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Evaluation of strength at early ages of self-compacting concrete with high volume fly ash

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Abstract

Self-compacting concrete (SCC) demands large amount of powder content and fines for its cohesiveness and ability to flow with out bleeding and segregation. In the present investigation, part of this powder is replaced with high volume fly ash based on a rational mix design method developed by the authors. Because of high fly ash content, it is essential to study the development of strength at early ages of curing which may prove to be a significant factor for the removal of formwork. Rate of gain in strength at different periods of curing such as 12 h, 18 h, 1 day, 3 days, 7 days, 21 days and 28 days are studied for various grades of different SCC mixes and suitable relations have been established for the gain in strength at the early ages in comparison to the conventional concrete of same grades. Relations have also been formulated for compressive strength and split tensile strength for different grades of SCC mixes.

Keywords: Self-compacting concrete; Conventional concrete; Fly ash; Mix design; Compressive strength; Split tensile strength; Workability

1. Introduction

Self-compacting concrete (SCC) represents a milestone in concrete research. SCC is a highly flowable, non-segregating concrete that can spread in to place, fill the formwork and encapsulate the reinforcement without any mechanical vibration for consolidation. SCC was originally developed at the University of Tokyo, Japan during the year 1986 by Prof. Okamura and his team to improve the quality of construction and also to overcome the problems of defective workmanship. A prototype of SCC for structural applications was first completed in 1988 and was named "High Performance Concrete", and later proposed as "Self Compacting High Performance Concrete". A committee was formed to study the properties of SCC, including a fundamental investigation on workability of concrete, which was carried out at the University of Tokyo, Japan [1].

SCC represents one of the most outstanding advancement in concrete technology during the last decade. Due to its specific properties, which are achieved by the excellent coordination of deformability and segregation resistance, SCC may contribute to a significant improvement in the quality of concrete structures and open up new fields for the application of concrete. The use of SCC offers many benefits to the construction practice: the elimination of the compaction work results in reduced cost of placement, a shortening of the construction time and therefore in an improved productivity. The application of SCC also leads to a reduction of noise during casting, better working conditions and the possibility of expanding the placing time in inner city areas. Other advantages of SCC are the improved homogeneity of the concrete and the excellent surface finish without blowholes or other surface defects, due to the optimised combination of the individual components of the concrete mix [2]. The designation "self-compacting" is based on the fresh concrete properties of this material and therefore the degree of compactability, deformability and viscosity of different mix compositions were investigated very frequently. Manu and

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Subramanian [3] reported the developments in the area of self-compacting concrete and the existing level of research along with a number of issues. Mix proportioning technique is one of such issues to be addressed.

To produce a homogeneous and cohesive mix, self-compacting concrete demands a large amount of powder content compared to conventional vibrated concrete. Jagadish et al. [4] reported that SCC often contains powder in the order of 450–600 kg/m^3 of concrete. Due to its rheological requirements, filler additions (both reactive and inert) are commonly used in SCC to improve and maintain the workability, as well as to regulate the cement content and to reduce the heat of hydration. Part of this powder content can be effectively replaced by mineral admixtures like fly ash, ground granulated blast furnace slag, silica fume, etc. [5]. Independent of the fact that SCC consists basically of the same components as normal vibrated concrete, there exist clear differences regarding the concrete composition in order to achieve the desired "self-compacting properties". On the one hand, SCC has to reach a high segregation resistance and on the other hand a high deformability. Therefore, the content of ultra fine materials in SCC is essentially higher. The use of fly ash in this regard provides benefits such as reduction in the water requirements with increased workability and increased strength at later ages of curing, which cannot be achieved through the use of additional Portland cement.

Binu et al. [6] presented a rational method of mix design based on the material characteristics for various grades of SCC by incorporating high volume fly ash as mineral admixture. Fly ash based SCC has proven records of long term strength and durability as it imparts a continuous hardening system to the concrete. Jagadish and Ranganath [7] studied the effect of fly ash on the long term strength in high strength self-compacting concrete. Because of high fly ash content, it is essential to study the development of strength at early ages of curing which may prove to be a significant factor for the removal of formwork.

2. Experimental investigation

2.1. Materials used

The following materials were used in the experimental investigation. The properties of constituent materials are listed in Tables 1 and 2:

Cement: Ordinary Portland cement (53 Grade) with specific gravity of 3.14 confirms to IS 12269:1987 (ASTM C 150-85A).

Fine aggregate: Locally available river sand of specific gravity 2.64, fineness modulus of 2.17, bulk density of 1320 kg/m^3 which confirms to Zone II as per IS: 2386 (Part I).

Coarse aggregate: Crushed granite coarse aggregate of 12 mm down size with specific gravity of 2.79 and bulk density of 1480 kg/m^3 confirms to ASTM C 33-86.

Table 1
Properties of the constituent materials

Material used	Specific gravity	Fineness modulus	Bulk density (kg/cm^3)	Blaine's specific surface fineness (m^2/kg)
Cement (53 Grade)	3.14	–	–	336
Fly ash (Class F)	2.12	–	–	428
Coarse aggregate (12 mm down size)	2.65	6.82	1620	–
River sand (Zone II)	2.40	2.69	1185	–
Quarry dust	2.60	2.64	1720	–

Table 2
Composition and physical properties of binders

Components	Cement (53 Grade)	Class F fly ash
SiO_2	21.4	57.9
Al_2O_3	4.9	33.54
Fe_2O_3	3.8	2.69
CaO	64.2	0.65
MgO	1.1	0.49
Alkalies as Na_2O	0.20	0.46
Sulphur as SO_3	2.1	0.13
K_2O	0.44	0.87
LOI	2.1	1.05
SSA (m^2/kg)	336	428
SG	3.14	2.12

LOI, loss on ignition; SSA, specific surface area; SG, specific gravity.

Water: Potable water confirms to ASTM D 1129, for mixing the concrete and curing of the specimens.

Fly ash: Class F fly ash obtained from Ennore Thermal Power Plant in Chennai with a specific gravity of 2.10 and fineness of 428 m^2/kg determined as per IS 1727:1967 confirms to (ASTM C 618).

Quarry dust: Quarry dust obtained from granite quarry of specific gravity 3.64 and Blaine's surface fineness of 280 m^2/kg.

High range water reducing admixtures (HRWRA): Poly carboxylic ether (PCE) based super-plasticiser confirms to ASTM C 494-92 Type A and Type F in aqueous form to enhance workability and water retention.

Viscosity modifying admixture (VMA): A polysaccharide based VMA, to enhance segregation resistance, to improve the viscosity and to modify cohesiveness of the mix.

3. Mix design

The conventional design of concrete mix is based on the assumption that particles of different sizes fill up larger voids effecting densest packing with the cement paste providing the necessary hardened cement paste to form concrete of design strength under a particular degree of control. This conventional concrete is basically a three constituent material matrix, cement being in a finely powdered form to facilitate fast chemical reaction with water and hence creating the necessary dense concrete matrix.

Based on the proposed method of mix design by Binu et al. [6], SCC consists of five constituent materials (cement, mineral admixture, coarse aggregate, fine aggregate and chemical admixture) in which the first two are in the finely ground state and they form the powder constituent of SCC. The filler material like fly ash facilitates better flow characteristics of SCC in the fresh state. The high fluidity, segregation resistance and minimum risk of blocking can be obtained with a high cement paste volume, low coarse aggregate and water content and the use of suitable SP. The mix design procedure has been developed considering the following aspects.

1. Consistent with good flow ability and better segregation resistance, the powder content has been fixed at an optimum range 400–600 kg/m^3 of concrete as per the specifications for SCC.
2. According to the particle packing theory, the amount of each of these aggregates can be calculated for a given packing factor as determined experimentally.
3. The next important controlling factor is the w/c ratio, or in general w/p ratio. Several earlier trials have been conducted to determine the best w/p ratio for the given targeted design strength. In all these cases, the VMA (% of the binder) must be maintained as 0.1 for the optimum cohesiveness. Chart has been developed for the optimum w/p ratio using the common materials used in this part of the country and the basic properties of the materials are listed in Tables 1 and 2. However, it is suggested that similar such charts can be developed to determine the optimum value of w/p ratio depending on the characteristics of the aggregates and powder to be used.

The present investigation is based on two different mix proportions for various grades of SCC arrived as per the method proposed by Binu et al. [6]. The mix proportions (A-series and B-series) for various grades of SCC (30–70 MPa) were determined. A-series is obtained by using fly ash alone as mineral admixture and B-series using quarry dust as inert filler along with fly ash and are tabulated in Table 3. AS30 stands for mix A for a grade of 30 MPa and BS30 stands for mix B for a grade of 30 MPa. Percentage of cement content varies from 25% to 89% of total powder, fly ash content varies from 52% to 8% of total powder and quarry dust (granite powder used as inert filler) varies from 22% to 3% of total powder for different grades of B-series from 30 to 70 MPa. For a grade of 30 MPa SCC (BS30), cement content is only 25% of total powder content and the rest 75% of the powder consist of fly ash and quarry dust. Whereas in AS30, cement content is 48% and the remaining 52% is occupied by fly ash alone. Poly carboxylic ether based super-plasticiser is used for the high workability and water retention. The dosage of super-plasticiser is optimised by conducting Marsh Cone test. Optimum dosage of super-plasticiser of 0.4–0.7 is used as percentage of binder for water/powder ratio of 0.34–0.31. VMAs are also used to enhance stability and viscosity and there by cohesiveness of the mix. Another mix proportions are arrived for the same grades from 30 to 70 MPa by using only fly ash as mineral admixture.

Tensile strength is one of the most important fundamental properties of concrete. An accurate prediction of tensile strength of concrete will help in mitigating cracking problems, improve shear strength prediction and minimise the failure of concrete in tension due to inadequate methods of tensile strength prediction. Oluokun Francise et al. [8] reported a relation between split tensile strength (f_t) and cylinder compressive strength (f_c) as $f_t = 0.206 (f_c)^{0.79}$ for conventional concrete. Many researchers developed similar such relations for conventional concrete. In the present investigation, attempts are made to develop such relations for different grade of SCC at early ages of curing.

4. Fresh and hardened concrete properties

Different ingredients were batched by weight as per the mix proportions given in Table 3 and mixed well in a pan mixer of capacity 60 kg and the workability tests such as slump flow test, V-funnel test, L-box test and GTM screen stability test as per specifications were carried out to test the flowability, filling ability, passing ability and segregation

Table 3
Mix proportions for various grade of SCC

Mix ID	Cement (kg/m^3)	Fly ash (kg/m^3)	Quarry dust (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	w/p ratio	SP % of binder	VMA % of binder
AS30	250	275	–	842	772	0.34	0.4	0.1
BS30	133	275	117	842	772	0.34	0.4	0.1
AS40	333	215	–	835	766	0.33	0.4	0.1
BS40	246	215	87	835	766	0.33	0.4	0.1
AS50	417	153	–	828	759	0.32	0.5	0.1
BS50	357	153	60	828	759	0.32	0.5	0.1
AS60	500	101	–	820	753	0.32	0.6	0.1
BS60	463	101	37	820	753	0.31	0.6	0.1
AS70	583	50	–	813	745	0.31	0.7	0.1
BS70	566	50	17	813	746	0.31	0.7	0.1

Table 4
Workability test results with recommended limits

Mix ID	w/p ratio	SP/b ratio	Slump flow (mm)	T_{50cm} slump flow (s)	V-funnel flow at T_f (s)	V-funnel at T_{min} (s)	L-Box T_{20}, T_{40} (s)	L-Box h_2/h_1	GTM segregation ratio
AS30	0.34	0.4	793	1.0	3	4	1.0, 1.5	1.0	3.0
BS30	0.33	0.4	675	1.5	5	6	2.0, 2.5	0.91	10.2
AS40	0.33	0.4	786	1.0	4	5	1.0, 1.5	0.99	4.2
BS40	0.33	0.4	690	2.0	5	5	2.0, 2.5	0.92	9.8
AS50	0.32	0.5	773	1.5	4	5	1.5, 2.0	0.96	5.5
BS50	0.32	0.5	685	2.0	4	5	1.5, 2.0	0.89	8.5
AS60	0.32	0.6	766	1.5	5	6	1.5, 2.0	0.95	6.2
BS60	0.31	0.6	695	2.0	4	5	1.5, 2.0	0.94	9.5
AS70	0.31	0.7	742	2.0	5	6	1.5, 2.0	0.95	6.8
BS70	0.31	0.7	680	2.0	4	6	1.5, 2.0	0.90	8.2
Recommended limits			600–800	<3	<6	$<T_f+3$	1 ± 0.5, 2 ± 0.5	>0.8	<15

w/p, water/powder (cement + fly ash + filler); SP/b, super plasticiser/binder (cement + fly ash).

resistance as per specifications. The workability test results (Table 4) are found to be with in the prescribed limits as per specifications and guidelines [9–11] and satisfy all the required rheological characteristics and self-compactability.

Standard cubes were tested for compressive strength as per IS: 516-1959, after 12 h, 18 h, 1 day, 3 days, 7 days, 21 days, 28 days and 56 days of curing. Standard cylindrical specimens were tested as per IS: 5316 and IS: 1199 for the split tensile strength of different grades of SCC mixes after 1 day, 3 days, 7 days, 21 days, 28 days and 56 days of curing. The test results for the compressive strength and tensile strength are given in Table 5. Compressive strength of SCC is compared with the expected strength of conventional concrete as per IS: SP: 23-1982 and is given in Table 6.

Table 5
Compressive strength of SCC and the expected strength of conventional concrete as per IS: SP: 23-1982

Mix ID	12 h	18 h	1 day	3 days	7 days	14 days	28 days
Expected strength (N/mm^2) for conventional concrete as per IS: SP: 23-1982							
CV30	2.91	4.20	5.40	12.60	20.10	25.68	30
CV40	3.88	5.60	7.20	16.80	26.80	34.24	40
CV50	4.85	7.00	9.00	21.00	33.50	42.80	50
CV60	5.82	8.40	10.80	25.20	40.20	51.36	60
CV70	6.79	9.80	12.60	29.40	46.90	59.92	70
Compressive strength (N/mm^2) obtained for different SCC mixes							
AS30	4.48	6.48	8.14	18.12	27.60	34.91	39.62
BS30	3.52	4.86	6.05	13.89	21.27	27.32	32.50
AS40	5.68	8.16	10.32	23.24	35.26	44.18	50.24
BS40	4.48	6.58	8.12	18.21	28.41	34.63	42.30
AS50	6.95	10.18	12.76	28.28	43.54	54.52	61.82
BS50	5.82	8.14	10.22	23.10	34.69	43.65	52.00
AS60	8.12	11.42	14.61	32.18	49.81	62.45	70.93
BS60	6.63	8.90	12.36	27.31	41.83	52.03	61.90
AS70	8.78	12.63	16.21	35.68	55.92	70.68	81.25
BS70	7.84	11.30	14.30	31.42	48.80	60.90	71.50

Table 6
Results on the Split tensile strength of SCC (AS30–AS70 and BS30–BS70)

Curing period (days)	Tensile strength in N/mm^2 for different grades of SCC mixes									
	AS30	AS40	AS50	AS60	AS70	BS30	BS40	BS50	BS60	BS70
1	1.40	1.65	2.01	1.56	2.14	1.21	1.49	1.26	1.94	1.98
3	2.40	2.99	3.42	3.30	3.65	2.00	2.47	2.98	3.38	3.61
7	3.12	3.96	4.58	4.85	5.48	2.76	3.35	3.76	4.35	4.84
14	3.66	4.60	5.64	5.64	6.67	3.25	3.98	4.75	5.24	5.73
28	4.06	5.01	5.95	6.72	7.54	3.72	4.53	5.06	5.79	6.45

5. Results and discussion

Graphs are plotted for the gain in compressive strength at early ages of curing of various grades of SCC. Fig. 1 shows the rate of gain in strength for AS30–AS70 from 12 h to 28 days of curing. Similar curve is plotted for BS30–BS70 in Fig. 2. AS30–AS70 series shows comparatively higher strength than BS30–BS70 series because of higher cement content and flowability. The exclusion of quarry dust in AS30–AS70 series enables higher flow and self-compacting characteristics with an increase in compressive strength. But this increase is only marginal when the savings in cement in BS30–BS70 series is considered. Fig. 3 shows the comparison of compressive strength of AS30 and BS30. Similar trend is followed by other grades too. Test results are compared with conventional concrete of same grades. It is observed that the strength gain at early ages of curing of SCC is better than conventional concrete of the same grades.

Table 7
Relationship for the expected compressive strength of SCC in comparison to that of conventional concrete

Period of curing	SCC	Conventional concrete
12 h	$0.108f_{c28}$	$0.097f_{c28}$
18 h	$0.155f_{c28}$	$0.140f_{c28}$
1 day	$0.198f_{c28}$	$0.180f_{c28}$
3 days	$0.444f_{c28}$	$0.420f_{c28}$
7 days	$0.689f_{c28}$	$0.670f_{c28}$
14 days	$0.869f_{c28}$	$0.856f_{c28}$
28 days	$1.000f_{c28}$	$1.000f_{c28}$

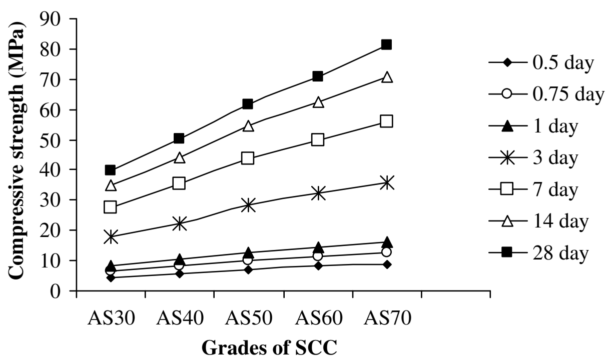

Fig. 1. Compressive strength of SCC (AS30–AS70) at early ages of curing.

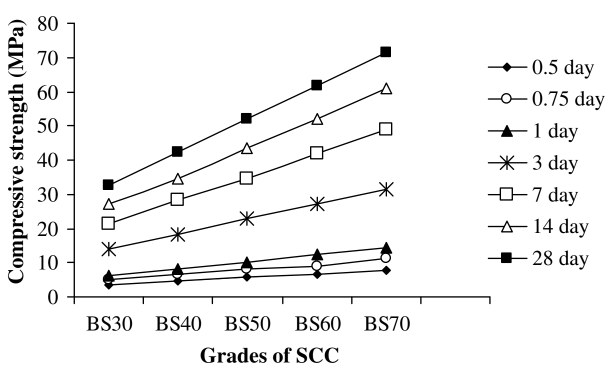

Fig. 2. Compressive strength of SCC (BS30–BS70) at early ages of curing.

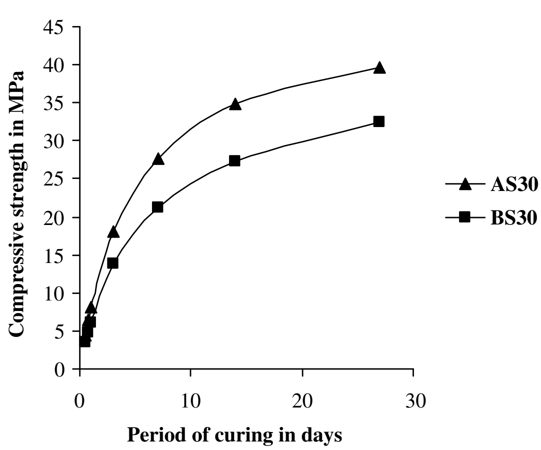

Fig. 3. Comparison of compressive strength of AS30 and BS30.

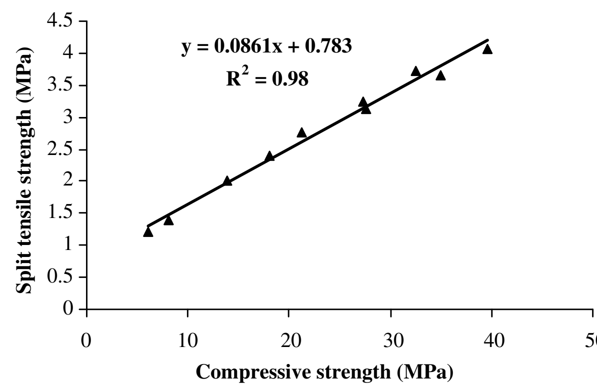

Fig. 4. Relation between compressive strength and split tensile strength of AS30 and BS30.

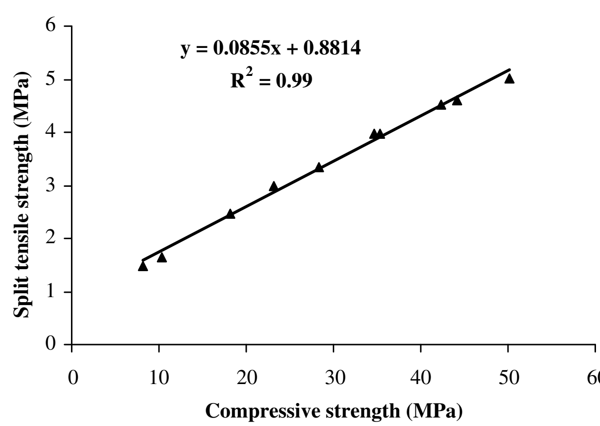

Fig. 5. Relation between compressive strength and split tensile strength of AS40 and BS40.

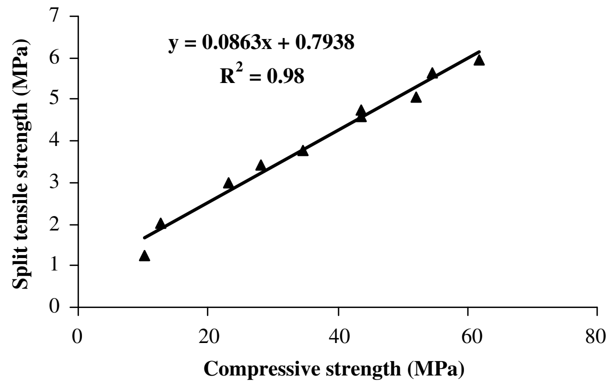

Fig. 6. Relation between compressive strength and split tensile strength of AS50 and BS50.

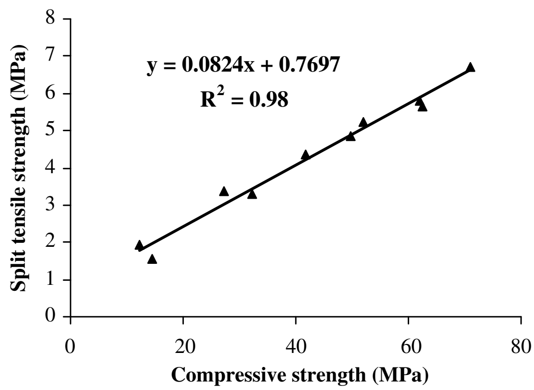

Fig. 7. Relation between compressive strength and split tensile strength of AS60 and BS60.

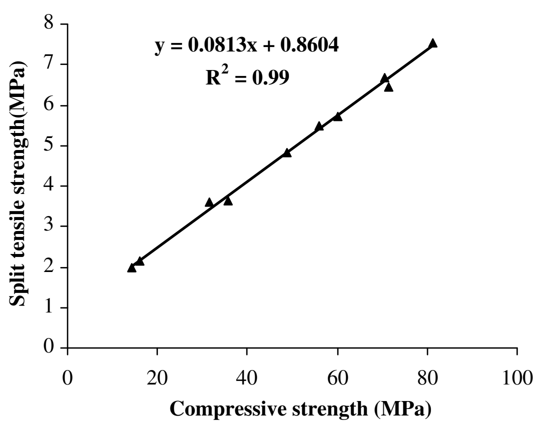

Fig. 8. Relation between compressive strength and split tensile strength of AS70 and BS70.

The rate of gain in strength for conventional concrete at various periods of curing as per IS: SP 23-1982 is given by

$$f_{ct} = f_{c28} \times t/(4.7 + 0.833 \times t)$$

where f_{ct} is compressive strength at an age of curing 't' in days; f_{c28}, compressive strength in MPa at 28 days of curing; and t is age in days.

Table 8
Relation between split tensile strength and Compressive strength for various grades of SCC

Grades of SCC	Relationship obtained
SCC30	$f_{ct} = 0.0861 f_{ck} + 0.783$
SCC40	$f_{ct} = 0.0855 f_{ck} + 0.882$
SCC50	$f_{ct} = 0.0863 f_{ck} + 0.794$
SCC60	$f_{ct} = 0.0824 f_{ck} + 0.770$
SCC70	$f_{ct} = 0.0813 f_{ck} + 0.861$
Combined	$f_{ct} = 0.0843 f_{ck} + 0.818$

Compressive strength of SCC at various ages of curing are found to be comparable with the relation suggested by IS: SP 23-1982. It is observed that the rate of gain in strength for different grades of SCC is slightly more than the expected strength as per IS: SP 23-1982.

Similar to IS Code formula for conventional concrete as per SP 23-1982, a relation is developed for SCC based on the compressive strength at various ages of curing, i.e. (12 h, 18 h, 1 day, 3 days, 7 days, 21 days and 28 days). The relation is given by

$$f_{ct} = f_{c28} \times t/(4.2 + 0.85 \times t)$$

Table 9a
Comparison of proposed relation with the experimental results (AS30–AS70)

Sl. No.	As per test results		As per proposed equation $f_{ct} = 0.0843 f_{ck} + 0.818$	
	Compressive strength (N/mm^2)	Tensile strength (N/mm^2)	Tensile strength (N/mm^2)	Percentage error
1	8.14	1.4	1.5	6.66
2	10.32	1.65	1.69	2.36
3	12.76	2.01	1.90	5.78
4	14.61	1.56	2.05	–
5	16.21	2.14	2.18	1.80
6	18.12	2.40	2.35	2.12
7	23.24	2.99	2.78	7.5
8	28.28	3.42	3.21	6.54
9	32.18	3.30	3.53	6.50
10	35.68	3.65	3.82	3.66
11	27.60	3.12	3.14	0.64
12	35.26	3.96	3.79	4.48
13	43.54	4.58	4.49	2.00
14	49.81	4.85	5.02	3.38
15	55.92	5.48	5.53	0.90
16	34.91	3.66	3.76	2.65
17	44.18	4.60	4.54	1.30
18	54.52	5.62	5.41	3.88
19	62.45	5.64	6.08	7.20
20	70.68	6.67	6.77	1.47
21	39.62	4.06	4.15	2.16
22	50.24	5.01	5.05	0.79
23	61.82	5.95	6.02	1.16
24	70.93	6.72	6.79	1.03
25	81.25	7.54	7.66	1.56
Average percentage error				3.23

where f_{ct} is compressive strength at an age of curing 't' in days; f_{c28}, compressive strength in MPa at 28 days of curing; and t is age in days.

Based on this relation, the expected strength at various ages of curing are determined and tabulated in Table 7.

It s also observed that the requirement of cement for a grade of 30 MPa is only 133 kg/m^3 as per BS30, seems to be much lower than that of AS30 and conventional concrete of the same grade.

Praveen Kumar et al. [12] reported that for strength development at early ages similar to normal concrete, minimum cement content of about 300 kg/m^3 is required to obtain 7-day strength of the order of 30 MPa. However, test results presented here demonstrate that the cement requirement is only 246–250 kg/m^3 to obtain 7-day strength of about 30 MPa.

6. Relationship between compressive strength and split tensile strength of SCC

Based on the test results on the compressive strength and split tensile strength of various grades of different SCC mixes at different ages of curing graphs are plotted with tensile vs. compressive strength and suitable linear relations are developed between tensile strength and compressive strength for various grades of SCC ranges from 30 to 70 MPa. Figs. 4–8 show the relation between tensile strength and compressive strength of various grades of SCC. Relation between split tensile strength and compressive strength obtained are tabulated in Table 8. A single relationship has been proposed, which is suitable for all grades of SCC. The proposed equation is given by

$$f_{ct} = 0.0843 f_{ck} + 0.818$$

where f_{ct} is tensile strength in MPa and f_{ck} is compressive strength in MPa.

Percentage error of the proposed equation with regard to the test results are determined and tabulated in Tables 9a and 9b. It is observed that as the percentage error is less than 3.7% on an average and the proposed equation can be well accepted.

Table 9b
Comparison of proposed relation with the experimental results (BS30–BS70)

Sl. No.	As per test results		As per proposed equation $f_{ct} = 0.0843f_{ck} + 0.818$	
	Compressive strength (N/mm^2)	Tensile strength (N/mm^2)	Tensile strength (N/mm^2)	Percentage error
1	6.05	1.21	1.32	8.33
2	8.12	1.49	1.50	0.66
3	10.22	1.71	1.68	1.06
4	12.36	1.94	1.86	4.30
5	13.89	2.0	1.99	0.50
6	14.3	2.16	2.02	6.93
7	18.21	2.47	2.35	5.10
8	21.27	2.76	2.61	5.74
9	23.10	2.98	2.77	7.58
10	27.31	3.38	3.12	8.33
11	27.32	3.25	3.12	4.16
12	28.41	3.35	3.21	4.36
13	31.42	3.61	3.47	4.03
14	32.5	3.72	3.56	4.49
15	34.63	3.98	3.74	6.41
16	34.69	3.98	3.74	6.41
17	41.83	4.35	4.34	0.23
18	42.30	4.53	4.38	3.42
19	43.65	4.63	4.50	2.88
20	48.80	4.84	4.93	1.82
21	52.00	5.06	5.20	2.60
22	52.03	5.24	5.20	0.77
23	60.90	5.73	5.95	3.69
24	61.90	5.79	6.04	4.13
25	71.50	6.45	6.85	5.84
Average percentage error				4.15

7. Conclusions

1. SCC mixes are prepared for different grades ranges from 30 to 70 MPa with all required rheological characteristics such as flow ability, filling ability, passing ability and segregation resistance.
2. Relations have been established for the gain in compressive strength at early ages of curing (12 h to 28 days) for different grades of SCC mixes and the relations are compared with the IS Code formula for conventional concrete as per IS: SP 23-1982.
3. The proposed equation for the compressive strength is given by $f_{ct} = f_{c28} \times t/(4.2 + 0.85 \times t)$.
4. It is observed that the rate of gain in strength for different grades of SCC is slightly more than the expected strength of conventional concrete of the same grades.
5. It is found that strength at 12 h of all grades of SCC is more than 10% of the 28-day strength and 1-day strength is about 18–20% of the 28-day strength.
6. Suitable relations are developed between tensile strength and compressive strength of different grades of SCC (Table 8).
7. A single relation is developed for the tensile strength of all grades of SCC, which is given by $f_{ct} = 0.0843 f_{ck} + 0.818$.
8. The percentage error of the proposed relation in comparison to the experimental results is found to be less than 3.7% on an average, which proves the reliability of the proposed equation.

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