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Development of Ternary Blends for

High-Performance Concrete

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Abstract

The purpose of this study is to develop ternary blends with optimum amounts of fly ash and silica fume to be used in high-performance concrete. Two series of air-entrained concrete mixtures were investigated in this study: series 1 included concretes with a total cementitious materials content (CM) of 350 kg/m^3, and a water-to-cementitious materials ratio (W/CM) of 0.40, and series 2 included concretes with a total CM of 450 kg/m^3 and a W/CM of 0.34. In each series, one silica fume and three fly ashes were used; these consisted of two ASTM Class F and one ASTM Class C fly ashes. Properties of the fresh and hardened concrete such as slump, air content, bleeding, setting time, autogenous temperature rise, plastic shrinkage, compressive strength, drying shrinkage and the resistance to chloride-ion penetration were determined. The results have shown that the combined use of fly ash and silica fume in concrete are more advantageous in terms of the following parameters: the dosage of superplasticizer, plastic shrinkage, chloride-ion penetrability and the drying shrinkage.

Introduction

Ternary-blended cements based on ordinary portland cement (OPC), ground–granulated blast furnace slag (GGBFS) and pozzolans have been the subject of investigations as early as in the 50's [1]. Studies conducted in France resulted in the commercial production of ternary cements since 1953, and in some parts of Australia, ternary and even quaternary cements have been intermittently available since 1966 [1]. In Canada, a ternary-blended cement including a combination of silica fume and fly ash is currently being produced by St Lawrence Cement (Joliette, Qc). A ternary-blended cement incorporating silica fume and GGBFS is being produced by Lafarge Canada Inc (St. Constant, Qc), and a quaternary-blended cement is currently being developed by Ciment Québec, Canada.

According to several researchers, ternary blends made of portland–cement, silica fume and fly ash offer significant advantages over binary blends and even greater enhancements over straight portland cement [2-4]. When combined in concrete, silica fume and low calcium fly ash acts complementary to each other, the silica fume improving the early-age performance of concrete with the fly ash continuously refining the properties of the hardened concrete as it matures. In terms of durability, such blends are vastly superior to portland cement concrete. In some cases, price differences between the individual components may allow the ternary blends to compete with portland cement on the basis of material costs [2].

According to recent research, the resistance to chloride-ion penetration of the concrete made with ternary-blended cement is higher than that of concrete made either with portland cement alone or a blend of portland cement and fly ash [3]. This is mainly due to the refinement of the pore structure of the concrete made with ternary-blended cement. Researchers have shown that the resistance to chloride-ion penetration of high-volume fly ash concrete incorporating silica fume was much less affected by a reduced curing period than high-volume fly ash concrete without silica fume addition [5].

Since the main advantage of ternary blends appears to be the superior durability of the concrete, the overall objective of this research is to develop blends with optimum amounts of fly ash and silica fume to be used in high-performance concrete.

RESEARCH SIGNIFICANCE

The use of supplementary cementitious materials such as fly ash, slag and silica fume in cement and concrete in order to improve the durability of concrete has increased in recent years. Among the new blended cements recently developed and commercialized in North America for the mentioned purpose are ternary blends. This research shows the benefits of using ternary systems based on portland cement, fly ash and silica fume in concrete.

SCOPE

Two series of air-entrained concrete mixtures were investigated in this study: series 1 included concretes with a total cementitious materials content (CM) of 350 kg/m^3, and a water-to-

cementitious materials ratio (W/CM) of 0.40, and series 2 included concretes with a total CM of 450 kg/m^3 and a W/CM of 0.34. For each series, three fly ashes were used; these consisted of two ASTM Class F and one ASTM Class C fly ashes.

For series 1, thirty concrete mixtures were made and tested. Three replacement levels (i.e. replacement by mass of the portland cement) of 20, 30 and 40% were used with each fly ash. Two replacement levels of silica fume, 4 and 8%, were used in combination with the fly ashes. Reference mixtures with portland cement alone and mixtures incorporating binary blends of portland cement and fly ash, and portland cement and silica fume were also made and tested for comparison purposes.

For series 2, eighteen concrete mixtures were made and tested. Three replacement levels, 30, 40 and 50% were used with a low-calcium Class F fly ash. One replacement level, i.e. 40 percent, was selected to be used with the higher-calcium content Class F fly ash and the Class C fly ash. Two replacement levels of silica fume, 4 and 8 percent, were used in combination with the fly ashes. Similarly to Series 1, reference mixtures with portland cement alone and mixtures with binary blends of portland cement and fly ash, and portland cement and silica fume were also made and tested for comparison purposes.

Properties of the fresh and hardened concrete such as slump, air content, bleeding, setting time, autogenous temperature rise, plastic shrinkage, compressive strength, drying shrinkage and the resistance to chloride-ion penetration were determined.

MATERIALS

Cement

ASTM Type I, normal portland cement was used. Its physical properties and chemical compositions are presented in Table 1.

Fly ash

Two ASTM Class F fly ashes from Jim Bridger Facility (supplied by FHWA, USA), and Coal Creek, North Dakota, and one ASTM Class C fly ash from Pleasant-Prairie, Wisconsin were used in this study. Their physical properties and chemical compositions are also given in Table 1.

FHWA fly ash has a low CaO content of 6.6%, Coal Creek fly ash has an intermediate CaO content of 14.7%, and Pleasant-Prairie fly ash has a high CaO content of 26.0%.

Silica fume

Silicon metal fume from Niagara Falls, New York was used in this study. Its physical properties and chemical compositions are also presented in Table 1.

Admixtures

A water reducer composed by modified polymers and lignosulfonates (WR), a sodium salt of naphthalene sulfonate polymer based superplasticizer (SP), and a synthetic resin type air-entraining admixture were used (AEA).

Aggregates

Crushed limestone with a maximum nominal size of 19 mm was used as the coarse aggregate, and a local natural sand derived from Granite was used as the fine aggregate in the concrete mixtures. The coarse aggregate was separated into different size fractions and recombined to a specific grading shown in Table 2. The coarse and fine aggregates each had a specific gravity of 2.70, and water absorptions of 0.4 and 0.8%, respectively.

MIXTURE PROPORTIONS

The proportions of the concrete mixtures are summarized in Table 3 and 4. For all the mixtures, the coarse and fine aggregates were weighed as received. The coarse aggregate was then immersed in water for 24 hours. The excess water was decanted, and the water retained by the aggregates was determined by the weight difference. A predetermined amount of water was added to the fine aggregate that was then allowed to stand for 24 hours.

PREPARATION, CASTING AND CURING OF TEST SPECIMENS

All the concrete mixtures were mixed for a total of five minutes in a laboratory counter-current mixer. From each concrete mixture, sixteen 100H200-mm cylinders were cast for the determination of the compressive strength and the resistance to chloride-ion penetration. One 150x300-mm cylinder was cast for determining the autogenous temperature rise in the concrete. One container of approximately 7L capacity was filled with the fresh concrete for determining the bleeding, and one 150x150x150-mm mould was filled with mortar obtained by sieving the fresh concrete for determining the setting times of the concrete. For selected concrete mixtures, extra 100H200-mm cylinders were cast for the determination of the effect of the curing mode on the compressive strength and on the resistance to chloride-ion penetration of the concrete, and four 75x100x400-mm prisms were cast for the determination of the drying shrinkage.

The specimens were cast in two layers and were compacted on a vibrating table. After casting, all the molded specimens were covered with plastic sheets and water-saturated burlap, and left in the casting room for 24 hours. They were then demolded and the specimens were transferred to the moist-curing room at 23 ∀ 2EC and 100 % relative humidity until required for testing. The prisms for the drying shrinkage test were stored in lime-saturated water for 7 days prior to be transferred to a conditioned chamber at 20 ∀ 2EC and 50 % relative humidity. The extra cylinders, cast to investigate the effect of the curing-mode on the compressive strength and on the resistance to the chloride-ion penetration of the concrete, were cured in the moist curing

room for three days followed by an air curing at 23 ∀ 2EC and 50% relative humidity until required for testing.

For the plastic shrinkage test, the test program was based on the procedure developed by Kraai [6] and modified by Shaeles and Hover [7]. The testing mold consists of a thin slab 610x910x20-mm made of polyethylene white with an expanded metal lath attached to the inside perimeter to provide edge restraint, and the mortar mix is poured into this form. Because of the small thickness of the forms, the slabs were cast using mortars that were proportioned to represent the mortar component of the concrete mixes. The specimens were cast in one layer and were consolidated on a vibrating table; the finishing was made in the direction of the 610 mm side, and was similar for all the slabs. Immediately after finishing the slabs were transferred to a controlled chamber kept at a temperature of 33°C, a relative humidity ranging from 14 to 17% and a wind velocity of 3.7 m/s (Fig. 1). The crack area on the mortar surface was measured six hours after casting by multiplying the length and the average width of the crack using a ruler made for that purpose.

TESTING OF THE SPECIMENS

The slump, air content, bleeding and setting time of fresh concrete, and the properties of hardened concrete were determined following ASTM standards.

RESULTS AND DISCUSSIONS

Properties of fresh concrete

The unit weight, slump, air content, bleeding, setting time and maximum temperature rise of concrete are given in Table 5 and 6.

Dosage of SP

All the concrete mixtures incorporated a WR at a dosage of 200 mL per 100 kg of cement. The dosage of SP was adjusted to produce concrete with a slump of 100 to 150 mm, and ranged from 0 to 4.6 L per m^3 of concrete. In general, the required dosage of SP decreased with increased fly ash content and decreased silica fume content. Figure 2 shows a typical effect of fly ash and silica fume contents on the dosage of SP in concrete. Also, Figure 2 shows that, for approximately similar slumps, concrete made with cement only (350 kg and W/C=0.40) and concrete incorporating 30% of Coal Creek fly ash and 8% silica fume required the same dosage of SP. The use of fly ash in silica fume concrete offsets the effect of silica fume in increasing the dosage of SP in concrete to achieve a given workability. Therefore, it is possible to optimize the fly ash and silica fume contents in the concrete mixtures to minimize the dosage of SP. The results show that the effect of the two ASTM Class F fly ashes on the dosage of SP was similar; however, for similar types of concrete, the Class C fly ash required higher dosage of SP to achieve similar slumps.

Dosage of AEA

The dosage of AEA was adjusted to produce a concrete with air content ranging from 5 to 7%. The results show that for all the concrete mixtures, the dosage of AEA increased with increasing silica fume content, with other parameters held constant. For Class F fly ash concretes, the dosage of AEA increased with increasing fly ash content from 0 to 20%, but decreased with increasing fly ash content from 20 to 50%. For Class C fly ash, the dosage of AEA decreased with increasing fly ash content from 0 to 30% and remained constant there after.

Bleeding

Tables 7 and 8 show that the bleeding of the concrete mixtures investigated was very low and ranged from 0 to 0.037 ml/cm^2. In general, the bleeding increased with increasing fly ash content and decreasing silica fume content. The concrete mixtures incorporating 8% silica fume did not show any significant bleeding. For the concrete mixtures incorporating 4% silica fume, the bleeding remained negligible even after increasing the fly ash content up to 20% for concrete mixtures with W/CM of 0.40, and up to 40% for concrete mixtures with W/CM of 0.34.

Setting time

The initial and final setting times of concretes made with cement only ranged from 4h:35min to 5h:40min, and from 6h:05min to 7h:20min, respectively. In general, the use of fly ash increased the setting times of the concrete, and the use of silica fume decreased the setting times of the fly ash concrete. For example, the incorporation of 20% fly ash in the concretes increased the initial and final setting times by 1h:30min to 3h:30min and by 2h to 4h, respectively, depending on the type of the fly ash used. The incorporation of 8% silica fume in the 20% fly ash concretes decreased the initial and final setting time by about 30min and by 5min to 1h, respectively. When 40% fly ash was incorporated into the concrete made with cement only, the initial and final setting times were increased by 4h to 4h:30min and by 4h:30min to 6h:30min, respectively. When 8% of silica fume was added to these fly ash concretes, the initial and final setting times were decreased by 40 min to 1h:15min and by 1h to 1h:30min, respectively.

The results show that in general, the use of silica fume in fly ash concrete does not significantly reduce the setting times.

Autogenous temperature rise

The maximum autogenous temperature rise of the control concrete made with cement only ranged from 28.2 to 33.5 °C. For the concrete mixtures with W/CM of 0.40, the incorporation of 20 to 40% of fly ash decreased the maximum temperature rise by 5 to 10°C, respectively, and for the concrete mixtures with W/CM of 0.34, the incorporation of 30 to 50% of fly ash decreased the maximum temperature rise by 8 to 11°C, respectively. For all the concrete mixtures i.e. with/without fly ash, the effect of silica fume on the maximum temperature rise of the concrete was insignificant, which is in line with previous studies [8-9].

Plastic shrinkage

Table 7 gives the composition of the mortar mixtures investigated, designated according to the concrete mixture number each mortar represents. The table also gives the flow and the total cracking area of each mortar mixture. Figures 3 and 4 show the total cracking area of the mortar mixtures with W/CM of 0.40 and 0.34. Figure 5 shows pictures of selected slabs at the end of the test.

The results show that for the mortar mixtures made with Class F fly ash and with W/CM of 0.40, the use of 8% silica fume resulted in a significant increase in the cracking area, whereas the use of 40% fly ash did not affect the cracking area significantly. When using 4% silica fume and 20% fly ash, the synergetic effect of the materials has led to a mortar with a reduced cracking area compared to the other mixtures. However, When using 8% silica fume and 40% fly ash, the synergetic effect of the materials was not apparent, and the crack area increased. The same trend was also observed with Class C fly ash but with generally increasing cracking area, probably due to the increase in reactivity of this type of fly ash that decreases the free water, which in turn increases the plastic shrinkage.

For the mortar mixtures with lower W/CM (0.34), it appeared that the use of both fly ash and silica fume individually or together increased the cracking area.

The principal cause of plastic shrinkage in concrete is understood to be the excessively rapid rate of evaporation of the water from the surface of the concrete and the lack of bleed water to compensate the evaporating surface water [10]. Wittman [11] has demonstrated experimentally that the requisite for plastic shrinkage is a build-up of capillary tension in the mixing water present in the fresh concrete after the surface becomes dry. The plastic shrinkage begins shortly after the capillary pressure starts to develop and exerts enough pressure to cause contractions. The concrete cracks when the stress resulting from the contraction exceeds the tensile strength of the concrete.

Powers [12] proposed the following equation for determining the maximum capillary tensile pressure for a cement mixture:

$$P = 10^{-3} \frac{\gamma S}{w/c}$$

where P is the capillary tension pressure (MPa), γ is the surface tension of water (N/m), S is the

specific surface area of cement (m^2/kg), and *w/c* is water to cement ratio by mass.

Based on the generally accepted formula, the plastic shrinkage is directly proportional to the specific surface of the cementitious materials and inversely proportional to the W/CM [12-14]. The results found can then be explained as follows: when replacing a partial amount of cement with fly ash that is coarser than cement as shown in Table 1, the plastic shrinkage should decrease. However, when replacing a high amount of cement with fly ash (40%), the initiation of the cracking was delayed due to the availability of the free water, but once all the free water evaporated and the cracks begin to form, they continue to form and grow without any resistance possibly due to the delay in setting time of the mortar caused by the use of high amount of fly ash. On the other hand, when 8% of cement was replaced by silica fume, the plastic shrinkage and consequently the total cracking area was increased significantly due to the high specific area of the silica fume as shown in the above formula. However, when using 20% of Class F fly ash and 4% of silica fume, the increase of the specific surface area resulting from the use of silica fume was offset by the use of 20% of fly ash, and the delay in the setting time caused by the fly ash was offset by the use of silica fume. The synergetic effect of the two materials has led to a mortar with a less cracking area than those incorporating only silica fume or fly ash.

For the mortar mixtures with low W/CM, the free water was too low, and the evaporation duration was too short that the tensile strength development of the mortar became the main parameter controlling the plastic shrinkage and consequently the cracking area. This is why for low W/CM, even the use of fly ash seemed to increase the cracking area because it delays the strength development of the mortar. Consequently the synergy effect of the materials disappeared with low W/CM. This, however, needs more research to be confirmed.

Properties of hardened concrete

Compressive strength

The compressive strengths of the two series of concrete mixtures investigated are presented in Tables 8 and 9.

Series 1, W/CM = 0.40; CM = 350 kg

The results show that, for example, the 1-d and 91-d compressive strengths of the control concrete (made with portland cement only) were 30.1, and 52.1 MPa, respectively; those of the silica fume concretes were approximately 29.5 MPa at 1 day, and ranged from 54.5 to 58 MPa at 91 days; those of the fly ash concretes ranged from 6 to 20 MPa, and from 46 to 58 MPa at 1 day and 91 days, respectively; and those of the concretes made with the ternary systems ranged from 6 to 20 MPa, and from 45 to 65 MPa, respectively.

In general, the compressive strength decreased with increased fly ash content, and the decrease was more significant at 1 and 7 days. The use of silica fume in the concrete made with portland cement only did not affect significantly the 1-d compressive strength, but increased the 7-d, 28-d and 91-d compressive strengths of the concrete.

For the concrete made with the ternary systems, the results show that, in general, the use of silica fume in the fly ash concretes did not contribute to significant increase in the 1-d compressive strength. Thus, the silica fume cannot be used to overcome the adverse effect of the high fly ash content on the 1-d compressive strength of the concrete. The results also show that for the Coal Creek fly ash, the use of silica fume had no significant effect on the compressive strength of the concrete regardless of the fly ash content and the testing age. For the two other fly ashes, the use of silica fume increased the 7-d, 28-d and 91-d compressive strength of the fly ash concretes, and the increase was more significant for concretes made with Pleasant-Prairie fly ash with high CaO content. Overall, the effectiveness of the silica fume in increasing the compressive strength of the fly ash concretes was insignificant in concretes with high fly ash content.

Series 2, W/CM = 0.34; CM = 450 kg

The results of Table 11 show that the control concrete made with portland cement developed 1-d, and 91-d compressive strengths of 35.3 and 59.7 MPa; the silica fume concretes developed similar 1-d compressive strength but slightly higher 91-d compressive strength that ranged from 61.5 to 63 MPa. For the fly ash concretes, the 1-d and 91-d compressive strengths ranged from 12 to ~20 MPa and from 51 to 65 MPa, respectively, and the concrete made with the ternary systems developed 1-d and 91-d compressive strengths ranging from 10 to 18 MPa, and from 48 to 64 MPa.

The effects of silica fume and fly ash on the compressive strength of the concretes were similar to those observed for concrete mixtures of series 1.   However, for the concrete made with the ternary systems, the incorporation of the silica fume did not enhance the compressive strength of the concretes even at later age.

Effect of curing

Table 10 presents the results on the effect of the curing mode on the compressive strength of selected concrete mixtures. The results show that, in general, the air curing increased the 7-d compressive strength, but deceased significantly the 28-d and 91-d compressive strengths of the concretes. Two processes are affecting the compressive strength development under air curing. First, when the test prisms are transferred from 100% (moist curing) to 50% R.H. conditions, the trend to reach equilibrium between the internal (concrete) and external (storage) conditions induces a "confinement pressure" that contributes in increasing concrete strength. This behavior could likely explain the higher 7-day compressive strengths observed for the air-cured specimens (i.e. cured four days at 50% R.H. after 3 days of moist curing). In the longer term (i.e. after 7 days), however, the lack of available humidity during the air curing slows down the cement hydration and pozzolanic activity, thus resulting in reduced compressive strength values of the concrete.

The results also show that the strength development of fly ash concretes is more influenced by the curing mode than the control and the silica fume concretes. For the concrete made with the ternary systems, it appeared that the silica fume did not decrease significantly the sensitivity of the fly ash concretes to the curing mode. In fact, the air curing decreased the 28-d and 91-d compressive strengths of the control and the silica fume concretes by 4 to 8% and by 10 to 20%, respectively. For the fly ash concretes (40 to 50% of fly ash content), the air curing decreased the 28-d and 91-d compressive strengths by 8 to 20% and by 20 to 45%, respectively; when 8% of silica fume was added to the above fly ash concretes, the decrease was in the range of 6 to 20% and 20 to 36%, respectively.

The results also show a drop in strength at 91 days for the air-cured concretes. This is in line with the reported data in the literature dealing with the long-term strength losses of silica-fume high-strength concretes [15, 16]. In this study, the strength loss was observed for the silica fume and the fly ash concretes as well as for the concrete made with ternary systems. De larrard and Bostvironnois explained the strength losses by means of the internal stresses caused by the drying shrinkage; their calculation of the self-stress field due to drying shrinkage has indicated that the compression at the core of the specimen is of the same order as the drop in strength observed [16].

Chloride penetrability

The chloride penetrability results are presented in Tables 8 and 9.

Series 1, W/CM = 0.40; CM = 350 kg

Table 8 shows that the control concrete made with portland cement developed a chloride-ion penetrability ranging from low to moderate. The extra curing time from 28 to 120 days of such concrete did not affect significantly the chloride-ion penetrability of the concrete. When 4 and 8% of silica fume were incorporated in the control concrete, the chloride-ion penetrability dropped from the range of low to moderate to the range of very low to low; the chloride penetrability decreased with increased silica fume content, but remained the same when increasing the curing time from 28 to 120 days. As reported earlier [17], the positive effect of the silica fume on the chloride-ion penetrability of the concrete is mainly due to the fact that the incorporation of such material in the concrete results in finer pores in the hydrated cement paste.

The results also show that compared to that of the control concretes, the 28-d chloride-ion penetrability decreased when 20 to 40% of Class F fly ashes (with low and moderate CaO contents) were used, whereas the use of 20 to 40% Class C fly ash resulted in chloride penetrability values equal to or higher than the control. However, after 120 days of moist curing, regardless of the type and content of fly ash used, the fly ash concretes developed very low chloride-ion penetrability similar to that of concrete made with 8% of silica fume. Because fly ash is coarser and less reactive than the silica fume, its effect on refining the pores of the hydrated cement paste needs more curing time than the silica fume.

When both fly ash and 4% silica fume were used, the synergetic effect of both materials on the chloride-ion penetrability of the concrete, in which the silica fume decreasing the chloride-ion penetrability at early age and the fly ash decreasing it at later age, resulted in a concrete with very low chloride-ion penetrability at both ages, i.e, 28 and 120 days. A decrease in the chloride-ion penetrability in the case of the ternary systems incorporating 40% of the Class C fly ash, was observed at 120 days. The increase of the silica fume content from 4 to 8% did not significantly affect the resistance of concrete to the chloride-ion penetrability.

Series 2 W/CM = 0.34; CM = 450 kg

Table 9 shows that the results of the concretes made with low W/CM were similar to those of the concretes with W/CM of 0.40, the only exception was that the effect of the fly ash in reducing the 28-d chloride-ion penetrability was more significant and the synergetic effect was greater for concrete with low W/CM.

Effect of curing

Table 10 shows the results on the effect of the curing mode on the chloride-ion penetrability of some selected concrete mixtures. The results show that the curing mode had a significant effect on the chloride-ion penetrability of the control concretes and the fly ash concretes. For example, the control concrete (W/C = 0.40) developed a 28-d chloride-ion penetrability of 2020 Coulombs when moist cured, and 3880 Coulombs when air cured; the concrete incorporating 40% Class F fly ash developed a 28-d chloride-ion penetrability of 1160 Coulombs when moist cured and 5010 Coulombs when air cured. When silica fume was added to both control and fly ash concretes, the results show that the sensitivity of these concretes to the curing mode decreased considerably especially with 8% silica fume. For example, the concrete made with 40% of Class C fly ash developed a 28-d chloride penetrability of 2700 and 6500 Coulombs, when moist cured and air cured, respectively. When 8% of silica fume was incorporated in the concrete, theses values became 1110 and 1300 Coulombs, respectively. The results also show that in the long term, the air cured concrete made with the ternary blends developed similar or better resistance to chloride-ion penetrability than the moist-cured control concrete.

Drying shrinkage

Figure 6 shows the drying shrinkage of selected concrete mixtures having similar W/CM. The results show that at early age (up to 28 days), the silica fume concrete developed less drying shrinkage than the concrete made with portland cement only, which developed less drying shrinkage than the fly ash concrete. At later ages, both fly ash and silica fume concretes developed less drying shrinkage than the concrete made with portland cement only (this can be noted through the slopes of the curves in Fig. 6). This is primarily due to the fact that fly ash and silica fume refine the pore size distribution of the hardened concrete which lower the permeability of the water vapor through the hardened paste, thus lowering the drying shrinkage [18]. Because the fly ash is less reactive than silica fume, it needs more curing time to refine the pore size distribution of the hardened concrete. When both fly ash and silica fume were used in the concrete, the drying shrinkage values were between those of the fly ash and the silica fume

concretes.

Conclusions

From the above investigation, the following conclusions are drawn:

The use of both fly ash and silica fume in concrete appeared to be advantageous only for the following parameters: the dosage of superplasticizer, plastic shrinkage, chloride-ion penetrability and the drying shrinkage.

The results have shown that the use of fly ash in silica fume concrete offsets the effect silica fume has in increasing the dosage of SP in concrete to achieve a given workability.

For the plastic shrinkage, the results have shown that for the mortar mixtures with W/CM of 0.40 and low fly ash and silica fume contents (~20% and ~4%, respectively), the synergetic effect of the two materials has led to a mortar with less cracking area than those incorporating only silica fume or fly ash. For low W/CM (0.34) or high fly ash and silica fume contents (~40% and ~8%, respectively), the synergetic effect was insignificant. More work is needed to conform this.

Regarding the resistance of the concrete to the chloride-ion penetrability, the results have shown that, regardless of the type of fly ash, the W/CM, and the fly ash and the silica fume contents, the concrete made with the ternary system outperforms the concrete made with portland cement alone as well as the concrete made with the binary system. However, when the concrete was air cured in order to simulate a concrete with insufficient cure, the use of silica fume contributed in significantly reducing the sensitivity of the control and the fly ash concrete to the curing mode.

The drying shrinkage values of the concrete made with the ternary systems were between those of the fly ash and the silica fume concretes (binary systems).

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Table 1 - Physical Properties and Chemical Analyses of the Materials Used

	ASTM	Fly ash			Silica fume
	Type I cement	FHWA	Coal Creek	Pleasant-Prairie	

Physical Tests					
Specific gravity	3.15	2.28	2.44	2.51	2.30
Fineness					
-passing 45:m, %	94.0	74.5	76.1	83.5	97.2
-specific surface, Blaine, cm^2/g	4100	-	2050	2950	-
-nitrogen adsorption, m^2/g	-	-	-	-	19.5
Compressive strength of 51 mm cubes, MPa					-
-7-day	26.0	-	-	-	-
-28-day	31.9	-	-	-	-
Water requirement, %	-	-	94.7	98.3	115.7
Pozzolanic Activity Index, %					
-7-day	-	89.2	85.8	94.7	123.7
-28-day	-	95.7	88.9	101.8	-
Time of setting, Vicat test, min					
-initial setting	220	-	-	-	-
-final setting	325	-	-	-	-
Air content of mortar, volume %	5.5	-	-	-	-
Chemical Analyses, %					
Silicon dioxide (SiO_2)	19.5	59.7	49.7	35.0	94.0
Aluminium oxide (Al_2O_3)	4.6	17.4	15.3	19.3	0.1
Ferric oxide (Fe_2O_3)	2.0	5.4	8.3	5.6	0.1
Calcium oxide (CaO)	62.2	6.6	14.7	26.0	0.4
Magnesium oxide (MgO)	2.8	2.5	4.1	4.5	0.4
Sodium oxide (Na_2O)	0.2	3.4	2.6	1.8	0.1
Potassium oxide (K_2O)	0.9	1.3	2.0	0.4	0.9
Equivalent alkali ($Na_2O+0.658K_2O$)	0.8	4.3	3.9	2.0	0.7
Phosphorous oxide (P_2O_5)	0.2	0.4	0.1	1.1	0.1
Titanium oxide (TiO_2)	0.2	0.9	0.6	1.5	<0.01
Sulphur trioxide (SO_3)	3.1	0.5	1.0	2.0	0.3
Loss on ignition	2.4	0.4	0.2	0.4	2.7

Table 2 - Grading of Coarse and Fine Aggregate

Coarse Aggregate		Fine Aggregate	
Sieve Size, mm	Passing, %	Sieve Size, mm	Passing, %
19.0	100	4.75	100
12.7	67	2.36	90
9.5	34	1.18	67.5
4.75	0	0.60	42.5
		0.30	20
		0.15	6

Table 3 - Proportions of the Concrete Mixtures made with a total Cementitious Materials Content of 350 kg/m^3 and a Water-to-Cementitious Materials Ratio of 0.40.

Mix. no	Cement kg/m^3	Fly Ash			Silica Fume		Fine Aggregate, kg/m^3	Coarse Aggregate, kg/m^3	WR[1], mL/m^3	SP[2], L/m^3	AEA[3], mL/m^3
		Type	%	kg/m^3	%	kg/m^3					
1	356	-	0	0	0	0	756	1134	710	2.2	57
2	336				4	14	741	1111	699	4.3	70
3	326				8	28	749	1125	691	4.2	91
4	279	F	20	70	0	0	731	1098	697	1.1	78
5	267	H		70	4	14	736	1103	701	2.6	90
6	255	W		71	8	28	740	1109	708	2.9	111
7	245	A	30	105	0	0	730	1097	700	0.9	76
8	236			107	4	14	743	1116	715	1.5	82
9	221			107	8	28	738	1108	712	2.6	91

10	210		40	140	0	0	726	1089	700	0.3	60
11	195			139	4	14	721	1080	697	0.8	60
12	184			141	8	28	729	1094	707	1.1	81
13	278	C	20	69	0	0	732	1098	696	1.2	66
14	265	o		70	4	14	732	1097	697	1.7	74
15	254	a		71	8	28	740	1110	706	2.5	79
16	242	l	30	105	0	0	727	1091	694	0.8	59
17	232	-		107	4	14	740	1110	708	1.4	61
18	219	C		107	8	28	739	1109	709	2.2	67
19	209	r	40	139	0	0	727	1090	697	0	60
20	199	e		142	4	14	739	1109	711	1.0	41
21	186	e		143	8	29	743	1116	716	1.7	47
		e									
		k									
22	286	P	20	72	0	0	755	1132	716	1.8	51
23	272	l		72	4	14	754	1131	717	3.0	59
24	259	e		72	8	29	753	1130	719	3.3	66
25	247	a	30	107	0	0	744	1118	710	1.7	51
26	235	s		108	4	14	748	1124	715	2.3	59
27	224			110	8	29	758	1135	725	3.7	66

28	214	ant-Prairie	40	142	0	0	745	1117	712	0.9	51
29	200			143	4	14	744	1115	714	2.3	61
30	188			145	8	29	752	1129	723	2.6	72

1: Water Reducer; 2: Superplasticizer; 3: Air Entraining Admixture.

Table 4 - Proportions of the Concrete Mixtures made with a total Cementitious Materials Content of 450 kg/m^3 and a Water-to-Cementitious Materials ratio of 0.34.

Mix. no	Cement	Fly Ash				Silica Fume		Fine Aggregate, kg/m^3	Coarse Aggregate, kg/m^3	WR[1], mL/m^3	SP[2], L/m^3	AEA[3], mL/m^3
	kg/m^3	Type	%	kg/m^3	%	kg/m^3						

31	456	-	0	0	0	0	704	1056	911	3.1	86
32	436				4	18	701	1051	909	4.5	109
33	422				8	37	706	1057	918	4.6	128
34	315	F	30	136	0	0	679	1019	902	2.3	90
35	301	H		137	4	18	684	1027	911	1.5	106
36	283	W		138	8	37	684	1027	915	3.1	132
		A									
37	272		40	105	0	0	677	1017	908	1.8	81
38	257			107	4	18	682	1024	918	2.2	102
39	241			107	8	37	687	1031	926	2.9	124
40	227		50	227	0	0	673	1009	909	0.0	76
41	212			229	4	18	677	1016	918	0.9	92
42	195			229	8	37	677	1016	922	2.2	123

43	274	Coal-Creek	40	183	0	0	688	1032	914	1.0	51
44	257			183	4	18	688	1033	917	1.5	61
45	241			185	8	37	693	1040	926	2.4	72
46	277	Pleasant-Prairie	40	184	0	0	696	1045	922	2.0	72
47	259			185	4	19	697	1045	926	3.3	113
48	242			186	8	37	698	1045	930	3.7	124

Table 5 - Properties of the Fresh Concrete made with a total Cementitious Materials Content of 350 kg/m^3 and a Water-to-Cementitious Materials ratio of 0.40.

Mix. no	Fly Ash		Silica Fume, %	Unit Weight, kg/m^3	Slump, mm	Air Content, %	Total Bleeding water mL/cm^2	Setting Time, h:min		Maximum Autogenous Temperature rise, °C
	Type	%						Initial	Final	
1	-	0	0	2390	70	5.4	0	4:35	6:05	28.2
2			4	2330	170	6.8	0	5:30	7:00	28.2
3			8	2350	110	5.9	0	5:05	6:20	27
4	F	20	0	2320	150	7.0	0.019	6:15	8:20	23.7
5	H		4	2320	140	6.8	0	5:35	7:20	23.4
6	W		8	2320	130	7.2	0	5:40	7:15	22
7	A	30	0	2320	110	6.8	0.016	7:25	9:25	19.9
8			4	2350	140	6.0	0.003	7:00	8:30	21.5
9			8	2320	130	6.4	0.010	6:55	8:30	21.5
10		40	0	2305	100	7.3	0.046	9:15	11:35	19
11			4	2280	130	7.3	0.011	9:00	12:15	17
12			8	2290	110	7.4	0	8:00	10:30	17.6
13	C	20	0	2320	150	7.3	0.014	7:10	9:20	23.2
14	o		4	2305	120	7.6	0.013	7:05	9:30	23
15	a		8	2320	130	7.0	0.016	6:45	9:15	21.4
16	l	30	0	2305	150	7.2	0.027	7:30	9:50	20.4
17	-		4	2330	130	6.2	0.019	7:00	9:30	21.1
18			8	2320	120	6.4	0.018	6:50	9:15	19.6

19	C	40	0	2305	130	7.8	0.037	8:30	10:40	18
20	r		4	2330	130	6.0	0.025	7:50	10:35	18.5
21	e		8	2330	145	6.0	0	7:20	10:35	17.3
	e									
	k									
22	P	20	0	2390	120	5.6	0.005	8:00	10:00	24.1
23	l		4	2380	145	5.5	0	8:15	10:10	24.1
24	e		8	2360	110	5.6	0.005	7:30	9:30	24.3
25	a	30	0	2360	110	6.2	0.014	9:30	12:00	23.5
26	s		4	2360	140	5.6	0.005	9:00	11:05	23.8
27	a		8	2380	140	5.0	0	8:55	11:05	23.4
28	n	40	0	2360	120	5.4	0.013	9:50	12:35	-
29	t		4	2350	130	5.0	0	9:50	12:20	
30	-		8	2360	120	5.0	0	9:10	11:10	
	P									
	r									
	a									
	i									
	r									
	i									
	e									

Table 6 - Properties of the Fresh Concrete made with a total Cementitious Materials Content of 450 kg/m^3 and a Water-to-Cementitious Materials ratio of 0.34.

Mix. no	Fly Ash		Silica Fume, %	Unit Weight, kg/m^3	Slump, mm	Air Content, %	Total Bleeding water mL/cm^2	Setting Time, h:min		Maximum Autogenous Temperature rise, °C
	Type	%						Initial	Final	
31	-	0	0	2375	120	6.3	0.003	5:40	7:20	33.5
32			4	2350	180	6.8	0	5:30	6:50	32.7
33			8	2350	110	5.5	0	5:05	6:00	33.5
34	F	30	0	2305	170	6.8	0.005	9:00	10:40	25.8
35	H		4	2305	100	7.0	0	8:00	10:00	25.4
36	W		8	2290	150	7.1	0	8:00	9:20	25.4
	A									
37		40	0	2305	190	6.8	0.003	9:40	11:55	25.8
38			4	2305	180	6.8	0	9:30	11:30	25.4
39			8	2305	140	6.2	0	8:45	10:45	25.4

40		50	0	2290	135	7.0	0.018	9:10	11:25	22.2
41			4	2290	150	6.6	0.005	10:00	12:25	22.7
42			8	2280	170	7.0	0	9:30	12:30	
43	Coal-Creek	40	0	2330	155	6.2	0	6:55	8:40	22.8
44			4	2320	150	6.4	0	7:00	9:00	22.7
45			8	2320	160	6.0	0	6:40	8:30	23.3
46	Pleasant-Prairie	40	0	2360	105	5.3	0	9:05	11:35	-
47			4	2350	160	5.8	0	9:00	11:15	
48			8	2330	135	5.9	0	8:40	10:25	

Table 7 - Proportions, Flow and total Cracking Area of the Mortar Mixtures.

Materials.	W/CM = 0.40; CM = 350 kg/m³								W/CM = 0.34; CM = 450 kg/m³				
			FHWA Fly Ash			Pleasant-Prairie Fly Ash					FHWA Fly Ash		
	Mix. 1 Control	Mix. 3 8% SF	Mix. 5 4% SF 20% FA	Mix. 10 40% FA	Mix. 12 8% SF 40% FA	Mix. 23 4% SF 20% FA	Mix. 28 40% FA	Mix. 30 8% SF 40% FA	Mix. 31 Control	Mix. 33 8% SF	Mix. 35 4% SF 30% FA	Mix. 40 50% FA	Mix. 42 8% SF 50% FA

Cement, kg	663	610	504	398	345	504	398	345	813	746	537	407	340
SF, kg	0	53	27	0	53	27	0	53	0	67	33	0	67
FA, kg	0	0	133	265	265	133	265	265	0	0	244	407	407
Water, kg	269	269	269	269	269	269	269	269	277	277	277	277	277

Sand, kg	1404	1384	1356	1317	1298	1375	1346	1327	1253	1253	1167	1120	1100
SP*, kg	0	0.67	0.05	0	0	0.05	0	0	0.16	5.7	0	0	0
Flow, %	118	108	120	140	132	128	140	140	108	116	128	140	132
Total Cracking area, mm^2	70	1160	40	240	1200	490	530	1440	700	1250	2800	2510	3700

* the superplasticizer used was a sodium salt of naphthalene sulfonate polymer based superplasticizer in a dry powder form.

Table 8 - Compressive Strength and Chloride-ion Permeability of Concretes with a total Cementitious Materials Content of 350 kg/m^3 and a Water-to-Cementitious Materials Ratio of 0.40.

Mix. no	Fly Ash		Silica Fume,	Density of	Compressive Strength, MPa				Chloride-Ion Permeability, Coulomb	
	Type	%	%	Hardened Concrete (1-d) kg/m^3	1 d	7 d	28 d	91 d	28 d	120 d
1	-	0	0	2400	30.1	41.8	49.8	52.1	2020	1850
2			4	2380	29.3	42.8	51.3	54.6	1050	960
3			8	2370	29.5	45.5	55.9	57.9	390	330
4	F	20	0	2390	19.9	33.6	41.9	47.7	1450	670
5	H		4	2330	19.8	37.3	48.2	51.7	650	220
6	W		8	2310	17.8	37.1	47.3	49.4	420	200
7	A	30	0	2320	12.4	30.8	40.8	48.4	1120	380
8			4	2340	12.2	33.4	47.0	51.0	610	280
9			8	2320	12.5	33.9	46.6	51.3	410	180
10		40	0	2310	9.6	26.9	39.9	46.2	1160	250
11			4	2310	7.7	26.5	41.0	47.4	810	270
12			8	2280	7.6	24.8	39.4	45.2	710	220
13	C	20	0	2350	16.9	34.6	41.8	50.7	2080	670
14	a		4	2320	15.5	33.4	41.6	49.1	910	400
15	o		8	2340	15.8	35.8	-	52.6	600	270
16	l	30	0	2340	14.7	29.8	38.1	48.5	1850	400
17	-		4	2360	15.2	33.8	44.3	50.9	880	300
18			8	2340	14.3	33.5	46.1	53.2	570	240

19	C	40	0	2300	9.6	-	42.3*	49.7	1310	330
20	r		4	2360	10.4	28.6	42.3*	49.2	790	270
21	e		8	2350	9.6	28.4	43.0*	50.0	680	220
	e									
	k									
22	P	20	0	2400	18.6	40.4	50.6	58.6	2400	850
23	l		4	2360	16.3	40.5	53.3	59.4	890	340
24	e		8	2360	17.0	42.5	56.1	61.1	520	240
25	a	30	0	2390	14.5	41.3	51.0	58.0	2080	590
26	s		4	2370	12.2	41.2	52.8	60.0	900	280
27	a		8	2370	12.1	42.2	56.0	64.8	570	170
28	n	40	0	2370	6.2	31.5	46.7	56.7	2700	580
29	t		4	2380	5.9	33.6	52.2	63.9	1580	330
30	-		8	2360	5.7	32.0	49.0	59.4	1110	230
	P									
	r									
	a									
	i									
	r									
	i									
	e									

* tested at 32 days

Table 9 - Compressive Strength and Chloride-ion Permeability of Concretes with a total Cementitious Materials Content of 450 kg/m^3 and a Water-to-Cementitious Materials Ratio of 0.34.

Mix. no	Fly Ash		Silica Fume, %	Density of Hardened Concrete (1-d) kg/m³	Compressive Strength, MPa				Chloride-Ion Permeability, Coulomb	
	Type	%			1 d	7 d	28 d	91 d	28 d	150 d
31	-	0	0	2380	35.3	43.3	51.1	59.7	2250	1320
32			4	2370	35.6	46.1	57.0	63.1	890	890
33			8	2360	35.6	46.5	55.6	61.5	370	320
34	F	30	0	2320	18.7	42.2*	50.3	60.9	870	220
35	H		4	2290	17.6	40.2*	48.9	54.8	200	170
36	W		8	2290	16.2	43.6*	51.4	57.3	300	150
	A									
37		40	0	2330	16.9	35.4	48.0	57.7	520	160
38			4	2310	15.4	34.5	49.6	56.0	390	150
39			8	2320	14.5	35.3	51.7	59.1	270	-

40		50	0	2310	12.0	31.7	45.1	51.2	500	-
41			4	2290	10.6	30.7	43.0	50.9	470	-
42			8	2295	10.1	29.9	41.7	48.0	310	-
43	Coal-Creek	40	0	2360	19.7	34.2	46.4	56.4	890	-
44			4	2340	18.2	34.1	48.3	54.0	340	200
45			8	2330	16.9	35.6	48.9	56.7	190	170
46	Pleasant-Prairie	40	0	2385	16.4	42.3	55.8	65.4	980	290
47			4	2360	15.6	39.9	55.8	63.7	290	200
48			8	2340	13.8	40.4	56.9	63.0	260	180

* tested at 11 days.

Table 10 - Effect of Curing Mode on Compressive Strength and Chloride-ion Permeability of Concrete

Mix. no	CM*, kg/m³	W/CM**	Fly Ash Type	Fly Ash %	Silica Fume, %	Curing Mode***	Compressive Strength, MPa 7 d	28 d	91 d	Chloride-Ion Permeability, Coulomb 28 d	120 or 150 d+
1	350	0.4	-	0	0	H	41.8	49.8	52.1	2020	1850
						D	43.1	47.4	47.4	3880	5400
3					8	H	45.5	55.9	57.9	390	330
						D	48.0	51.3	50.2	890	1040
5			F	20	4	H	37.3	48.2	51.7	650	220
			H			D	39.9	46.6	43.1	2030	1430
10			W	40	0	H	26.9	39.9	46.2	1160	250
			A			D	29.7	36.4	34.2	5010	2320
12					8	H	24.8	39.4	45.2	710	-
						D	27.8	32.7	30.7	2100	-
23			Pleasant-Prairie	20	4	H	40.5	53.3	59.4	890	340
						D	43.2	46.9	42.5	2090	2160
28				40	0	H	31.5	46.7	63.9	2700	580
						D	34.2	38.9	34.4	6500	5600
30					8	H	32.0	49.0	59.4	1110	230
						D	32.8	38.0	37.9	1300	1090

31	450	0.34	-	0	0	H	43.3	51.1	59.7	2250	1320
						D	45.0	49.3	47.9	4310	3100
33					8	H	46.5	55.6	61.5	370	320
						D	48.6	53.6	50.6	940	860
35			F	30	4	H	40.2+	48.9	54.8	200	170
			H			D	43.6+	45.3	44.3	750	780
40			W	50	0	H	31.7	45.1	51.2	500	-
			A			D	33.5	41.5	40.2	1400	-
42					8	H	29.9	41.7	48.0	310	-
						D	32.6	39.1	38.0	280	-

* Cementitious materials.

** water-to-cementitious materials.

*** H: cured in the most curing room until required for testing.

D: cured in the most curing room for three days followed by an air curing at 23 ∀ 2EC and 50% relative humidity until required for testing.

+ tested at 11 days.

Fig. 1- Set up used for initiating plastic shrinkage

Fig. 2 - Dosage of the superplasticizer required by concretes to achieve a slump of 100-150 mm
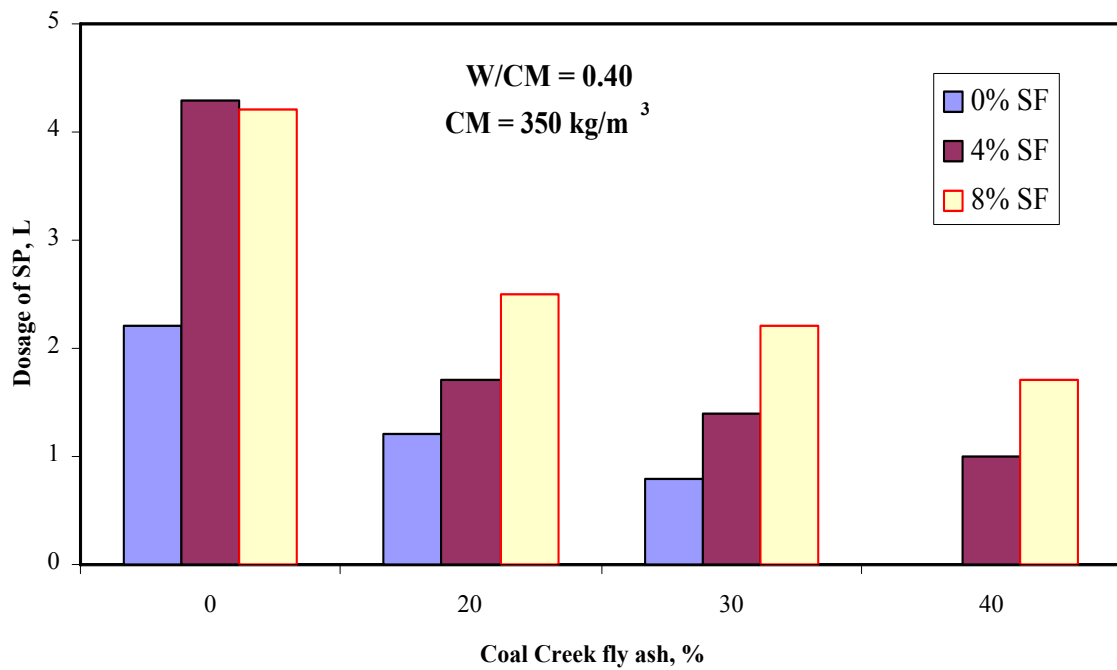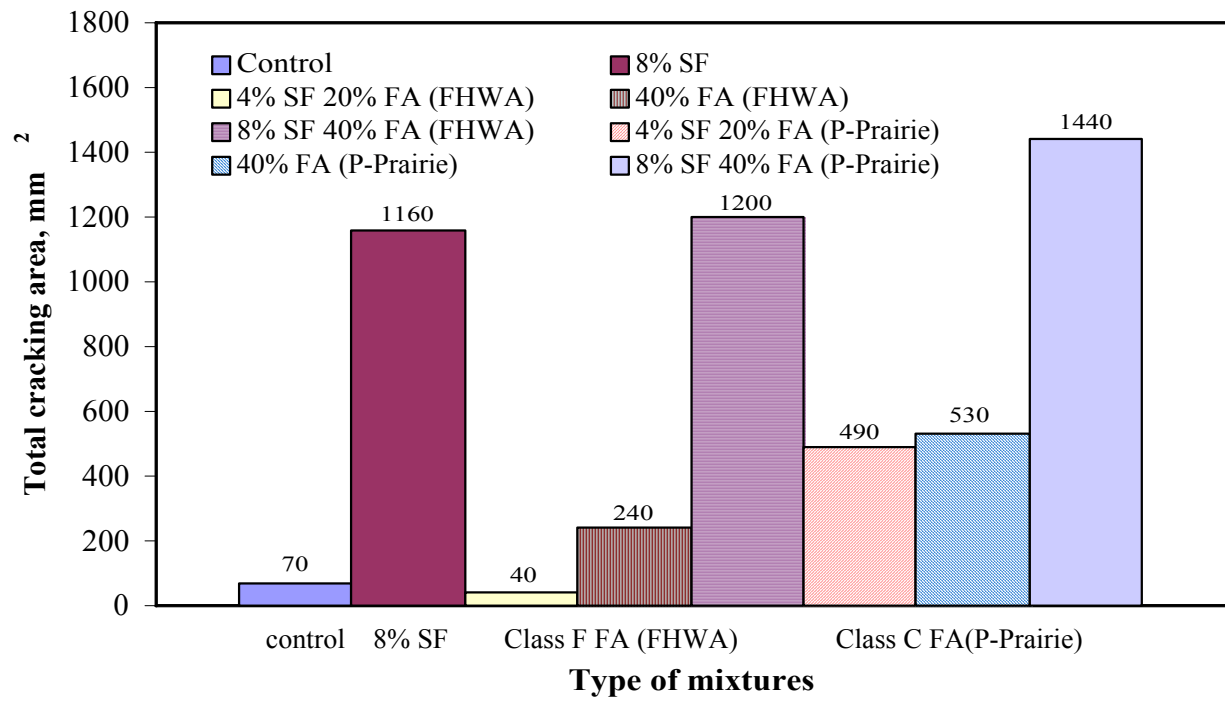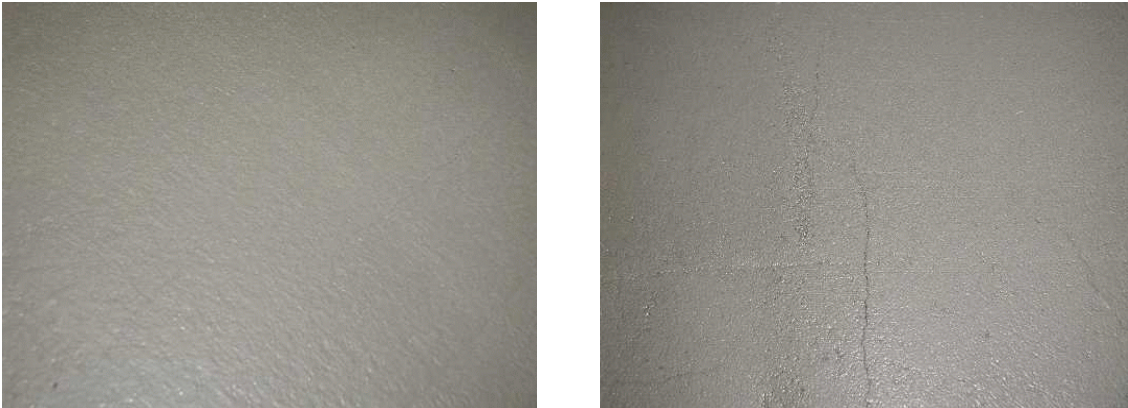
Fig. 3 - Total cracking area of the mortar mixtures

with W/CM = 0.40

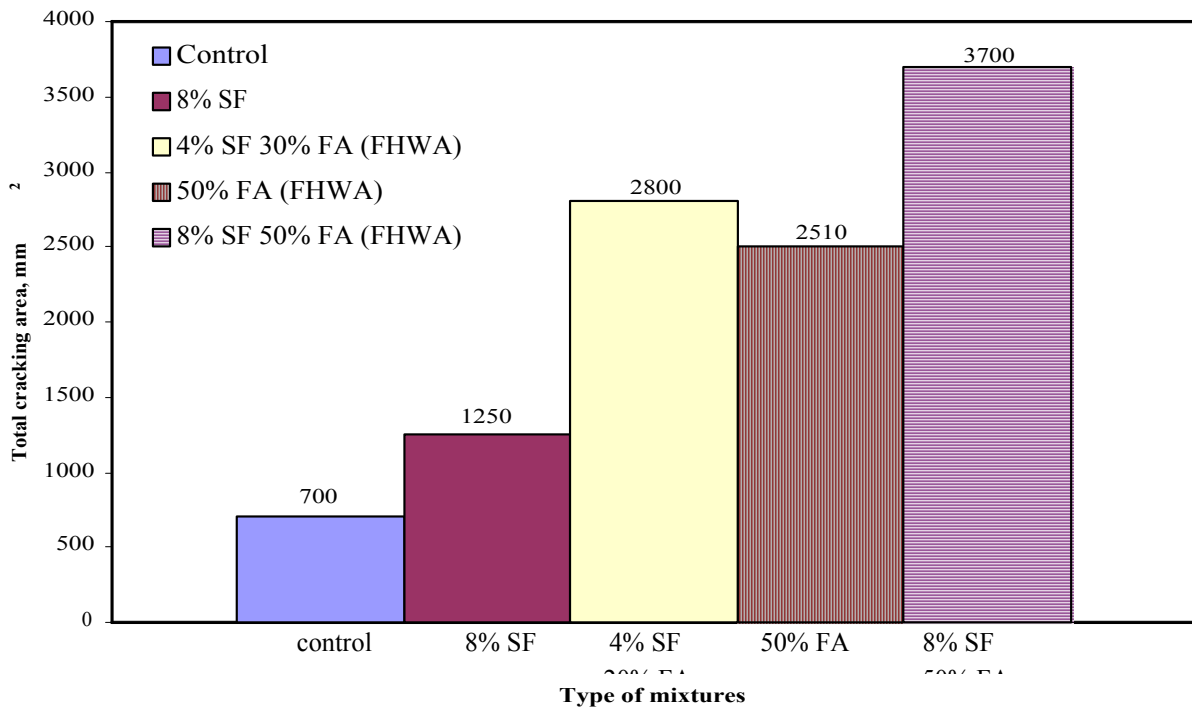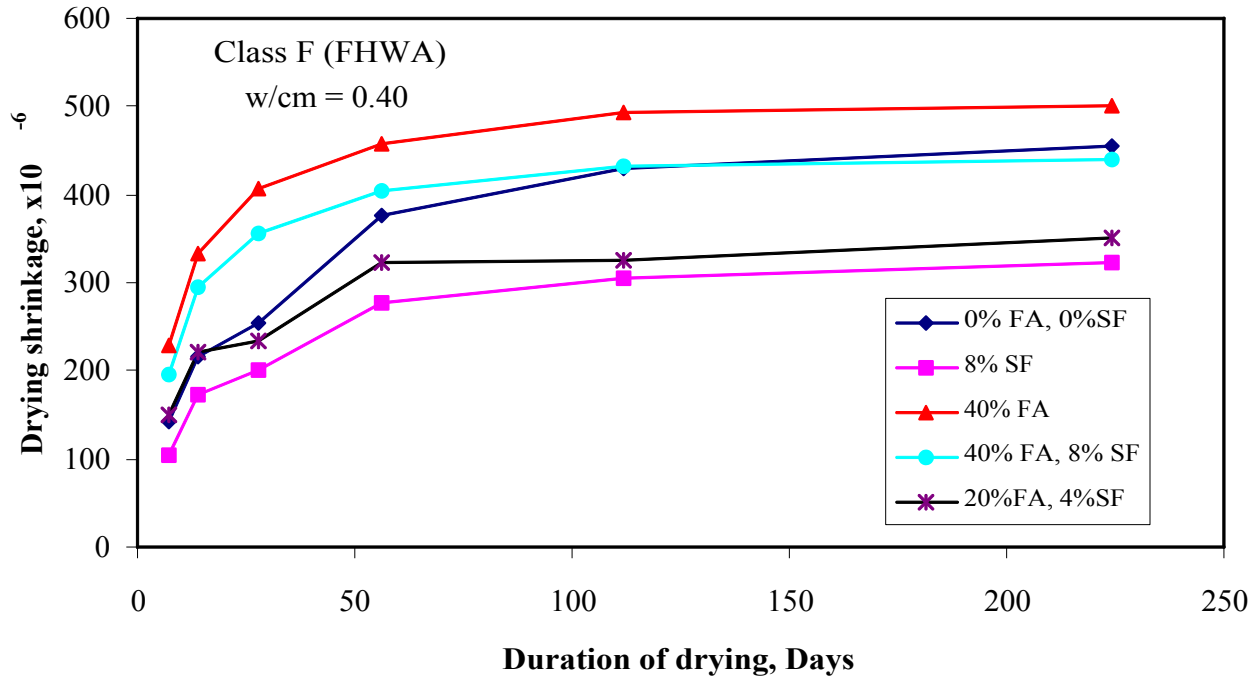**Fig. 4** - Total cracking area of the mortar mixtures with W/CM = 0.34

Fig. 5 Crack pattern of selected mortar mixtures made with FHWA Class F ash and W/CM= 0.40, it should be noted, however, that the mortar mixtures with 8% of silica fume cracked more than what appears on the photo. This is mainly due to the dark color of the silica fume mixtures that does not reflect the light of the camera.

Fig. 6 - Drying shrinkage of selected concrete mixtures