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TENSILE STRENGTH OF GREEN CONCRETE WITH FLY ASH AND CHEMICAL ADMIXTURES

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ABSTRACT

The effect of Class F fly ash of marginal quality, as partial replacement of fine sand, and of chemical admixtures (water-reducing and retarding and high-range water reducer) on the tensile strength of green concrete was investigated. The tests show that the fly ash significantly increased (by 25 to 40 percent) the tensile strength at 2 to 4 hours after mixing, compared with "similar" mixes without fly ash. On the other hand, the chemical admixtures with retarding properties significantly slowed down its growth over the first few hours.

Introduction

The present work is part of a comprehensive study examining the effect of high-volume marginal quality fly ash, as partial replacement of fine sand (whose availability in the northern part of Israel is limited) on the properties of fresh and hardened concrete.

Use of good-quality fly ash is nowadays a common practice in concrete technology. As fly ash can partially replace cement (the most expensive ingredient in concrete), it can be economically and technically advantageous, provided it is of good quality. As for using marginal-quality material as replacement of fine sand, its advantages are much less; in fact, its cost may actually exceed that of the sand, as it requires quality control, transportation by cement trucks, silos and proper arrangements at the concrete plant. However, the very high cost of fly ash removal from the power plants, if allocated to subsidize its use, would offset this difference in cost, making this solution worthwhile for the concrete producer; moreover, the quantities of fly ash consumed for this purpose can be quite significant, hence it may alleviate the attendant ecological problem.

Data on the tensile strength of green concrete, i.e. during the first few hours after casting while the material is still in a semi-plastic state, is very limited. The study of early tensile strength is complicated both in terms of the testing system and because the relevant material properties are time-dependent and change rapidly over the period in question. The fresh cement paste in concrete exhibits cohesion and a yield value, hence possesses mechanical strength, as soon as it is mixed. The principal source of this strength is the intergranular bond and its value depends on the size and concentration of particles sufficiently close for mutual attraction. Fly ash acts in this system as a multifunctional ingredient - plasticizer, fine aggregate, microfiller and active mineral admixture, and it may also influence the course of early hydration of the cement. Moreover, the consistency of the fresh mix (higher mixing water content), its temperature, chemical admixtures, and external conditions such as ambient temperature and evaporation rate - are also influencing factors.

It was found in a previous study (1) that the following factors yield higher early tensile strength, measured between one to four hours after exposure to various climatic conditions:

- Cement of higher initial rate of hydration, type I compared with type V.
- Higher cement content, 550 kg cement per cu.m. (925 lb. per cu.yd.) compared with 365 kg cement per cu.m. (615 lb. per cu.yd.).
- Stiffer consistency (lower water content), semi-plastic compared with plastic consistency.
- Higher temperature, 30°C (86°F) compared with 20°C (68°F).
- Higher evaporation rate, 0.95 kg per sq.m. per hour (0.19 lb. per sq.ft. per hour) to 0.63 kg per sq.m. per hour (0.13 lb. per sq.ft. per hour).

Research Significance

The present work studies the effect of Class F fly ash of marginal quality, as partial replacement of fine sand, and of chemical admixtures (water-reducing and retarding and high-range water reducer), on the tensile strength of green concrete, e.g. at 2, 3 and 4 hours after mixing.

Materials

Cement - ordinary Portland cement according to IS 1 (Israeli Standard). The cement was interground with about five percent (wt) fly ash.

Fly ash - from bituminous coal, ASTM Class F. Loss of ignition 5.96 percent; amount retained on 45μm mesh 17 percent, Pozzolanic Activity Index with Portland cement, ASTM C 618, 73 (minimum required 75).

Chemical admixtures - one water-reducing and retarding, WRR-I, ASTM C 494 type D, and two high range water-reducers, SP-I and SP-II (superplasticizers), ASTM C 494 type G.

The water-reducing retardant, is chemically based on sodium gluconate. The dosage recommended by the manufacturer was 0.125 liter per 100 kg cement at moderate temperature, and 0.190 liter per 100 kg cement at elevated temperature.

The first superplasticizer, SP-I, is chemically based on synthetic polymers based on sodium naphthalene formaldehyde sulfonate. The dosage recommended by the manufacturer ranges from 0.5 to 2.0 liters per 100 kg cement.

The second superplasticizer, SP-II, is chemically based on synthetic polymers. The dosage recommended by the manufacturer ranges from 0.8 to 1.2 liters per 100 kg cement.

Aggregates. The coarse aggregate, maximum particle size 19 mm (3/4 in.), medium and coarse sand were crushed dolomitic stone. The fine aggregate was very fine, F.M. 1.59. natural siliceous sea sand.

Mix proportions

In the first series, the cement content of all the concretes, with and without fly ash and/or chemical admixtures, was fixed at 280±5 kg/m^3 (470±10 lb/yd^3) and the fly ash content as fine sand replacement at 125 kg/m^3 (210 lb/yd^3).

In the second series, the cement content was reduced by 10 or 20 percent to 250 kg/m^3 (420 lb/yd^3) or 225 kg/m^3 (380 lb/yd^3). The fly ash content at the 10 percent cement reduction was 125 kg/m^3; at the 20 percent reduction the fly ash replaced the cement on a weight for weight basis

All concrete mixes were designed for similar consistency, as measured by the slump test. Hence, the amount of the mixing water was adjusted to give the desired slump of 160±10 mm (6½ ±½ in.).

Air entrainment was not employed.

The dosage used for WRR-I was 0.125 liter per 100 kg cement.
The dosage used for SP-I was 0.7 liter per 100 kg cement.
The dosage used for SP-II was 1.0 liter per 100 kg cement. Due to a mistake in batching a mix with 0.1 liter per 100 kg cement was also prepared and therefore regarded as water-reducing admixture.

Test program and procedure

All mixes were prepared at 21°C (70°F).

The first series comprised of ten concrete mixes: a reference mix and a fly ash mix; two mixes with water-reducing with and without fly ash; two mixes with SP-II, at 1/10 of the normal dosage, with and without fly ash; and four mixes with high-range water-reducing admixtures, two with and two without fly ash.

The second series was limited, comprising three mixes for comparison with the reference and fly ash-mixes: two mixes with 20 percent cement replacement by fly ash with and without water-reducing and retarding admixture, and one mix with 10 percent cement reduction and 125 kg/m^3 (210 lb/yd^3) fly ash.

The initial slump of all mixes was set at 160±10 mm (6½±½ in.) by adjusting the amount of mixing water.

The concrete mixes were prepared in a temperature-controlled laboratory with all materials weighed and stored at least 24 hours prior to mixing. They were mixed for five minutes in a free-fall mixer, then placed in two layers in the tensile strength test molds, thoroughly compacted by hand and steel-troweled.

Tensile Strength

The tensile strength was measured on prisms 7x7x11½ cm (2¾x2¾x4½ in.). The apparatus, designed so as to permit measurement without demolding, is shown in Fig. 1. The mold consists of three prisms with anchorage devices at both ends, the rear device being fixed to the mold, and the front one fixed at 2 cm (¾ in.) off the mold by a spacer which is removed before the test. To minimize friction between the green concrete and the mold during the test, a lightly-oiled teflon sheet is placed at the bottom of the mold, and smooth plastic sheets are inserted at the sides of each prism. Before the test the spacer and plastic sheets were removed. A pulling device was connected to the front anchorage and a gradual pulling force was applied by pouring loose sand into a bucket. The tensile strength was calculated by dividing the force required to rupture the concrete prism by the cross-sectional area.

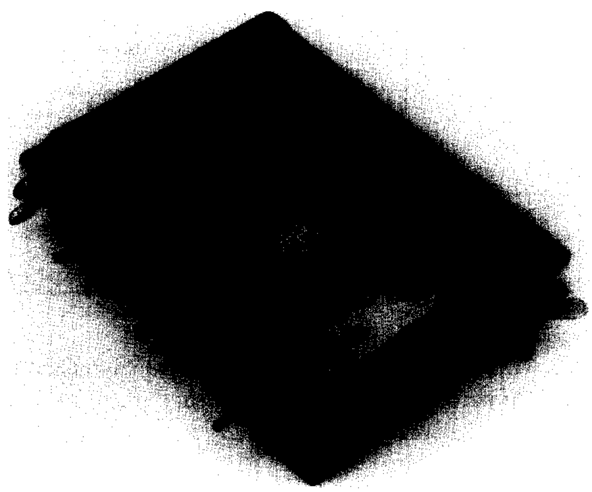

Fig. 1
Tensile strength mold.

Test Results

Water Requirement

The amounts of mixing water required to obtain the designated slump of 160±10 mm (6½±½ in.) of the various concrete mixes are given in Table 1.

The water-reducing retardant reduced the water requirement by 4 to 6 percent, and the high-range water reducer - by 13 to 17 percent in the concrete mixes without fly ash and somewhat less, 11 to 14 percent, in those with fly ash.

All concretes with fly ash as partial replacement of fine sand, required more water, average of about 18 liter/m^3 (10.5 percent), for the same consistency as that of "similar" mixes without fly ash.

Table 1 - The amount of mixing water required to obtain the desired consistency, 160±10 mm (6½±½ in.), as measured by the slump test

	Reference Concrete	Chemical admixtured concretes			
		Water reducing and retarding		High-range water reducer	
		(SP-II)	WRR-I	SP-I	SP-II
Mixing water liter/m^3 (lb/yd^3)	181 (305)	175 (295)	170 (286)	158 (266)	151 (255)
	Fly ash (125 kg/m^3, 210 lb/yd^3) concretes				
Mixing water liter/m^3 (lb/yd^3)	198 (333)	191 (322)	186 (314)	176 (297)	171 (288)
		Cement reduced concrete mixes			
		-20%C +20% FA	-20%C +20% FA +WRR-I	-10%C +125 FA	
Mixing water liter/m^3 (lb/yd^3)		180 (303)	173 (291)	191 (322)	

However, 20 percent (wt) replacement of cement with fly ash did not increase the water demand, and partial replacement of fine sand plus 10 percent cement reduction increased it by only 10 liters/m^3 (5.5 percent).

Tensile Strength

The tensile strength, average of three specimens, of the various concrete mixes at 2, 3 and 4 hours after mixing, is given in Tables 2 and 3, and in Figs. 2-5.

The data presented show clearly that high-volume fly ash, as partial fine sand replacement, increases the tensile strength of green concrete, e.g. at 2 to 4 hours after mixing, for all mixes, with and without chemical admixtures. Compared with "similar" mixes, same cement content and same consistency (higher water demand), the tensile strength of the concretes with fly ash was higher, Table 4, by 25 to 48 percent.

Replacement of 20 percent (wt) of the cement with fly ash (no change in water demand) reduced the tensile strength, Table 5, by only 4 percent. However, the tensile strength of the concrete with 10 percent cement reduction but with high-volume fly ash as partial fine sand replacement (relatively moderate increase in water demand) was higher by about 57 percent.

Table 2 - Tensile strength, MPa x 10^{-3} (ksi x 10^{-3}), of green concrete with and without chemical admixtures and/or fly ash

	Reference concrete	Chemical admixtured concretes			
		Water reducing & retarding		High-range water reducer	
		(SP-II)	WRR-I	SP-I	SP-II
Tensile strength MPa x 10^{-3} (ksi x 10^{-3})					
age, hr: 2	49 (7.1)	51 (7.4)	62 (9.0)	40 (5.8)	43 (6.2)
3	68 (9.9)	71 (10.3)	66 (9.6)	60 (8.7)	42 (6.1)
4	88 (12.7)	105 (15.2)	73 (10.6)	78 (11.3)	49 (7.1)
	Fly ash (125 kg/m³, 210 lb/yd³) concretes				
	Fly ash	(SP-II)	WRR-I	SP-I	SP-II
Tensile strength MPa x 10^{-3} (ksi x 10^{-3})					
age, hr: 2	67 (9.7)	65 (9.4)	62 (9.0)	60 (8.7)	44 (6.4)
3	91 (13.2)	92 (13.3)	65 (9.4)	87 (12.6)	55 (8.0)
4	123 (17.8)	122 (17.7)	87 (12.6)	118 (17.1)	75 (10.9)

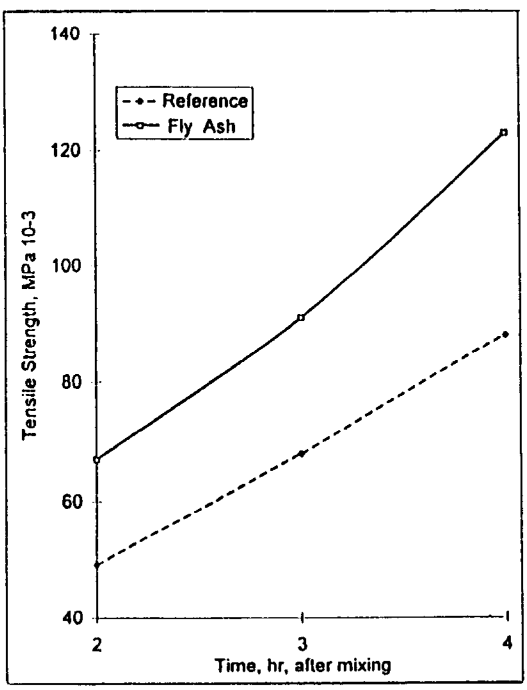

Fig. 2
Tensile strength of Reference concrete and fly ash concrete.

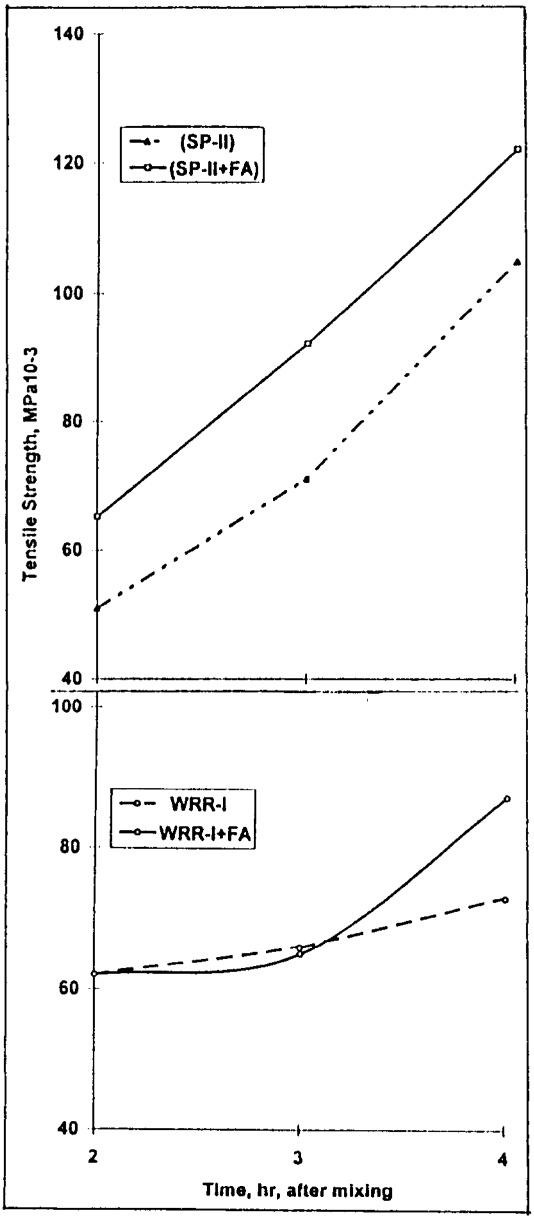

Fig. 3
Tensile strength of concretes with water-reducing and water-reducing retarding admixtures with and without fly ash.

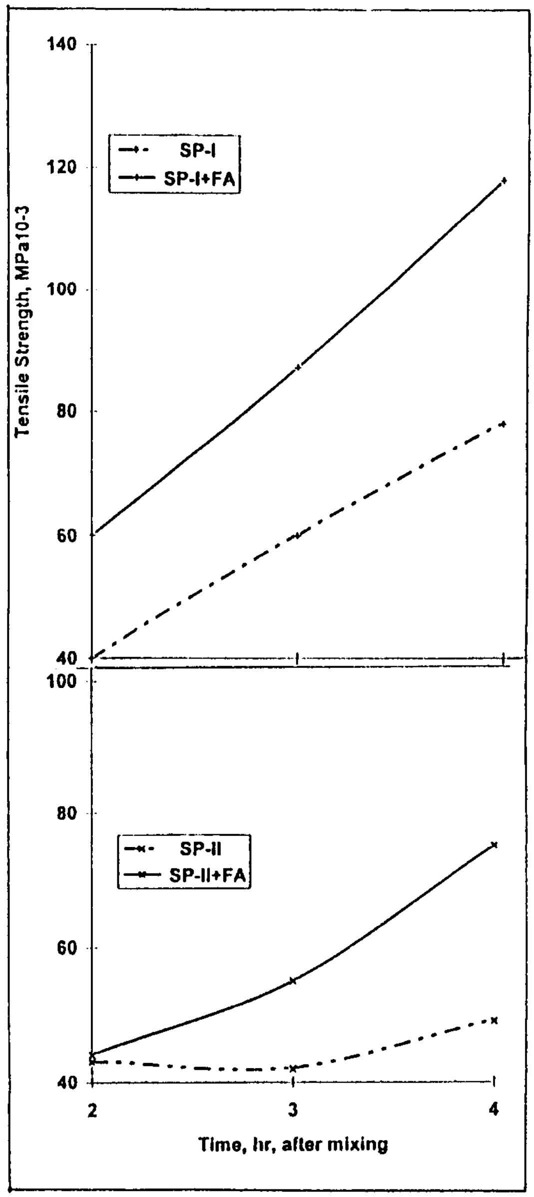

Fig. 4
Tensile strength of concretes with high-range water reducing admixtures with and without fly ash.

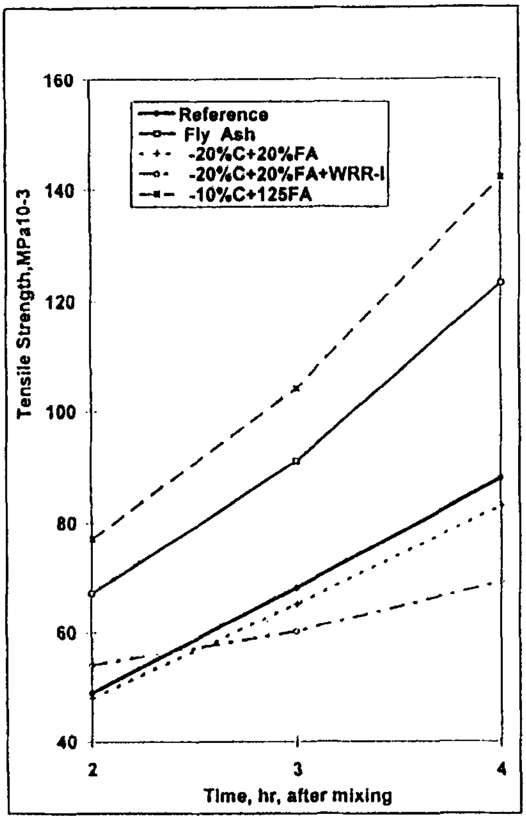

Fig. 5
Tensile strength of concretes with reduced cement content by 10 or 20 % with fly ash as cement replacement (20% wt) or as partial fine sand replacement (10%) and of Reference and fly ash concretes.

Table 3 - Tensile strength, MPa x 10^{-3} (ksi x 10^{-3}), of green concrete mixes with reduced cement content and with fly ash as cement replacement or as partial fine sand replacement.

	Cement reduced concrete mixes		
	-20%C +20% FA	-20%C +20% FA +WRR-I	-10%C +125 FA
Tensile strength MPa x 10^{-3} (ksi x 10^{-3})			
age, hr: 2	48 (7.0)	54 (7.8)	77 (11.2)
3	65 (9.4)	60 (8.7)	104 (15.1)
4	83 (12.0)	69 (10.0)	142 (20.6)

As could be expected, the other parameters - cement content, chemical admixtures and water content - also affect the tensile strength at 2 hours (beginning of measurement), and its further development (rate of growth) up to 4 hours.

The tensile strength values at 2 hours of the Reference and fly ash concrete mixes were increased, Table 6, by 40 percent at 3 hours and by about 80 percent at 4 hours.

Table 4 - Tensile strength, percent, of green concrete mixes with fly ash compared with "similar" concretes without fly ash

	Fly Ash vs. Reference	Chemical admixtured concretes			
		Water reducer & retarding		High-range water reducer	
		(SP-II)	WRR-I	SP-I	SP-II
Tensile strength, % age, hr:					
2	135	128	100	148	101
3	134	132	99	146	130
4	140	116	119	151	152
Average	136	125	-	148	-

On the other hand, the tensile strength growth of the concrete mix with the retardant WRR-I, was much lower, only 6 and 18 percent after 3 and 4 hours, respectively; that of its fly-ash counterpart with the retardant was the same at 3 hours but much higher, about 40 percent, at 4 hours.

The tensile strength growth of the concrete with the first high-range water reducer SP-I (chemical admixture with limited retarding effect), with and without fly ash was the highest, about 50 and 95 percent after 3 and 4 hours, respectively; on the other hand, for the second high-range water reducer SP-II with its strong retarding effect, it was zero at 3 hours and only 14 percent at 4 hours. However, also with this admixture it was much better for the fly ash concrete mix - 25 and 70 percent at 3 and 4 hours respectively.

The tensile strength pattern is presented in Fig. 6 for concretes without fly ash and in Fig. 7 for those with fly ash. However, since further tests are required to establish the exact values, it is suggested that the comparison be confined to the general trend.

Table 5 - Tensile strength, percent, of green concrete mixes with reduced cement content and with fly ash as cement replacement or as partial fine sand replacement compared with Reference concrete.

	Cement reduced concrete mixes		
	-20%C +20% FA	-20%C +20% FA +WRR-I	-10%C +125 FA
Tensile strength, % age,hr:			
2	97	88	156
3	96	91	153
4	96	95	164
Average	96	-	157

Table 6 - Tensile strength, percent, at 3 and 4 hours after mixing compared with 2 hours strength of concrete with and without chemical admixtures and/or fly ash

	Reference concrete	Chemical admixtured concretes			
		Water reducing & retarding		High-range water reducer	
Tensile strength, % age, hr:					
2	100	100	100	100	100
3	139	139	106	150	98
4	180	206	118	195	114
	Fly ash (125 kg/m³, 210 lb/yd³) concretes				
	Fly ash	(SP-II)	WRR-I	SP-I	SP-II
Tensile strength, % age, hr:					
2	100	100	100	100	100
3	136	142	105	145	125
4	184	188	140	197	170
		Cement reduced concrete mixes			
		-10%C +20% FA	-20%C +20% FA +WRR-I	-10%C +125 FA	
Tensile strength, % age, hr:					
2		100	100	100	
3		135	111	135	
4		173	128	184	

It could be expected that the concretes with the lowest water cement ratio, namely those with a high-range water reducer, would have the highest tensile strength. However, as the actual strength is the combined result of the various parameters affecting it, the concrete SP-II had the lowest tensile strength due to the strong retarding effect of the admixture. On the other hand, the concrete with the same admixture but at 1/10 of the dosage, which therefore probably had no retarding effect (or a very slight one) but a moderate water-reducing effect, had somewhat higher strength than the Reference concrete at 2 and 3 hours and a much better one at 4 hours.

Discussion

This work studies the tensile strength of green concretes, namely during the first 2 to 4 hours after mixing.

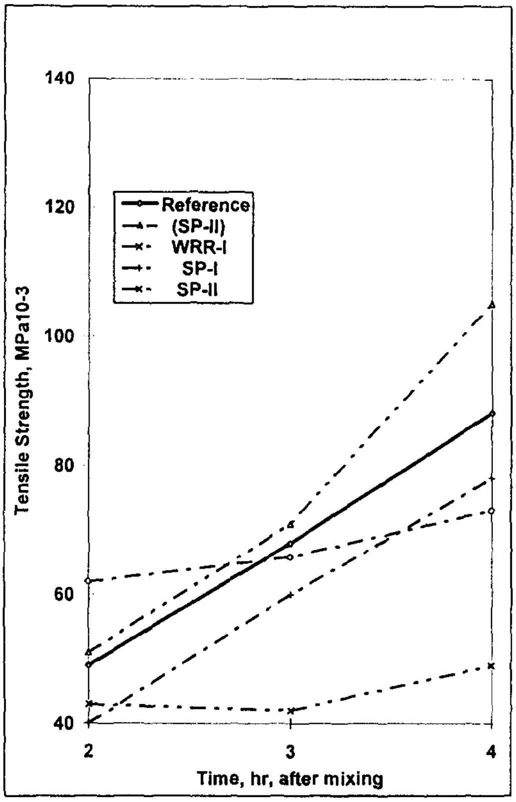

Fig. 6
Tensile strength of the various concretes without fly ash.

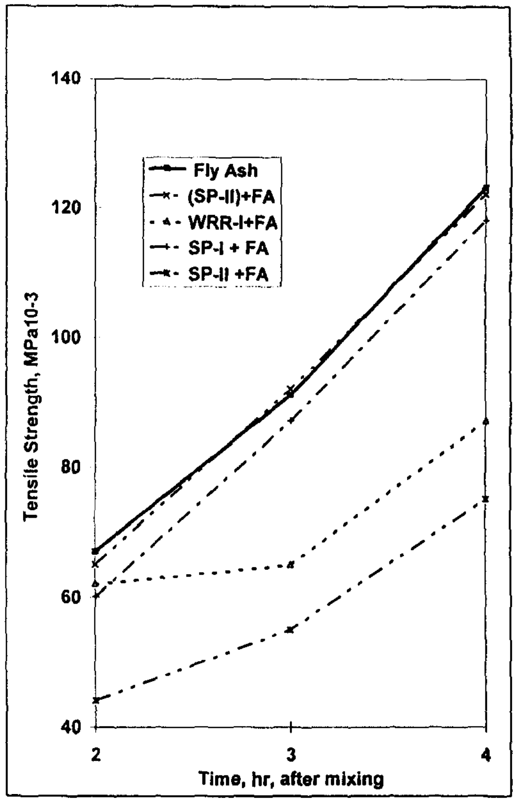

Fig. 7
Tensile strength of the various concretes with fly ash.

Fresh cement paste (neat or in concrete) exhibits cohesion and a yield value, hence possesses mechanical strength as soon as it is mixed. The principal source of this strength is the intergranular bond by Coulomb attraction and van der Waals forces. Its value depends on the size and concentration of particles sufficiently close for mutual attraction. Thus, richer mixes and those with low mixing water content should have higher strength.

Fresh concrete is a chemically active system governed by complex and simultaneous interaction of the cement, water, chemical and mineral admixtures, and ambient climatic conditions. Hydration of the cement with time raises the concentration of solid fine particles and brings about an increase in strength.

Fly ash acts in this system as a multifunctional ingredient - plasticizer, fine aggregate, microfiller and active mineral admixture. It may also influence the course of early hydration by deposing significant amount of alkali sulfates into the mix water, as well as by nucleation on its sites.

Chemical admixtures generally reduce the amount of the mixing water. Retardants may slow down significantly the rate of early hydration. Moreover, high-range water reducers (superplasticizers) make for transformation of the flocculent structure with points of contact between the solid particles into a disperse one with the particles separated.

Hydration during these first four hours, which can be called the "pre-setting period", is considered to be small or even negligible. Hwang and Shen (2) investigated the mechanics of fresh cement paste in the plastic state by measuring the development of penetrative resistance and found almost none before four hours, after which setting began and strength rose rapidly. By contrast, Legrand and Wirquin (3), using highly sensitive vane equipment, observed an increase in strength already after 1½ to 2 hours. Nonat and Mutin (4) suggest that the cement paste setting process can be described as two fundamental steps: coagulation and rigidification. The coagulation establishes contacts between cement particles already during the first minutes after mixing. The rigidification of the coagulated structure is provided by formation of hydrates in the contact zone; the increase in strength at this stage is proportional to the quantity of precipitated hydrates.

The results of the present study show tensile strength developing already from the beginning of measurement, two hours after mixing, with its growth rate significantly affected by the fly ash and chemical admixtures. This strength increase can be attributed to formation of hydration products that strengthen the inner skeleton structure. This is clearly demonstrated by comparing the tensile strength growth of the Reference concrete, Fig. 2, with the zero or very small growth of the retarded concretes WRR-I and SP-II, Figs. 3 and 4.

On the other hand, all concrete mixes with fly ash as partial replacement of the fine sand (i.e. cement content unchanged) have higher initial (at two hours) tensile strength and higher rate of strength growth, Figs. 3-4, particularly for the retarded concretes between 3 to 4 hours after mixing. Apparently, as mentioned before, van der Waals forces are the dominant factor governing the green concrete tensile strength; therefore, the greater the number of contacts between the solid particles the higher the strength. Fly ash, which is much finer than the sand it replaced, provides the concrete mix with much more fine particles and therefore many more contact points, hence the higher tensile strength of the fly ash concretes at this early stage of hydration.

The effect of the fly ash particles is also demonstrated by comparing the tensile strength of the retarded concretes with the "similar" fly-ash mixes. While the retardant prevented production of sufficient hydration products for strengthening the inner skeleton structure, the fly ash evidently "bridged" the gaps between the solid particles and enabled the system to acquire higher tensile strength.

It is not obvious that fly ash would increase the strength also later on, from 8 to 24 hours, when the dominant source of strength would be the hydrated products. In fact, due to the alkali sulfates that it can contain, it might decrease the hydration rate. Further tests are scheduled to study the tensile strength after 4 hours.

Conclusions

1. Fly ash as partial replacement of fine sand increases the tensile strength of green concrete, at 2 to 4 hours after mixing, by 25 to 40 percent.
2. Chemical admixtures with retarding effect reduce the initial tensile strength and its growth over the first few hours.

3. Fly ash as partial replacement of fine sand increases the water demand required to obtain the same consistency (slump) by about 10 percent.

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