capillary pressure within the concrete that reduces the distance between the cement and aggregate particles, causing the concrete to shrink. This shrinkage is called primary plastic shrinkage and could reach a few thousand microstrains.

Phase III: Autogeneous shrinkage

As cement hydrates, hydration products form around the cement particles and fill up the water-filled spaces between solid particles (cement and aggregates) in the concrete. As hydration continues, hydration products develop into a network that bonds all loose aggregate particles together. As a result, the role of capillary action becomes less important. As the rate of cement hydration increases, plastic settlement and bleeding contraction decrease and autogeneous shrinkage develops. In fresh concrete, the amount of autogeneous shrinkage is very small (less than a few hundred microstrains). The majority of autogeneous shrinkage occurs after the setting of concrete.

Phase IV: Secondary plastic shrinkage

During this stage, concrete begins to harden and the hydration process of cement slows. Plastic shrinkage tends to stop as concrete strength develops.

The most commonly observed form of plastic shrinkage is mostly the combination of plastic settlement, bleeding contraction, and autogeneous shrinkage. When shrinkage is subjected to internal and/or external restraint, tensile stresses develop, and the concrete may crack.

Freshly placed concrete occasionally does not have enough time to develop enough tensile strength to resist the contraction stresses induced in the capillary pores by rapid evaporation (Uno, 1998). Due to this, cracks can develop throughout the top face of the concrete. These cracks are normally parallel and at the surface but there were cases where such cracks extend throughout the entire depth of the slab (said to be aggravated by drying shrinkage).

Ravina and Shalon (1968) concluded that the first crack formed coincides with the transition from the intensive, practically unrestrained, linear shrinkage of fresh mortar to the much slower rate due to the restraint on stiffening of the mortar.

The results of their study showed that cracking set in 1.5 to 24 hours after placing. The cracks increased in number and became wider 0.5 to 1.5 hours after their appearance and retained their shape afterwards. The first crack formed was usually the widest one with its width ranging from 0.10 to 4.80 mm. Most of the cracks were perpendicular to the longitudinal axis and crossed the whole slab sample. Most of the observed cracks cut through the whole slab of 7 cm thick which was seen in the drilled core samples in Figure 2.1.

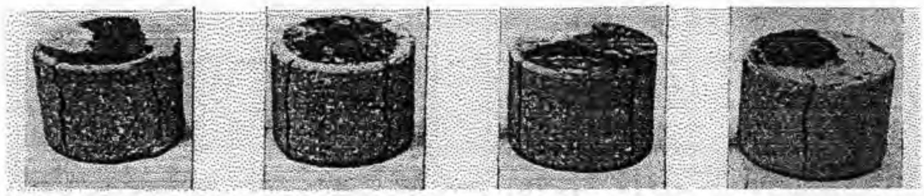


Figure 2.1: Cores drilled through cracks through a test slab (Ravina and Shalon, 1968)

2.2 Factors Affecting Plastic Shrinkage Cracking

The plastic shrinkage cracking phenomenon was said to be usually associated with hot-weather concreting, putting much emphasis on the elevated temperatures (Ravina and Shalon, 1968). In hot-dry regions, plastic cracking was common particularly in flat slabs usually appearing two to three hours after placing. However, Ravina and Shalon stated that during the course of their study, in spite the fact that plastic shrinkage cracking has been observed in hot and moderate regions, there was still no agreement to its causes.

There were two main opinions represented by Lerch on one hand, and the group of Blakey, Bresford and Mattison on the other. Lerch (1957) stated from his field studies that if the rate of evaporation is greater than which bleeding water rises to the surface, then plastic shrinkage cracking are likely to occur. On the other hand, Blakey, Beresford, and Mattison (1958) stated that the primary cause the cracking is the settlement of the fresh concrete and that cracking due to evaporation could only happen when atmospheric conditions are in the region of 90°F (32.22°C), 10 percent relative humidity, and a 30mph (0.03 kph). Later on, the cracks discussed by Lerch was termed as, "plastic shrinkage cracks" while those dealt with Blakey, Beresford, and Mattison were termed as "presetting cracks". This research studies only plastic shrinkage cracks.

Aside from evaporation rate, other factors which influence plastic shrinkage cracking was studied (Uno, 1998). It was found that high strength concrete mixes containing high proportions of cement produces concrete with low bleed rates and were in turn had high susceptibility to plastic shrinkage cracking (Samman, Mirza, and Wafa, 1996). In terms of the depth of concrete sections, it was found that the depth of a section determines the bleed capacity of the concrete since a deeper section will contain more solids to settle and would correspondingly allow more bleed water to rise to the surface. In light of this ability, deeper sections would tend to resist the premature onset of cracks which would imply that deeper sections would be less prone to plastic shrinkage cracking. Use of high proportions of fine aggregate, special cements, or fine supplementary cementitious materials (such as fly ash and silica fume) in some concretes was seen to have a tendency to decrease the bleed rate of concretes because of the greater surface area of such materials. Such materials also do not contribute to significant strength gain (in very short period of time) which would imply that at high proportions, these concretes would call for special precautions at lower rates of evaporation. Regarding the plastic state of the mix, tests on 104 concrete samples confirmed that extremely dry or extremely fluid mixes were susceptible to cracking.

Almusallam, Maslehuddin, Abdul-Waris, and Khan (1998) studied about the effects of mix proportions on plastic shrinkage cracking of concrete in hot environments and found out that the cement content and water-cement ratio significantly affects the parameters that control plastic shrinkage in the concrete. These parameters are the measured rate of bleeding, water evaporation, and time and intensity of the cracks. Lean-stiff concrete mixes cracked earlier than rich-plastic concrete mixes but the intensity of the crack in rich-plastic concrete was greater. The plastic shrinkage cracking happened at a rate of evaporation from 0.2 to 0.7 $kg/m^2/h$ as compared to the suggested ACI 305 evaporation rate of 1 $kg/m^2/h$. The bleeding rate and rate of evaporation is least in the lean-stiff concrete mix made with a cement content of 300 kg/m^3 with a water-cement ratio of 0.40.

In their study, plastic shrinkage cracking was investigated by taking note of the time of the occurrence of the first crack and the total crack area (expressed as a percentage of the total concrete surface area). Figure 2.2 illustrates the effect of water-cement ratio and cement content to the initiation time of the cracks. Test results showed that stiff mixes (having low water-cement ratio) cracked earlier than that of semi-plastic or plastic mixes (mixes having medium to high water-cement ratio). Also, lean mixes cracked earlier than rich mixes. The researchers explained that the delay in cracking due to the increase in cement content and water-cement ratio could be attributed to the increase in bleeding and to the lean tensile strength of the lean concrete mixes as compared to rich concrete mixes.

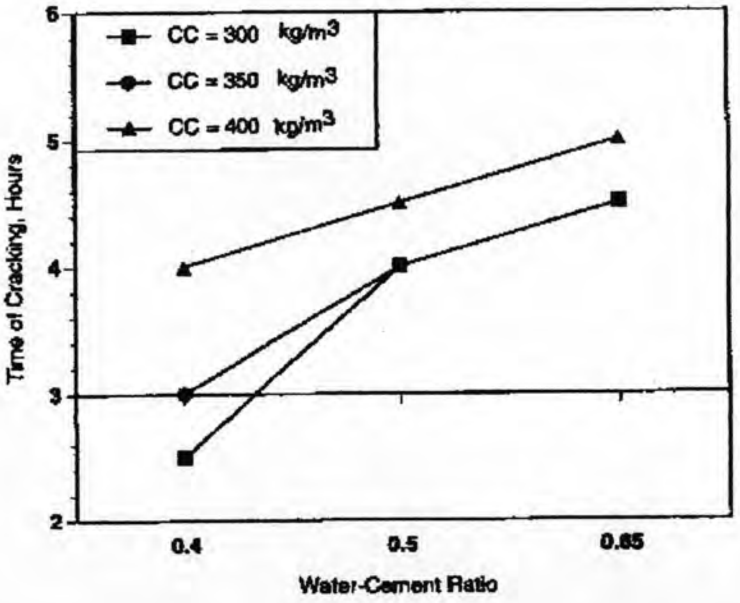


Figure 2.2: Effect of water-cement ratio on time to initiation of cracks (Almusallam, Maslehuddin, Abdul-Waris, and Khan, 1998)

Figure 2.3 shows the effect of mix proportions on the area of cracks from the same investigation. The total crack area was found to increase with both the cement content and water-cement ratio. This was attributed to the decrease in the tensile strength of concrete. Another possible cause was the increased capillary pressure due to the increase in the water-cement ratio. Whitman (1976) stated that plastic shrinkage leads to a highest concentration of fresh concrete having a water-cement ratio within the range of 0.5 to 0.6.

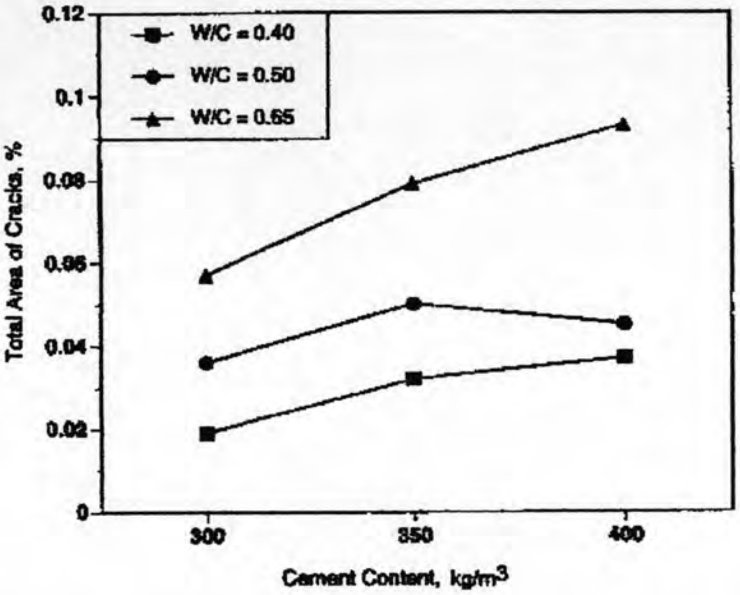


Figure 2.3: Effect of cement content on total crack area
(Almusallam, Maslehuddin, Abdul-Waris, and Khan, 1998)

Although the lean stiff mixes cracked earlier than the rich plastic mixes, the latter had higher crack intensity than the former. This reduction in the crack intensity in lean mixes was attributed to the high volume fraction of aggregates.

In most of the mixes in the stated study, it was observed that the rate of evaporation was greater than the rate of bleeding. Bleeding was observed to cease after 1 to 3 hours while evaporation rate still continued until nearly 6 hours. This gave the researchers another cause for the early cracking of lean mixes when compared to rich mixes since lean mixes experienced low bleeding.

2.2 Use of Pozzolan in Concrete

ASTM C618 describes pozzolan as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious properties but in finely divided form and in the presence of moisture will chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Pozzolan are often added to concrete to make concrete mixtures which are more economical, reduce permeability, increase strength, or influence other concrete properties. Such effects would depend upon which type of pozzolan and how much pozzolan was used. Pozzolan could be used individually or in combination with Portland as blended cement or as partial replacement of cement as well.

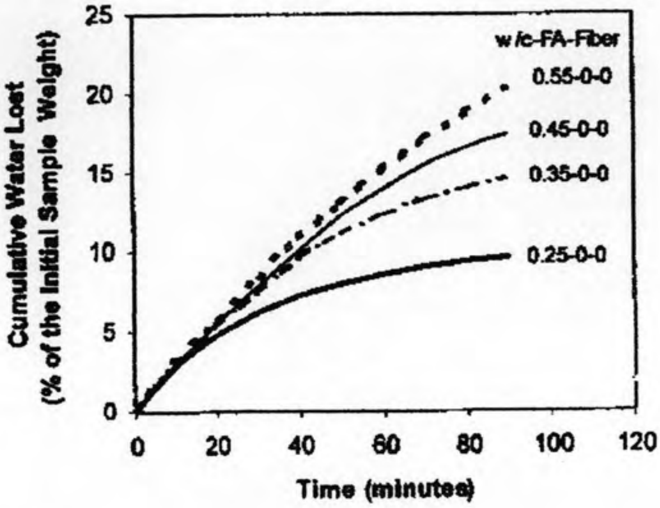
Pozzolanic materials can be divided into two groups: natural pozzolan and artificial pozzolan. Examples of natural pozzolan are: clay, shale, volcanic tuff, and pumicite. However, artificial pozzolan such as fly ash, blast-furnace slag, silica fume, and rice husk ash are more commonly used.

When used as replacement for cement, pozzolanic materials are generally substituted for 10 to 50 percent of cement. Such replacement could improve workability, permeability, and resistance to chemical attack. On the other hand, strength gain is usually slower than for normal concrete.

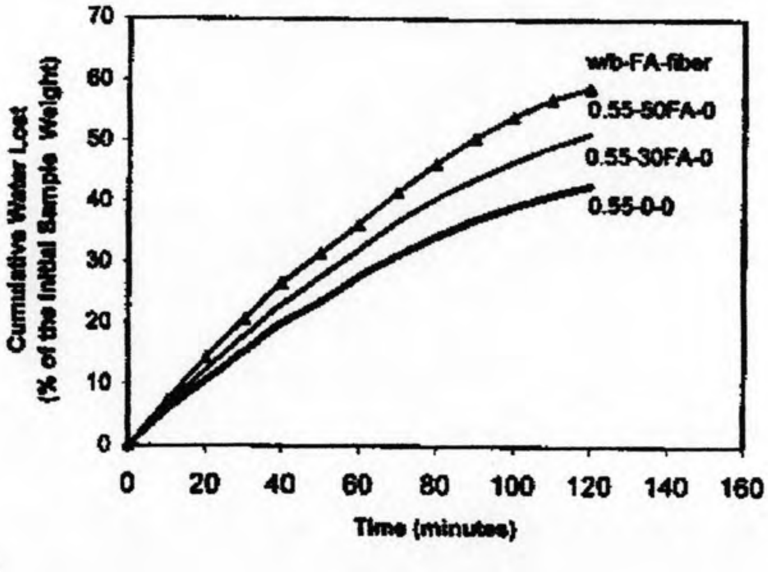
2.2.1 Effect of Fly Ash on Plastic Shrinkage Cracking of Concrete

Cement pastes made with high fly ash content demonstrated a higher percentage of water loss than pastes made with low fly ash content due to the slow hydration of the fly ash which brought about a very porous paste structure at the very early age (Wang, Shah, and Phuaksuk, 2001). Specimens were monitored under a lab drying condition and used Image Analysis to measure maximum crack width and crack area. The use of ultrafine fly ash resulted in a high capillary pressure in the paste due to the finer pore structure. The comparison of the behavior of water loss by using plain concrete and concrete with fly ash (FA) and ultrafine fly ash (UFA) due to water-cement ratio, fly ash content, and fly ash type could be seen in Figures 2.4. Interestingly, Figure 2.5 shows that pastes with 30 and 50% fly ash have a smaller total cracking area than the control specimen. This was may be partially due to a relatively large pore size that reduces pore pressures in the pastes with fly ash. Plastic shrinkage patterns due to the effect of fly ash type and content is illustrated in Figure 2.6.

(a)



(b)



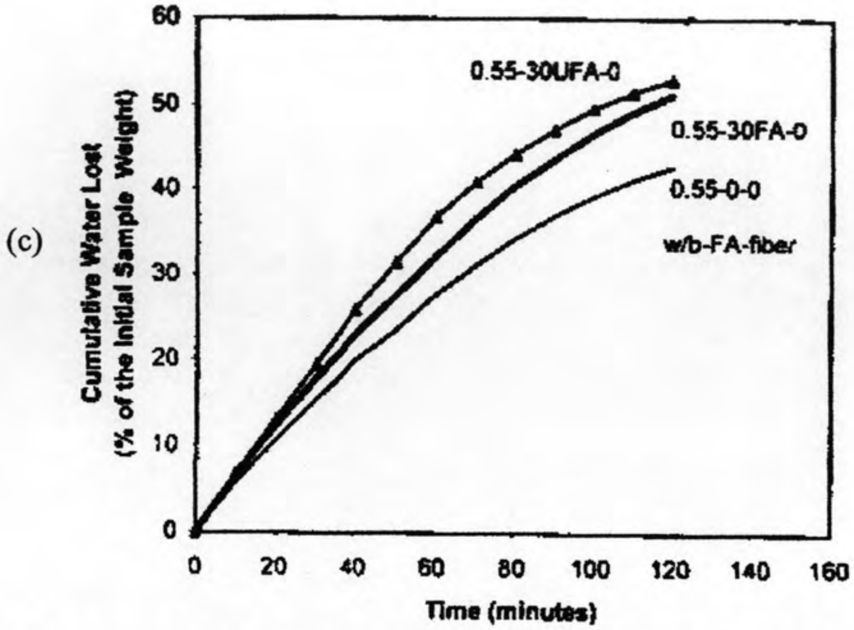


Figure 2.4: Effect of (a) water-cement ratio, (b) fly ash content, and (c) fly ash type on water loss (Wang, Shah, and Phuaksuk, 2001)

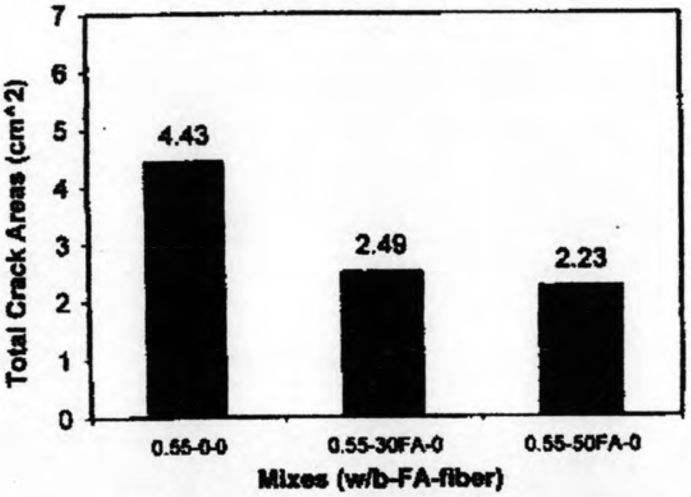


Figure 2.5: Effect of fly ash content on total crack area (Wang, Shah, and Phuaksuk, 2001)

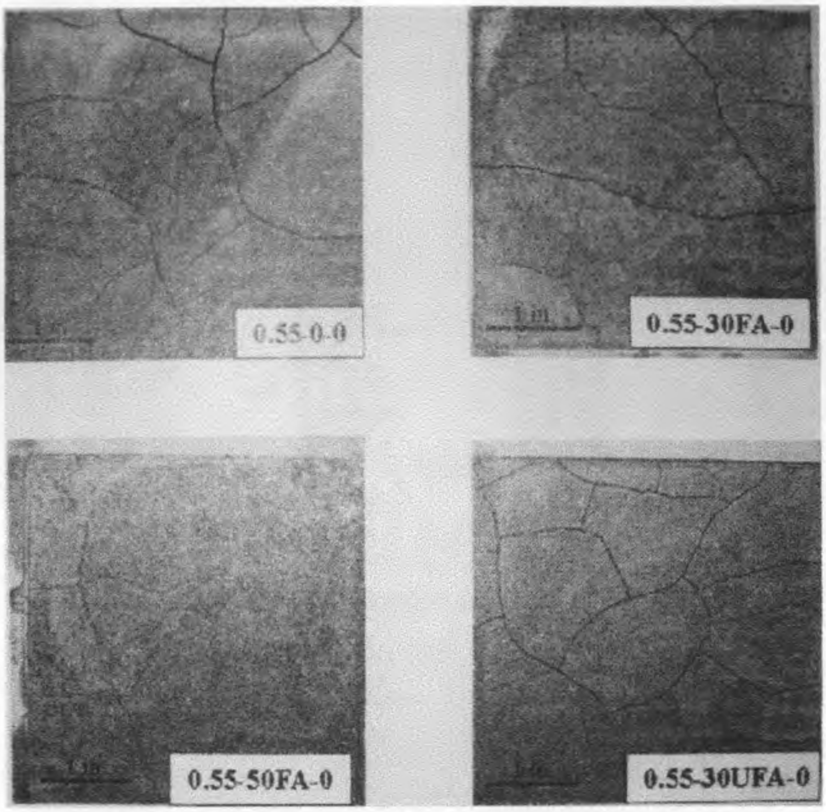


Figure 2.6: Effect of fly ash type and content on plastic shrinkage cracking (Wang, Shah, and Phuaksuk, 2001)

Using concrete with fly ash replacements of 0 to 50 percent, comparisons of crack width, length, and area were done by Stitmannaithum, Raksamata, and Chalanun (2002). After testing using a fan box and Image Analysis in measuring required values, it was observed that the crack width increased when fly ash replacement exceeded 35-40% (Figure 2.7). However, the crack length decreased as fly ash content increased as shown in Figure 2.8. This in turn reduced the crack area as the amount of fly ash increased (Figure 2.9). The reduction in crack length and area was due to the ability of the fine fly ash particles to be able to fill voids. This characteristic of fly ash allowed improvement in cohesion due to the reduction in interparticle friction.

In the case of plastic shrinkage cracks, the use of fly ash with low water/cementitious material ratio increased the cracking area (Bouzoubaa, Bilodeau, Sivasundaram, Fournier, and Golden, 2004). Researchers explained that for mortar mixtures with low w/cm ratio, the free water was too low and evaporation duration

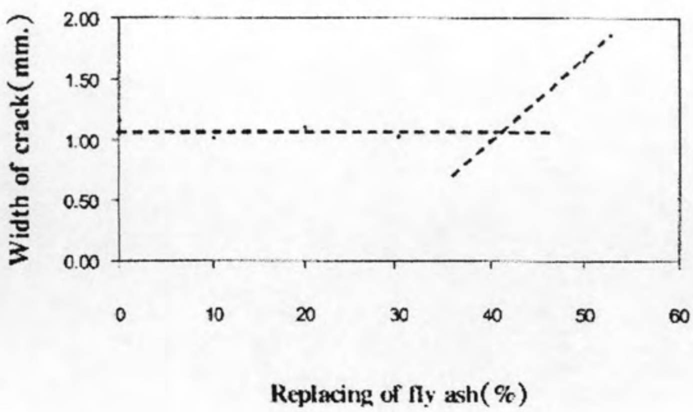


Figure 2.7: Effect of fly ash on crack width (Stitmannaithum, Raksamata, and Chalanun, 2002)

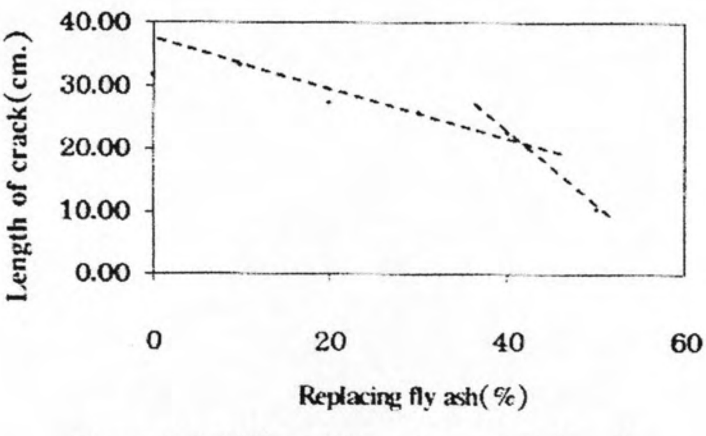


Figure 2.8: Effect of fly ash on crack length (Stitmannaithum, Raksamata, and Chalanun, 2002)

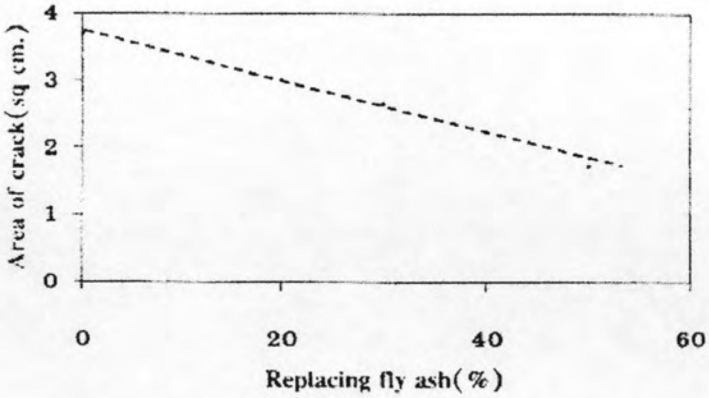


Figure 2.9: Effect of fly ash on crack area (Stitmannaithum, Raksamata, and Chalanun, 2002)

was too short so the tensile strength development of the mortar became the main parameter that controls the plastic shrinkage. However, it was suggested that this still needs to be confirmed. Figures 2.10 and 2.11 demonstrate the total cracking area of the mortar mixtures with a water-cement ratio of 0.40 and 0.34. Figure 2.12 illustrates the picture of slabs at the end of the experimental tests.

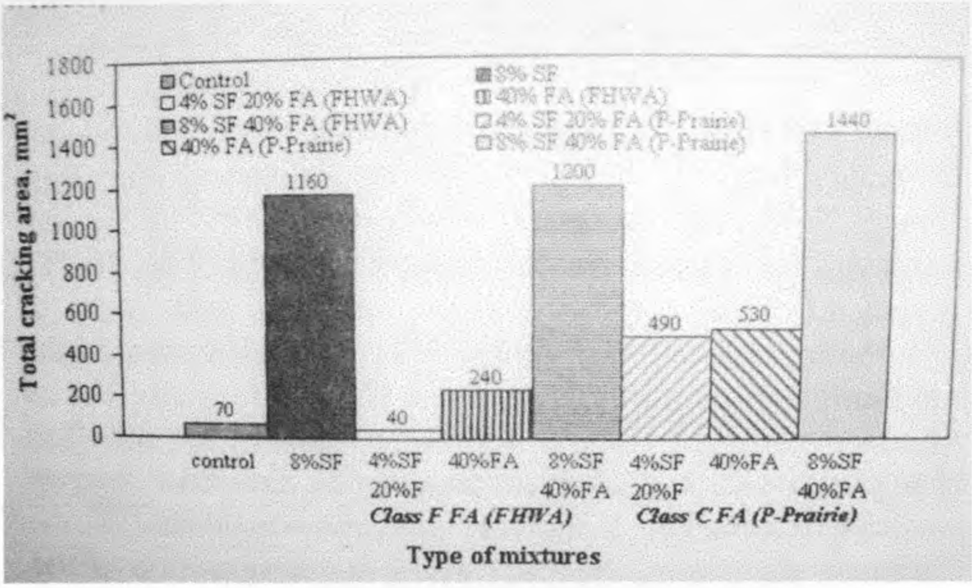


Figure 2.10: Total cracking area of mortar mixtures with water-cement ratio of 0.40 (Bouzoubaa, Bilodeau, Sivasundaram, Fournier, and Golden, 2004)

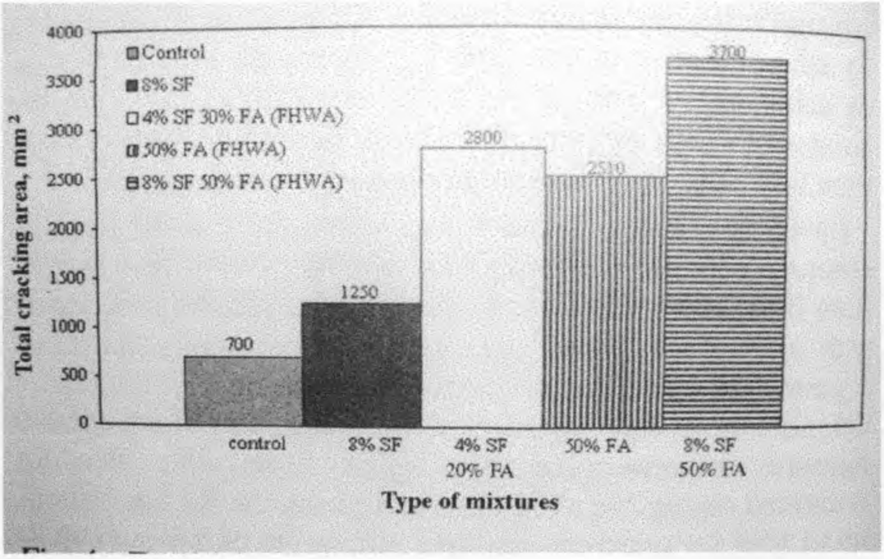


Figure 2.11: Total cracking area of mortar mixtures with water-cement ratio of 0.34 (Bouzoubaa, Bilodeau, Sivasundaram, Fournier, and Golden, 2004)

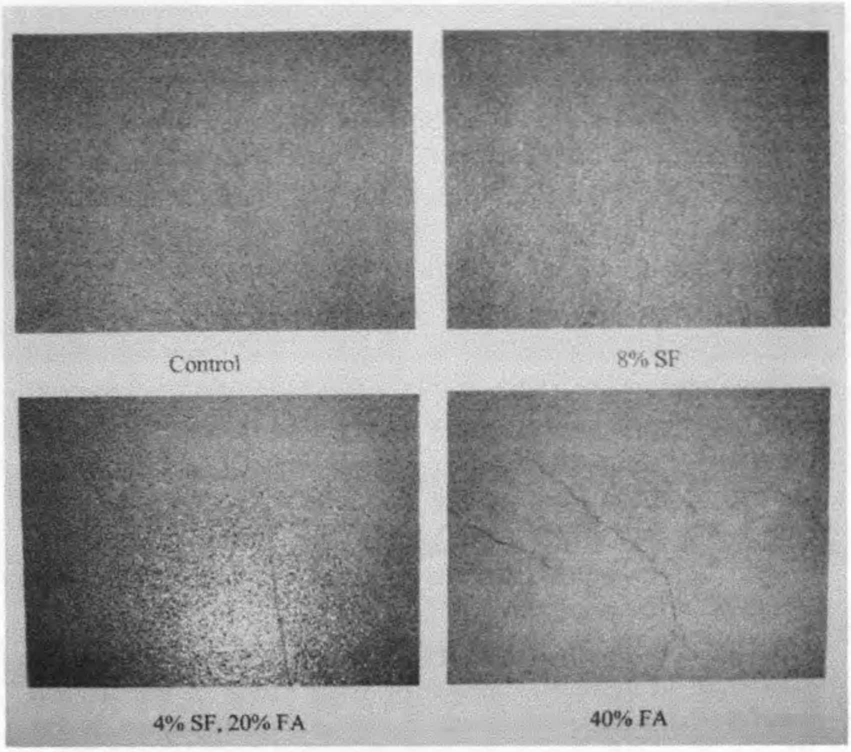


Figure 2.12: Crack pattern of selected mortar mixtures made with Federal Highway Association (FHWA) Class F fly ash and water-cement ratio of 0.40 (Bouzoubaa, Bilodeau, Sivasundaram, Fournier, and Golden, 2004)

Subramaniam, Gromotka, Shah, Obla, and Hill (2005) investigated the influence of ultrafine fly ash (UFFA) on the shrinkage cracking potential of concrete. Ultrafine fly ash, with the mean particle size of 3μm in this study, exhibited its benefits in reducing shrinkage strains and decreasing the potential for restrained shrinkage cracking. Increasing the volume of UFFA as well as decreasing the water-cement ratio resulted in an increase in the compressive strength, rate of strength gain, and further improvements in age when concrete cracks in restrained shrinkage tests.

2.2.2 Effect of Silica Fume on Plastic Shrinkage Cracking of Concrete

Bouzoubaa, et.al. (2004) used Portland cement with silica fume for comparison such as that of cement with fly ash in the same research stated in the previous section. Bleeding increased when the amount of silica fume content is decreased. The effect of silica fume on the maximum temperature rise of the concrete was insignificant. Similar to that of cement with fly ash, plastic shrinkage cracking area increased in silica fume cement with low water/cementitious ratio because of the delay of strength development of the mortar. Results of this investigation can be seen in Figures 2.10 to 2.12. In Figure 2.12, the mortar mixtures with 8% silica fume cracked more than what it appears mainly because the dark color of the silica fume did not reflect the camera light or flash.

For a constant water-binder ratio of 0.40 with silica fume replacements of 0, 5, 10, 15%, it was observed that there was no systematic effect of the silica fume content (Hammer, 2001). As shown in Figure 2.13, the differences seen are not significant. The investigation concluded that for silica fume in a high strength concrete up to 15% by cement weight, added as volume replacement for cement, does not have significant influence in terms of settlement and plastic shrinkage at moderate drying conditions of 50% relative humidity at 20°C and no wind.

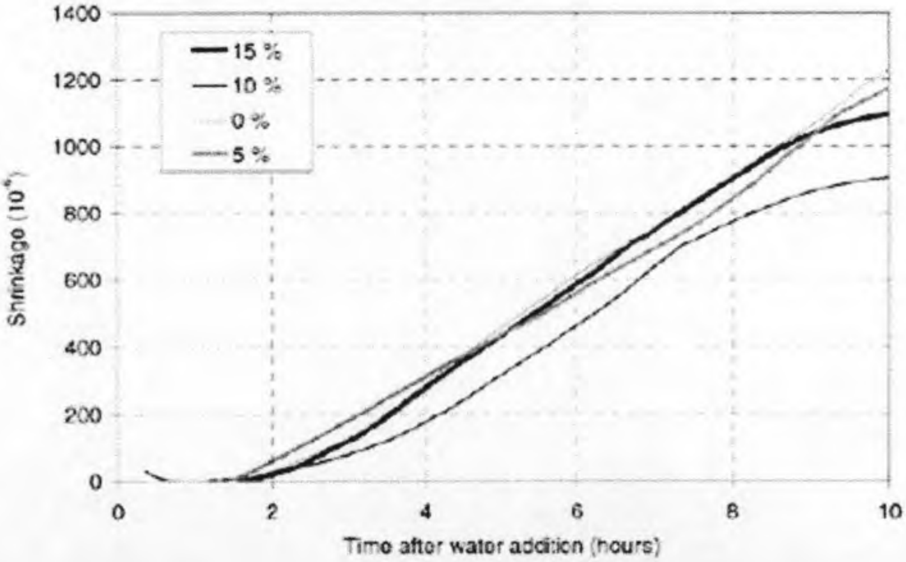
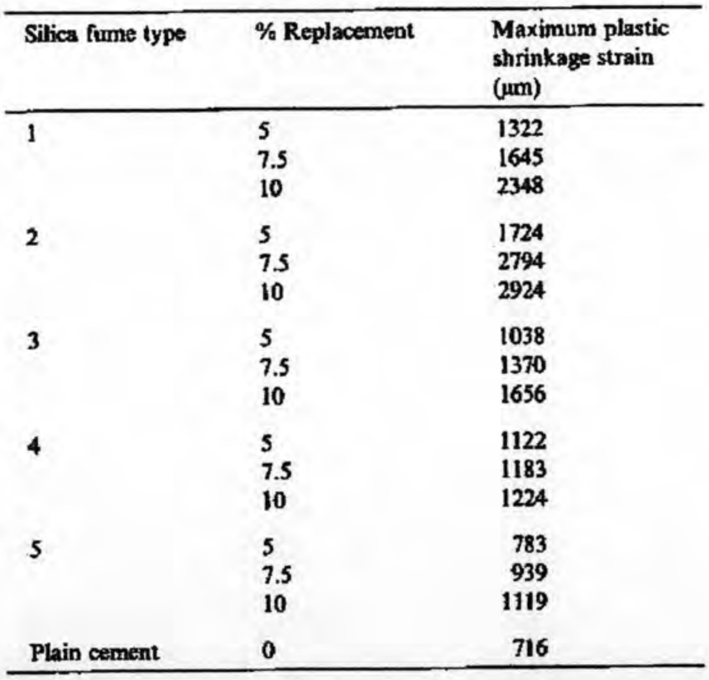


Figure 2.13: Plastic shrinkage of concretes with 5, 10, and 15% silica fume when exposed to 50% relative humidity at 20°C (Hammer, 2001)

In a study done by Al-Amoudi, Maslehuddin, and Abiola (2004), they found out that the highest plastic shrinkage was noted in the concrete specimens prepared with undensified silica fume (Type 2 silica fume in Table 2.1). This may be attributed to the undensified nature of this type of silica fume that leads to a lower bulk density and a higher specific surface area as compared to the other densified silica fume cements investigated. Results of this investigation are summarized in Table 2.1. Silica fume cement is thought to be more susceptible to plastic shrinkage cracking than any other type of concrete, particularly in structures that has large surface areas. The plastic shrinkage strain increased with increasing dosage of silica fume and the fineness (of silica fume), in terms of its specific surface area and bulk density, was said to be good indicators for assessing plastic shrinkage cracking potential in hot weather conditions. However, there was no definite relationship that was noted between the microscopic properties of the silica fume and the plastic shrinkage strains.

Table 2.1: Maximum plastic shrinkage strain in plain and blended cement concretes, exposed to a wind velocity of 12 km/h, temperature of 45°C and relative humidity (RH) of 35% (Al-Amoudi, Maslehuddin, and Abiola, 2004)



Silica fume type	% Replacement	Maximum plastic shrinkage strain (μm)
1	5	1322
	7.5	1645
	10	2348
2	5	1724
	7.5	2794
	10	2924
3	5	1038
	7.5	1370
	10	1656
4	5	1122
	7.5	1183
	10	1224
5	5	783
	7.5	939
	10	1119
Plain cement	0	716

Another study done by the same group (2005) focused on the effect of the use of superplasticizer on the plastic shrinkage of both plain and silica fume concretes primarily on evaluating the plastic shrinkage strain as well as the time for maximum plastic shrinkage strain. The type of superplasticizer was found to improve the ability of silica fume concrete to resist plastic shrinkage cracking. The maximum plastic shrinkage strain was measured in the undensified silica fume cement concrete with superplasticizers.

From the literature review done for this research, it has shown that plastic shrinkage cracks in concrete must not be overlooked as the use of different materials in the concrete mix might further improve or worsen such cracks. Fly ash was chosen to be investigated in this research due to its availability. If proven to be able to reduce plastic shrinkage cracks, then such material would be an economical means for such purpose. On the other hand, comparisons would be done with the effect of silica fume on plastic shrinkage cracking of concrete since it is known to enhance concrete properties at an earlier age than fly ash.