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Properties of Self-Compacting Concrete Incorporating Silica Fume and Fly Ash.

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PROPERTIES OF SELF COMPACTING CONCRETE INCORPORATING SILICA FUME AND FLY ASH

خواص الخرسانة ذاتية الدمك والمحتوية على غبار السيلكا والرماد المتطاير

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الملخص العربى

يتناول هذا البحث بالدراسة المعملية لتأثير غبار السيلكا بنسب ٥، ١٠، ١٥% والرماد المتطاير بنسب ١٠، ٢٠، ٣٠، ٤٠، ٥٠، ٦٠% وكذلك خليط من غبار السيلكا والرماد المتطاير بنسب ٢٥%رماد متطاير+٥% غبار سيلكا ، ٢٠%رماد متطاير+١٠% غبار سيلكا، ١٥%رماد متطاير+١٥% غبار سيلكا وذلك على الخواص الطازجة والمتصلدة للخرسانة ذاتية الدمك. وقد تمت دراسة الخواص المتصلدة على مقاومة الضغط عند اعمار ٢٨، ٥٦، ٩٠، ٢٧٠ يوم ومقاومة الشد الغير مباشر ومقاومة الانحناء عند عمر ٢٨ يوم. وقد حققت نتائج الخرسانة الطازجة المتطلبات العامة للأكواد المختلفة للخرسانة ذاتية الدمك كما أظهرت نتائج مقاومة الضغط والشد والانحناء أن اضافة الرماد المتطاير كإحلال جزئي للأسمنت بنسبة ٣٠% يعطى أعلى قيمة لهذه المقاومات وأن هذه المقاومات تزداد باحلال الاسمنت بغبار السيلكا حتى نسبة احلال تساوى ١٥% ، وأظهرت النتائج ايضا ان اعلى قيمة للمقاومات الثلاثة يمكن الحصول عليها باحلال الاسمنت بنسبة ٢٠%رماد متطاير+١٠% غبار سيلكا. كما أظهرت النتائج زيادة فى مقاومة الضغط مع زيادة العمر.

ABSTRACT

Self compacting concrete (SCC) is a new category of high-performance concrete that exhibits a low resistance to flow to insure high flowability and a moderate viscosity to maintain a homogeneous deformation through restricted sections. In this paper, cement has been replaced by fly ash (FA) in various proportions from 10% to 60% or silica fume (SF) in proportions of 5%, 10% and 15% or combination from FA and SF by the proportions 25%FA+ 5%SF, 20%FA +10%SF and 15% FA +15%SF. Fresh properties based on the results of slump flow, L-box and V-funnel tests were measured while hardened properties based on the compressive strength, indirect tensile strength and flexural strength were measured. Tests results showed that fresh properties of all mixes satisfied the SCC requirements. The maximum strengths were attained at FA percentage of 20% while for SF this percentage was 15%. With the utilization of hybrid FA and SF, the maximum strengths were recorded at 20% FA+10%SF. An increase in the compressive strength was recorded for all mixes with increasing age up to 270 days.

KEYWORDS: Self compacting concrete; Silica fume; Fly ash; Mechanical properties

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1. INTRODUCTION

Self-compacting concrete (SCC) is a kind of concrete that can flow through and fill gaps of reinforcement and corners of moulds without any need for vibrations or compaction during the pouring process. Because of that, SCC must have sufficient paste volume and proper paste reology. Paste volumes are usually higher than that of conventionally placed concrete and typically consist of high powder contents and low water powder ratio [1]. In general, the cost of SCC is 20-40 % higher than that of conventional concrete [2]. Self compacting concrete (SCC) can also be pumped from the bottom of a form or dropped from the top with recommended maximum fall height 1.8 m [3]. The constituent materials used for the production of SCC are the same as those for conventionally vibrated normal concrete except that SCC contains a lesser amount of aggregates, larger amount of powder (cement and filler particles smaller than 0.125 mm) and special plasticizer to enhance flowability. High-volume of mineral powder is a necessity for a proper SCC design. For this purpose usually natural and/ or artificial mineral additives such as; limestone powder, fly ash, silica fume and blast furnace slag are used.

Incorporating of mineral additives to concrete mixtures has many beneficial effects, such as improvement of rheological and durability properties. Kim et al. [4] studied the properties of super flowing concrete containing fly ash and reported that the replacement of cement by 30% fly ash resulted in excellent workability and flowability. Miura et al. [5] evaluated the influence of supplementary cementitious materials on workability and concluded that the replacement of cement by 30% of fly ash can significantly improve rheological properties. But to the best knowledge of the authors, the percentage replacement of Class F fly ash, in the various published studies, did not exceed 30% by weight of the total cementitious materials. However, an economical SCC mixture, made with 50% of fly ash and water-to-powder ratio of 0.45, and having a 28-day compressive strength of 35 MPa, was reported [6]. Halit [7] found that SCC could be obtained with a high-volume FA and ten percent SF additions to the system positively affected both the fresh and hardened properties of high-performance high-volume FA SCC. Dehwah [8] showed that the chloride permeability in SCC specimens incorporating quarry dust powder or fly ash was moderate and it was low in the specimens incorporating silica fume plus quarry dust powder. In the present paper, the effect of replacing cement by fly ash or silica fume or a combination of both on the fresh and hardened properties of SCC was investigated experimentally.

2. Experimental Program

2.1. Materials

Natural dolomite from Gabal Ataa in Suez area was used as a coarse aggregate. The dolomite has a nominal maximum size of about 14 mm. It was washed carefully before mixing to remove any impurities and organic matter which may weaken its bond with the cement paste It was immersed in water for about 24 hours, then dried in the air for another 24 hours to reach the saturated and surface dry condition before casting .Natural siliceous sand was used as a fine aggregate. Clean tap water without special taste, smell, color or turbidity was used with water/ cementitious materials (W/CM) ratio of 0.44. Ordinary Portland cement produced from Suez company and meeting the requirements of ESS 373/1991 was used. The used silica fume was brought from factories of the Egyptian ferro-alloys company located in Aswan, Egypt and Fly ash were used as a mineral admixture. Table 1 shows chemical constuents of portland cement and the minerals additives used in this study . Physical properties of the used SF and FA are given in Table 2.

Sika Viscocrete 5-400 was used as a viscosity enhancing admixture (VEA). It has a dual action. It gives excellent flowability and in the same time enhances the stability (viscosity) of concrete. It meets the requirements for Superplasticizers according to SIA 162 (1989) pr EN 934-2 and ASTM-C-494 type G and F. Table 3 shows properties of used superplastisizer.

Table 1 Chemical composition of OPC, SF & FA

Oxide	OPC	SF	FA
SiO_2	21.0	95	56.2
AL_2O_3	6.1	0.2	20.17
Fe_2O_3	3.0	0.5	6.69
CaO	61.5	0.4	4.24
MgO	3.8	0.5	1.92
SO_3	2.5	0.3	0.49
Na_2O	0.4	0.3	0.58
K_2O	0.3	1.2	1.89
H_2O	-	0.85	-
P_2O_5	-	-	0.01
TiO_2	-	-	1.1
L.O.I	1.6	-	-
Insoluble residue	0.9	-	-
Loss of Ignition	-	-	0.58

Table 2 Physical properties of SF&FA

Properties	SF	FA
Blain fineness (cm^2/g)	-	2870
Specific surface area (cm^2/gm)	15.2×10^3	-
Bulk density (kg/m^3)	355	-
Specific gravity	2.15	2.25
Color	Light gray	Gray

Table 3: Properties of superplastisizer

Property	Test results
Appearance	Turbid liquid
Specific gravity	1.11 kg/ lit
Chloride content	Nil
Ph-value	**8.0 ± 0.5**

2.2. Mix proportions

One control and 12 mixtures arranged in three groups with mineral additives and chemical admixtures were prepared with a total cementitious materials content of 400 kg/m^3. The content of water and dosage of VEA are expressed as a percentage of the total cementitious materials (CM). Phase 1 was designed to investigate the effect of using fly ash (FA) percentages as a partial replacement of cement content on the properties of SCC. Six mixes were designed with FA perentages of 10, 20, 30, 40, 50 and 60 %. Phase 2 was designed to investigate the effect of silica fume (SF) percentages as a partial replacement of cement content on the properties of SCC. Three mixes were designed with SF perentages of 5, 10 and 15%. Phase 3 was designed to investigate the effect of different combinations of FA and SF percentages as a partial replacement of cement on the properties of SCC. Three combinations of 5%SF+25%FA, 10%SF+20%FA and 15%SF+15%FA were investigated.

In all mixes the w/c ratio was kept constant at 0.44 and the Viscosity enhancing admixture at 3 % of the cementiuos weight. A control mix was designed without the addition of any mineral admixture for comparison. Table 4 show the materials required to produce one cubic meter from each invstigated mix.

2.3. Mixing Procedures

The dry materials were weighed accurately using a sensitive balance with accuracy up to 10 gm and mixing was performed using a small rotary drum mixer. The mixing procedures consisted of mixing all dry materials till obtaining a homogeneous mix (about 60 seconds) and then 2/3 of the gauging water was added gradually while the mixer was rotating and the concrete was mixed for 120 seconds. The admixture (viscocrete 5-400) was then added to the remaining water (1/3 of the gauging water) and introduced over 30 seconds and the concrete was mixed for another 120 seconds to insure full mixing of the concrete mix.

Table 4. Materials required to produce one cubic meter of the different SCC mixes

Mix code	Cement content kg/m^3	SF	FA	Water Kg/m^3	Sand (kg/m^3)	Dolomite (kg/m^3)	VEA kg/m^3
M10-0	360	-	40	176	884.85	884.85	12
M20-0	320	-	80		879.61	879.61	
M30-0	280	-	120		874.37	874.37	
M40-0	240	-	160		869.13	869.13	
M50-0	200	-	200		863.89	863.89	
M60-0	160	-	240		858.66	858.66	
M0-5	380	20	-		886.25	886.25	
M0-10	360	40	-		882.42	882.42	
M0-15	340	60	-		878.59	878.59	
M25-5	280	20	100		873.16	873.16	
M20-10	280	40	80		871.95	871.95	
M15-15	280	60	60		870.74	870.74	
CTM	**400**	-	-		**890.08**	**890.08**	

2.4. Specimens Preparation

Immediately after testing of concrete in the fresh state, the concrete batch was poured gently in oiled steel molds of the different tests specimens. Fresh properties of SCCs are observed through slump flow diameter, slump flow time, T50, V-funnel test flow time (efflux time and the flow time at T5 minute) and L-box test (average velocity, Vav, and height ratio, H2/H1). Cube specimens, 100 ×100×100 mm, were prepared for evaluating the compressive strength. The compressive strength was determined according to ASTM C 39 after 28, 56, 90 and 270 days of water curing. Cylindrical concrete specimens, 100 mm in diameter and 200 mm high, were prepared to evaluate the split tensile strength. They were tested for split tensile strength according to ASTM C 496 after 28 days of water curing. Prismatic concrete specimens, 100 × 100 mm cross section and 500 mm length with 400 mm loaded span were utilized to determine the flexure strength according to ASTM C 293 after 28 days of water curing. Pouring of concrete was carried out in one layer to the top edge of the mold without any compaction or vibration. The excess concrete was scrapped off and the top surface was finished using trowel. The molds were maintained horizontal during and after placing until hardening after 24. Three specimens representing same constituent were used for each test throughout this study and the average values were reported. After 24 hours, the specimen were removed from the molds and immersed in clean water at a temperature of 20 ± 5°c up to the date of testing .

3. RESULTS AND DISCUSSION

3.1. Effect of FA Addition.

The fresh properties for all concrete mixes investigated in this phase are given in Table 5. It is clear that the slump flow diameters for all seven mixes are kept in the range of 690-775 mm. This satisfies the requirements of EFNARC [9] which stated that the range of slump flow diameter of SCC must be within the range of 600-800 mm. The guide line for slump flow test (600-800)± 50 mm as per the Egyptian code. The slump flow durations (T50) of all seven SCC mixes are in the range of 1.5-5 sec. The Brite EuRam research suggested that a time of 3-7 sec is accepted for civil engineering applications and from 2-5 sec for housing applications [9]. The time measured via the V-funnel flow, Efflux time, is in the range of 3-8.5 sec. The V-funnel flow time after five minute, T5 minute, is in the range of 5.5-12 sec. The Average flow velocities through L-box are in the range of 13.6-27.45 m/s. Finally the height ratios, H2/H1, are in the range from 0.86-1. The EU research team suggested a minimum accepted ratio of 0.8.

Table 5: Fresh properties of SCCs incorporating FA

Mix Code	Slump Flow diameter (cm)	T_{50} (Sec)	Efflux time (Sec)	T_5 (Min)	L – Shape box test results				
					T_{20} (Sec)	T_{40} (Sec)	T_{60} (Sec)	*Velocity* (cm/sec)	H_2/H_1
MC.T	69	4.5	6.5	11.5	1.5	3	4.25	13.6	0.92
M10-0	75.5	3	9	12	1	1.5	2	25.6	0.97
M20-0	73	2.5	8.5	11	1.5	2.5	4.25	14.5	0.94
M30-0	70	3	8	12	1.5	2.5	4.5	14.2	0.86
M40-0	72.5	3.5	3. 5	7	1.5	2.5	3	16.44	0.95
M50-0	75.5	4	3.5	5.5	1	1.75	2.5	22.29	0.97
M60-0	77.5	5	3	5	1	1.3	1.9	27.45	1

The effect of FA addition on the compressive strength of SCC at ages of 28, 56, 90 and 270 days is shown in Fig. 1. It is clear that, at all ages the compressive strength increases with increasing FA content up to 20 %, after that it decreases to a values less than that of control mix (MC.T) at FA % greater than 30%. At 28 days, for example, the compressive strength increases by about 6%, 33% and 4% compared to the control mix with the addition of FA by 10 %, 20% and 30% respectively. With the addition of FA by 40 %, 50% and 60%, the compressive strength decreases compared to the control mix by about 16%, 40% and 46 % respectively.

The effect of testing age (28, 56, 90 and 270days) on the compressive strength of SCC incorporating different amounts of FA percentages is illustrated in Fig. 2. It is clear that the compressive strength increases with increasing testing age.

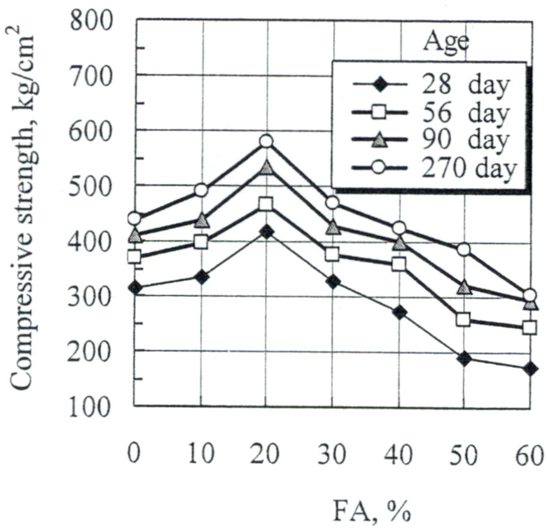

Fig. 1: Effect of FA addition on the compressive strength of SCC.

The increase is more significant up to testing age of 56 days. After 56 days small enhancement in the compressive strength is observed. For SCC mix containing 10% FA, as an example, the compressive strength increases by about 19%, 31%, 47% on increasing testing age to 56, 90 and 270 days respectively compared to that measured at 28 days.

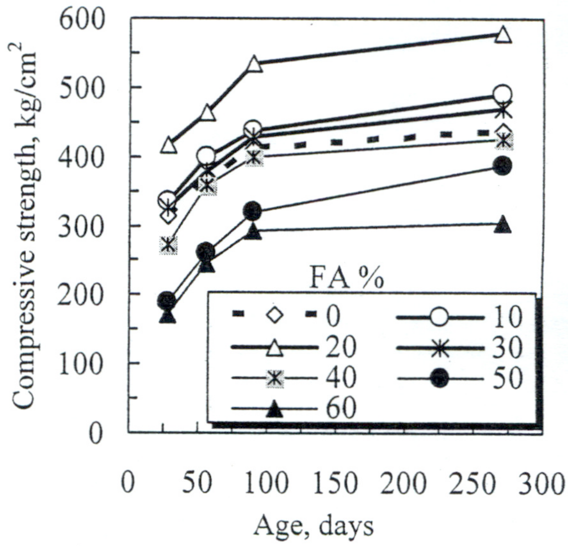

Fig. 2: Effect of testing age on the compressive strength.

The effect of FA addition on the indirect tensile strength and flexural strength of SCC at age of 28 day is shown in Figs. 3 and 4. It is clear that, the tensile strength and flexural strength show similar trend, i.e. they increases with increasing FA content up to 20 % and after that they decrease to a values less than that of control mix (MC.T) at FA % greater than 30%.

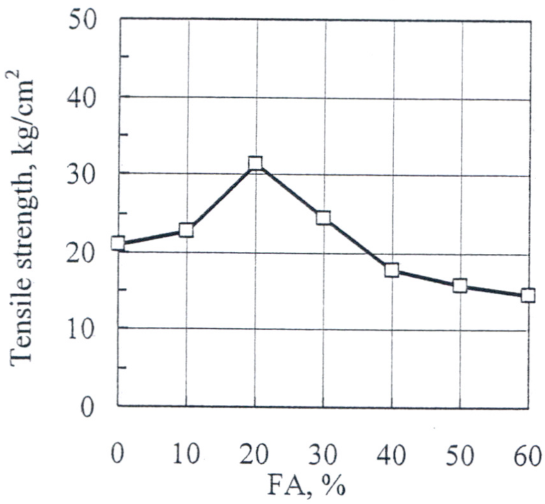

Fig. 3: Effect of fly ash addition on the tensile strength of SCC.

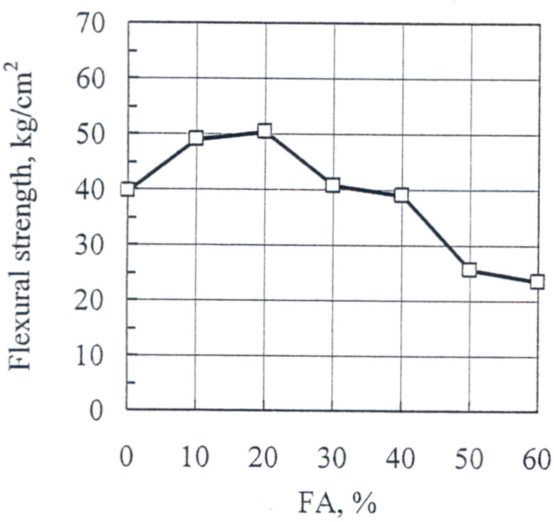

Fig. 4: Effect of fly ash addition on the flexural strength of SCC.

Fly ash at lower percentages, up to 20%, fills the micro pores in concrete. According to Bosiljkov [10], this filler material acts as a nucleation site and accelerates the hydration of clinker minerals, especially C3S, resulting in an improvement in the early strength [11, 12]. Improvement of fine-particle packing can considerably enhance the stability and workability of fresh paste matrix and denseness of the interfacial transition zone in hardened concrete [13, 14]. Thus, compared to conventional concrete with the same w/c ratio and cement type, concrete with FA content up to 20% possesses generally improved strength characteristics. The addition of fine FA up to 20% enhances the rate of cement hydration and strength development as well as to improving the deformability and stability of fresh SCC. The reduction in the compressive strength at higher percentages of FA addition can be attributed to the low pozzolznic reaction of the FA with the calcium hydroxide, $Ca(OH)_2$, produced from cement hydration. Thus the higher replacement level of FA in concrete, the higher reduction in the hardened properties since there is no enough $Ca(OH)_2$ to react with FA. So, the the utilization of high volume FA can be used in non structural appilications , where early strength is not required. Miao Liu [15], Siddique [16], Mehmet [17], and Khatib [18] reported the similar results .

3.2. Effect of SF Addition.

The fresh properties for all concrete mixes investigated in this phase are given in Table 6. It is clear that the slump flow diameters for all four mixes are kept in the range of 690-790 mm. The slump flow durations (T50) of all four SCC mixes are in the range of 2-4.5 sec. The time measured via the V-funnel flow, Efflux time, is in the range of 6-9 sec. The V-funnel flow time after five minute, T5 minute, is in the range of 7-12 sec.

The Average flow velocities through L-box are in the range of 13.6-26.7. Finally the height ratios, H2/H1, are in the range from 0.88-1. Thus all mixes incorporating different percentages of SF satisfied the requirements of the different codes of practice.

Table 6: Fresh properties of SCC incorporating SF.

Mix code	Slump Flow diameter (cm)	T_{50} (Sec)	Efflux time (Sec)	T_5 (min)	L – Shape box test results				
					T_{20} (Sec)	T_{40} (Sec)	T_{60} (Sec)	Velocity (cm/sec)	H_2/H_1
MC.T	69	4.5	6.5	11.5	1.5	3	4.25	13.6	0.88
M0-5	73.5	3	9	12	1	2	3	25.7	0.9
M0-10	76	2.5	7	9	1	2	4.25	26	0.98
M0-15	79	2	6	7	1	2	3	26.7	1

The effect of SF addition on the compressive strength of SCC at ages of 28, 56, 90 and 270 days is shown in Fig. 5. The addition of SF to SCC shows a significant increase in the compressive strength at all ages.

At 28 days, the compressive strength increases by about 34%, 44% and 47% compared to the control mix with the addition of SF by 5%, 10% and 15% respectively. At 56 days, the compressive strength increases by about 26%, 38% and 43% compared to the control mix with the addition of SF by 5%, 10% and 15% respectively. At 90 days, the compressive strength increases by about 19%, 32% and 41% compared to the control mix with the addition of SF by 5%, 10% and 15% respectively. At 270 days, the compressive strength increases by about 14%, 28% and 37% compared to the control mix with the addition of SF by 5%, 10% and 15% respectively.

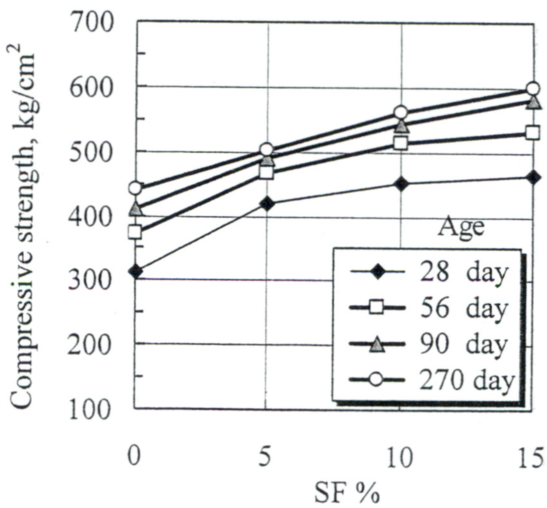

Fig. 5: Effect of SF addition on the compressive strength of SCC.

The effect of testing age (28, 56, 90 and 270 days) on the compressive strength of SCC incorporating different amounts of SF percentages is illustrated in Fig. 6. It is clear that the compressive strength increases with increasing testing age. The increase is more significant up to testing age of 56 days. After 56 days small enhancement in the compressive strength is observed. For SCC mix containing 5% SF, the compressive strength increases by about 11%, 17%, 19% on increasing testing age to 56, 90 and 270 days respectively compared to that measured at 28 days. For SCC mix containing 10% SF, the compressive strength increases by about 14%, 20%, 24% on increasing testing age to 56, 90 and 270 days respectively compared to that measured at 28 days. For SCC mix containing 15% SF, the compressive strength increases by about 15%, 26%, 30% on increasing testing age to 56, 90 and 270 days respectively compared to that measured at 28 days. This is due to the continuity of cement hydration with increasing age.

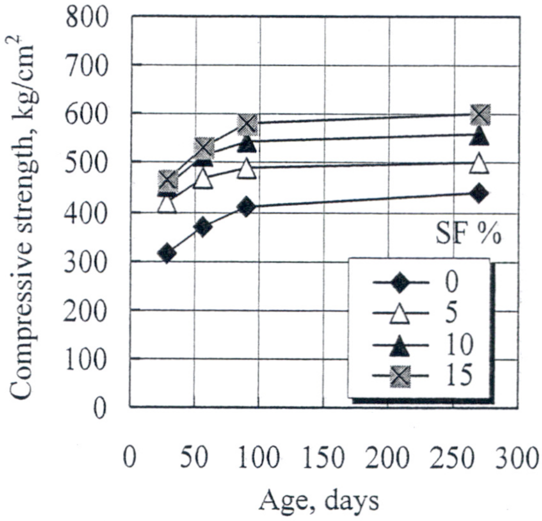

Fig. 6: Effect of testing age on the compressive strength of SCC.

The effect of SF addition on the indirect tensile strength and flexural strength of SCC at age of 28 day is shown in Figs 7 and 8 respectively. It is clear that, the tensile and flexural strengths increase with increasing SF content up to 15 %. The tensile strength increases by about 29% and the flexural strength by 28% when the SF is added by 5%, while they increase by about 44% and 41% when SF addition is increased to 10%. At SF percentage of 15%, the indirect tensile strength and flexural strength increase respectively by about 67% and 55% compared to that of the control mix without SF.

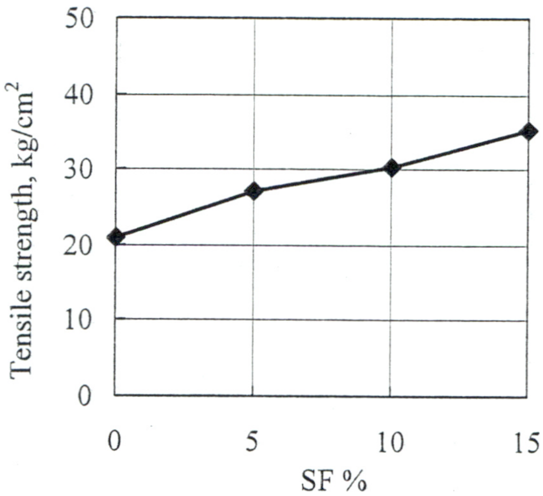

Fig. 7: Effect of SF addition on the tensile strength of SCC.

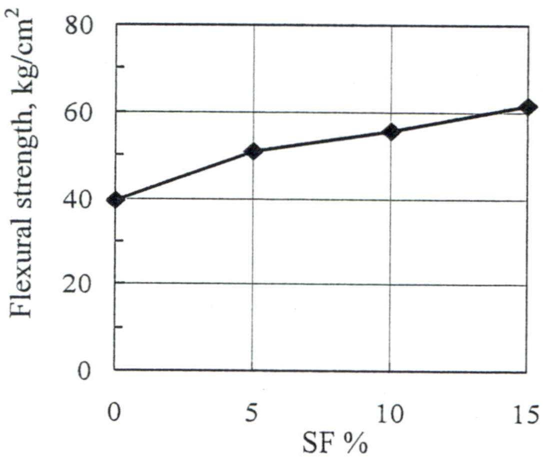

Fig. 8: Effect of SF addition on the flexural strength of SCC.

The enhancement in the mechanical properties of SCC due to the addition of SF can be attributed to two reasons: First, silica fume provided a higher filling capacity, lower internal voids, and higher uniformity of mechanical properties, physical effect. Second, silica fume reacts with calcium hydroxide formed during the hydration of cement and produced calcium silicate hydrate (C–S–H), chemical effect.

3.3. Effect of FA+SF Addition.

The fresh properties for all concrete mixes investigated in this phase are given in Table 7. It is clear that the slump flow diameters for the three SCC concrete mixes incorporating different combinations of FA+SF are kept in the range of 700-740 mm.

The time measured via the V-funnel flow, Efflux time, is in the range of 6-8 sec. The V-funnel flow time after five minute, T5 minute, is in the range of 8-11.5 sec. The Average flow velocities through L-box are in the range of 28-38. Finally the height ratios, H2/H1, are in the range from 0.91-0.97.

Table 7 : Fresh properties of SCC incrporating FA+SF.

Mix code	Slump Flow diameter (cm))	T_{50} (Sec)	Efflux time (Sec)	T_5 (Min)	L – Shape box test results				
					T_{20} (Sec)	T_{40} (Sec)	T_{60} (Sec)	*Velocity* (cm/sec)	H_2/H_1
MC.T	69	4.5	6.5	11.5	1.5	3	4.25	13.6	0.88
M25-5	70	4	8	10	2.5	4	5.5	28	0.94
M20-10	73.5	2	6	8	1.5	3.5	4.5	38	0.91
M15-15	74	3	7	9	1.5	3.5	5	36	0.97

The effect of different combinations of FA+SF addition on the compressive strength of SCC at ages of 28, 56, 90 and 270 days is shown in Fig. 9. It is clear that, the maximum enhancement in the compressive strength is attained at 20%Fa+10%SF for all testing ages.

At 28 days the maximum enhancement in the compressive strength was 40%, while this ratio was 10% and 33% respectively for 25%FA+5%SF and 15%FA+15%SF. At 56 days the maximum enhancement in the compressive strength was 44%, while this ratio was 22% and 41% respectively for 25%FA+5%SF and 15%FA+15%SF. At 90 days the maximum enhancement in the compressive strength was 44%, while this ratio was 15% and 36% respectively for 25%FA+5%SF and 15%FA+15%SF. At 270 days the maximum enhancement in the compressive strength was 44%, while this ratio was 16% and 41% respectively for 25%FA+5%SF and 10%FA+10%SF.

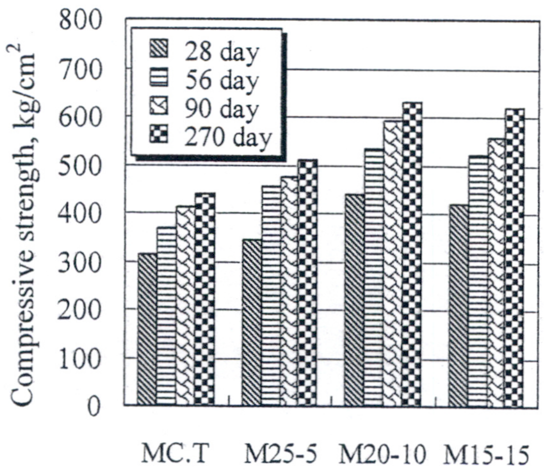

Fig. 9: Effect of FA+SF addition on the compressive strength of SCC.

The effect of testing age (28, 56, 90 and 270 days) on the compressive strength of SCC incorporating different combinations of FA+SF by different percentages is shown in Fig. 10. It is clear that the compressive strength increases with increasing testing age. The increase is more significant up to testing age of 56 days. After 56 days fewer enhancements in the compressive strength is observed. For SCC mix containing 25% FA+5%SF, the compressive strength increases by about 31%, 37%, 47% on increasing testing age to 56, 90 and 270 days respectively compared to that measured at 28 days. For SCC mix containing 20%FA+10% SF, the compressive strength increases by about 22%, 35%, 44% on increasing testing age to 56, 90 and 270 days respectively compared to that measured at 28 days.

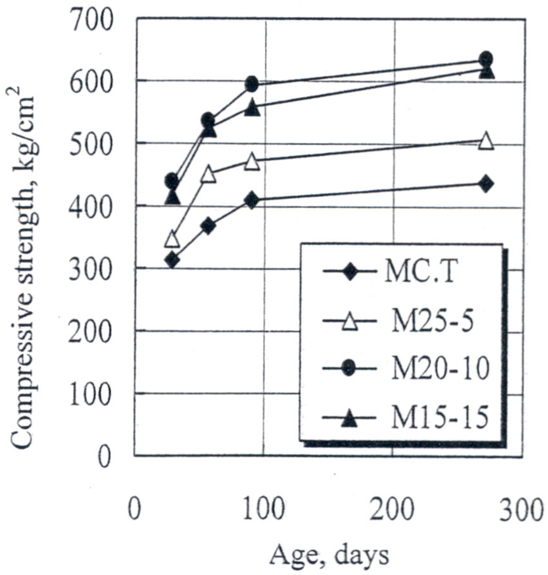

Fig. 10: Effect of testing age on the compressive strength of SCC.

The effect of FA+SF addition on the indirect tensile strength and flexural strength of SCC at age of 28 day is shown in Fig. 11 and Fig. 12. It is clear that, the maximum enhancement in the tensile strength and flexural strength is attained at 20%FA+10%SF, where they increase by about 39% and 21 % respectively compared to that of the control mix. At 25%FA+5% SF, the tensile strength increases by about 23% while the flexural strength increases by about 4%. At 15%FA+15%SF, the tensile strength increases by about 36% while the flexural strength increases by about 20%.

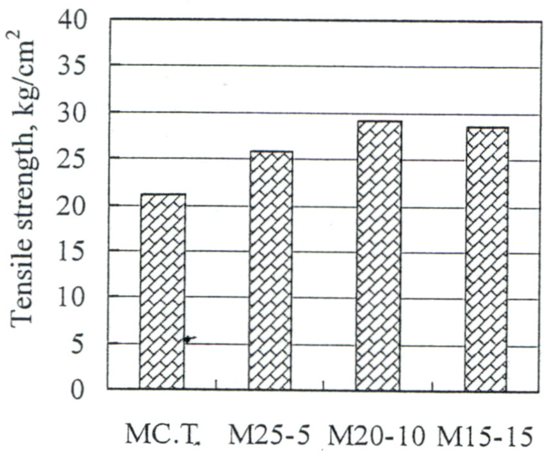

Fig. 11: Effect of FA+SF addition on the tensile strength of SCC.

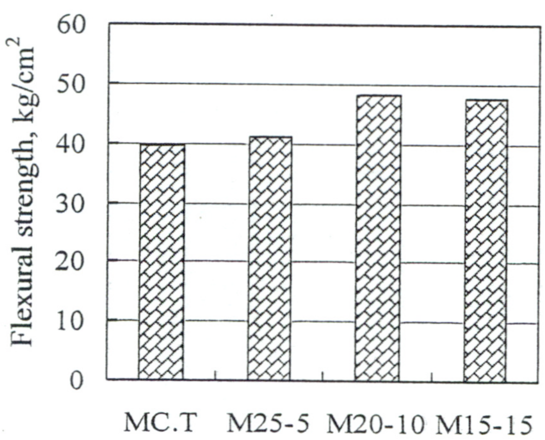

Fig. 12: Effect of FA+SF addition on the Flexural strength of SCC.

4. CONCLUSIONS

1- Self compacting concrete can be produced and satisfies the general requirements of the different codes of practice by adding fly ash or silica fume or combination of them.

2. The maximum compressive, tensile and flexural strengths were achieved at fly ash percentage of 30 %.

3. All mechanical strengths of the investigated SCC increased with the addition of silica fume up to 15%.

4. The maximum compressive, tensile and flexural strengths were obtained at 20% fly ash +10% silica fume.

5. The compressive strength of SCC incorporating different percentages of fly ash, silica fume or combination of them increased with age.

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