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Effect of Fibers and Filler Types on Fresh and Hardened Properties of Self-Compacting Concrete

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ABSTRACT

This paper deals with studying the fresh and hardened properties of self-compacting concrete, by using three types of filler (silica fume, clinker powder & lime stone powder), and two types of fibers (steel & glass fibers) with volume fractions of (0.5%) and (0.1%) respectively. For each type of fillers, the fresh properties are measured by using Slump test, J- ring and V-funnel, while hardened properties include the compressive strength, splitting tensile strength and flexural strength. The results show that adding fibers to the self-compacting concrete (SCC) well reduces the workability and improves the hardened properties. Also, the study concluded that better workability is obtained by using (lime stone, silica fume and clinker powder) as fillers, respectively. While the higher hardened properties are gained by using silica fume were rather than those of other types of fillers.

KEYWORDS: Self-compacting concrete (scc), Silica fume, Limestone Dust, Fibers, Clinker Powder, Fillers, Mechanical Properties, Superplasticizers.

تأثير أنواع الألياف وأنواع المواد المالئة على الخواص الطرية والمتصلبة للخرسانة ذاتية الرص

الخلاصة

في هذا البحث تم الأخذ بنظر الاعتبار دراسة الخواص الطرية والمتصلبة للخرسانة ذاتية الرص باستعمال ثلاثة أنواع من المواد المالئة وهي على التوالي غبار السيليكا ، مسحوق الكلنكر ومسحوق الحجر الجيري وكذلك باستعمال الألياف الحديدية والألياف الزجاجية بنسب حجمية % 0.5 و %0.1 على التوالي. فحصت الخواص الطرية للخرسانة ذاتية الرص لكل نوع من المواد المالئة والألياف باستعمال فحص الانتشار وفحص إعاقة الحلقة -J-Ring وفحص المرور والانعزال –فحص القمع- V-Funnel. بينما كانت فحوصات الخرسانة المتصلبة هي فحص مقاومة الانضغاط ،فحص مقاومة الانشطار وفحص مقاومة الانحناء. أظهرت النتائج المختبرية بأنه عند إضافة الألياف إلى الخرسانة ذاتية الرص قللت من قابلية التشغيل للخرسانة بينما تحسنت خواص الخرسانة المتصلبة. كذلك بينت الدراسة إن أفضل قابلية تشغيل تم الحصول عليها عند استخدام مسحوق الحجر الجيري، غبار السيليكا ومسحوق الكلنكر كمادة مالئة على التوالي. بينما خواص عالية للخرسانة الذاتية الرص المتصلبة تم الحصول عليها عند استخدام غبار السيليكا بالمقارنة مع الأنواع الأخرى من المواد المالئة المستعملة.

الكلمات الدالة: الخرسانة ذاتية الرص، غبار السيليكا، مسحوق الحجر الجيري، الألياف، مسحوق الكلنكر، المواد المالئة الخواص الميكانيكية، الملدنات.

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INTRODUCTION

Self-compacting concrete (SCC) is considered a relatively new type of concrete developed in Japan in the late 1980. Which can be placed and compacted under its self-weight with little or no vibration effort, and which is at the same time cohesive enough to be handled without segregation or bleeding. SCC can also provide a better working environment by eliminating the vibration noise. It is capable of flowing through narrow opening and complex structural element or highly congested reinforcement, and provides a void-free surface. It is also known as self-consolidating concrete, self-leveling concrete and high fluidity concrete [1,2].

There are many advantages of using SCC [3]:-

1. Improving the workability and flow ability of concrete without segregation.
2. Reducing the construction time and labor cost;
3. Eliminating the need for vibration;
4. Reducing the noise pollution;
5. Improving the filling capacity with low voids of highly congested structural members.
6. Facilitating constructability and ensuring good structural performance
7. Better surface finishes
8. Improved durability,
9. Increased bond strength,
10. Greater freedom in design.

Fiber reinforced self-compacting concrete (FRSCC) contains only one type of fibers. The use of two or more types of fibers in a suitable combination may potentially not only improve the overall properties of self-compacting concrete, but may also result in performance synergie. The combining of fibers, often called hybridization [4].

Zoran et al., from Serbia (2008) [5] studied the effect of different types of additives (fly ash ,silica fume and hydraulic lime) on properties of self-compacting concrete.

The researchers are concluded that the addition of fly ash to the mixture containing hydraulic lime improves the behavior of self-compacting concrete with fly ash and hydraulic lime (SCCFAHL) concrete, but has smaller filling capacity than other mixtures, also they concluded that incompatibility between silica fume and superplasticizers requiring an increase of water/cement ratio for the same concrete workability.

In china Buquan etal .,(2003) [6], investigated the influences of fiber content on properties of self-compacting concrete (SCC) by using mineral admixtures such as slag and fly ash and different fiber contents (0.5,1.0, and 1.5) %. They concluded that addition of steel fibers improves (by up to 20%) the compressive strength of the self-compacting slag fly ash fiber reinforced concrete (SCSFRC) at early ages (3 and 7 day), also the adding of steel fibers improved the flexural strength. It was found that, the increase of volume friction (V_f) of fibers decreased the flowability of fresh concrete and increases the air content.

In India Jeenu etal .,(2007) [7] carried out a study on the flexural behavior of hybrid fiber reinforced SCC by adding (0.25, 0.5, 0.75 and 1.0) % of macro steel fibers (0.9 mm diameter). The influence of hybrid fibers on SCC mixture was also studied also by replacing macro steel fiber with micro steel fiber of 0.34 mm diameter for a total fiber content of 0.75%. Fresh concrete properties of SCC such as workability and flow ability are usually decreased and hardened properties such as compressive strength, flexural strength and tensile strength are improved by the addition of fibers. Also they concluded that the optimum percentage of macro fibers addition is 0.75% by volume and 50% replacement of this by micro fibers improved the performance of concrete.

EXPERIMENTAL PROGRAM

Materials

Cement

The cement used throughout this work was Ordinary Portland Cement produced by badosh Cement Factory. The chemical analysis and physical test results of the used cement are given in Tables (1) and (2) respectively. It conforms to the Iraqi specification No. 5/1984.

Table (1): Physical Properties of Cement

Physical properties	Test result	Limits of Iraqi Spec. No. 5/1984
Specific surface area Blaine method, cm^2/gm	2800	$\geq$2300 cm^2/gm
Standard consistence, %	27.5	-
Setting time, Vicat's method: Initial setting, min. Final setting, min.	 137 165	 $\geq$ 45 minutes $\leq$ 600 minutes
Fineness on sieve No. 170, %	3	$\leq$22%
Compressive strength of 5 cm cubic mortar samples, N/mm^2: 3 days 7 days	 23.8 29.6	 $\geq$15 N/mm^2 $\geq$23 N/mm^2
Tensile strength, N/mm^2: 3 days 7 days	 1.63 2.48	 $\geq$1.6 N/mm^2 $\geq$2.4 N/mm^2

Table 2: Chemical Analysis of Cement and Fillers

Compound Composition	Cement	Specification IQS, No.5,1984	Lime Stone	Clinker Powder
Al_2O_3 Aluminum Oxide (%)	5.8	3.0 – 8.0	0.45	3.68
SiO_2 Silicon Dioxide (%)	21.35	17.0 – 25.0	6.32	12.60
Fe_2O_3 Iron Oxide (%)	2.6	0.5- 6.0	0.26	1.49
CaO Lime (%)	62.3	60.0 – 67.0	48.6	40.36
SO_3 Sulphur Trioxide (%)	2.5	2.5-2.8	0.28	0.42
MgO Magnesium Oxide (%)	3.33	Not more than 5%	1.68	2.0

Fine aggregate

Rounded natural sand of 4.75 mm maximum size was used for concrete mixes of this investigation. It brought from Khazer region, Mosul, Iraq. The sieve analysis of the used sand is shown in Table (3). It conforms to the limits of B.S: 882:1992. The specific gravity, absorption, and material finer than sieve No. 200 (75 μm) of the used fine aggregate were (2.68, 2.66%, and 0.8%) respectively.

Table (3): Sieve Analysis of Fine Aggregate

Sieve Size (mm)	Accumulated Percentage Passing (%)	Accumulated Percentage Retained (%)	Limits of B.S: 882:1992 (Fine F) Specification
4.75	100.0	0.0	-
2.36	89.0	11.0	80-100
1.18	74.5	25.5	70-100
0.60	55.5	44.5	55-100
0.30	21.5	78.5	5-70
0.015	3.5	96.5	-

Coarse aggregate

The washed coarse aggregate used was rounded aggregate of 12.5 mm maximum size. It brought from Khazer region, Mosul, Iraq. The sieve analysis of this aggregate is shown in Table (4). It conforms to the B.S: 882:1992. The specific gravity, absorption, and material finer than No. 200 (75 μm) sieve of the used coarse aggregate were (2.66, 0.4 %, and 0.2%) respectively.

Table (4): Sieve Analysis of Coarse Aggregate

Sieve Size (mm)	Accumulated Percentage Passing (%)	Accumulated Percentage Retained (%)	Limit of B.S: 882:1992 (5-14 mm) Specification
14	100	0.0	90-100
10	76.0	12.20	50-85
5	0.9	88.40	0-10
2.36	0.0	100	-

Fillers

Three types of fillers silica fume, clinker powder and limestone powder been used in this research. The dosages of used fillers were 10% by weight of cement. The chemical analysis of fillers was given in Table 2.

Chemical Admixtures

Chemical Admixture type Visco Crete – SF 18 was used as high range water reducing admixture and viscosity modifying agent. The dosage used was 2% by weight of cement. The properties of visco Crete – SF 18, as provided by the manufacturer, are shown in Table (5).

Table (5): Physical Properties of Visco Crete –SF 18

Name	Sika Visco Crete – SF 18
Chemical base	Modified poly carboxylates based polymer
Appearance / color	Light brownish liquid
pH value	3-7
Density	1.1 g/cm^3 ±0.02 (at + 20 °c)
Dosage	1.0-2.0% by weight of cement

Fibers

Two types of fibers are used in this research, glass and steel fibers with volume fractions 0.1% and 0.5% respectively. Table (6) shows the properties of the used fibers.

Table (6): Details of Steel and Glass Fibers

Type of fiber	Steel	Glass
Length(mm)	25	13
Diameter (mm)	1	0.014
Aspect ratio	25	928.5
Fraction volume (%)	0.5%	0.1%
Density(kg/m^3)	7890	2600

Tap Water

Ordinary tap water was used in this investigation for both mixing and curing purposes.

Mix Proportions

Nine concrete mixtures, with mix proportion of 1:2:1.75 and water –cement ratio 0.35 are used. The mix proportions are provided in Table (7). The quantities of materials were**,** Cement 369 kg/m^3, fine aggregate 880 kg/m^3, coarse aggregate 770 kg/m^3, water 154 kg/m^3, Visco Crete –SF 18, 2% by weight of cement and fillers, 10% by weight of cement**.**

Table (7): Details of the Mixes used Throughout this Investigation

No. Mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	MIX 6	Mix 7	Mix 8	Mix 9
Filler Types	Silica fume 10% by weight of cement as a replacement (1)			Clinker Powder 10% by weight of cement as a replacement (2)			Limestone Powder 10% by weight of cement as a replacement (3)		
Fiber Types	0%	Steel 0.5%	Glass 0.1%	0%	Steel 0.5%	Glass 0.1%	0%	Steel 0.5%	Glass 0.1%

Mixing Procedure

Mixing procedure and mixing time are more critical as compared to conventional concrete mixtures.

The following mixing procedure (with a total mixing time of 7 minutes) was found to be satisfactory to produce self-compacting, where used during all batches in this study:

(i) Loading and mixing aggregates for 1 minute;
(ii) Adding and mixing cement, and filler for 1 minute;
(iii) Adding water premixed with Visco Crete SF -18 and mixing for 2 minutes;
(iv) Carefully adding (to prevent balling) and mixing fibers for 3 minutes.

Casting and Curing

After Preparation the materials and mixing procedure was completed, tests were conducted on the fresh concrete to determine slump flow time and diameter, J-Ring test, and V-funnel flow time. For each concrete mixture, three 100-mm cubes, three cylinders 100 mm in diameter and 200 mm height and three beams of size 100x100x400 mm were cast. All specimens were casted in one layer without any compaction. The cubes were used for the compressive strength, the cylinders were used for the splitting tensile strength and beams were used for the flexural strength tests. Then the specimens were kept covered with polyethylene sheet in the laboratory for about (24 ± 2) hrs. After that the specimens remolded carefully, marker and immersed in water until the age of test.

Test Procedures

Testing of Fresh Concrete

Slump flow, J-Ring, and V-funnel tests were performed in the laboratory on fresh SCC to find filling ability, passing ability and segregation resistance. Table (8) gives the specifications of the workability tests of SCC, According to EFNARC.

Table (8) : Specifications of Workability tests of SCC, According to EFNARC [8]

Property	Description	Testing Method	Specification Limit
Filling ability	Ability of to fill a formwork completely under its own weight.	Slump flow	(650 – 800) mm
			T_{500} mm (2-5) sec
Passing ability	Ability to overcome obstacles under its own weight. E.g. reinforcement and small openings etc.	J-ring	<20 mm
Segregation resistance	Homogeneous composition of concrete during and after the process of transport and placing.	V-funnel	T_0 (6-12) sec
			T5min-T0 (0-3) sec

Testing of Hardened Concrete

***Compressive strength test*:**

Based on BS 1881: part 5[9], the compressive strength was carried out on (100 x 100 x 100 mm) cube specimens by compression testing machine Matest type, Italy manufacturing, with capacity 2000 kN. The compressive strength was taken as the average value of three specimens.

Splitting tensile strength test:

The splitting tensile strength was conducted on cylinders of (100 x 200 mm) by compression testing machine Matest type, Italy manufacturing, with capacity 2000 KN. The average of three test specimens was taken. The test was carried out in accordance with ASTM C 496-86 [10].

Flexural strength test

A testing machine, Matest type, Italy manufacturing, with capacity 150 KN was used for testing the flexural strengths of (100 x 100 x 400-mm) beam specimens. This test was done according to ASTM C 78-84, using Third-Point Loading, with span length 270 mm [11]. The flexural strength was taken as the average value of three specimens.

RESULTS AND DISCUSSION

Fresh Concrete Properties

Table (9) presents the various workability (Slump flow, J-Ring and V-funnel) test results of different self-compacting concrete mixes. All of the workability test results conformed to the criterion of self-compacting concrete (SCC) except results of Mix 6.

The results of fresh concrete tests are shown in Table (9), which included the slump flow diameter and time, V-funnel flow time and J-Ring test. As seen in this Table, the slump flow diameters of all mixtures were in the range of 730 – 545 mm. The slump flow times were in the range of 2.85 – 8.5 Seconds, the J-Ring test values were in the range 8.5 – 30.5 mm, and the V-funnel flow times were in the range 1.89 – 4.41Seconds. Therefore, all concrete mixtures were considered as self-compacting concrete except Mix6.

Table (9) shows that the incorporation fiber decreases the slump flow of all concrete mixtures containing steel and glass fibers compared control mixes (0% fiber). This can be attributed to the fact that the incorporation fiber increases the internal resistance to flow. As can be seen from Table(9), workability tests of SCC mix seem to be more affected by the inclusion of glass fibers with 0.1% volume fraction compared to steel fibers with 0.5% volume fraction.

Also From Table (9), it can be seen that the addition of 10% limestone dust, silica fume or clinker powder cause any decrease in workability of self-compacting concrete. This behavior may be attributed to the very high surface area of limestone dust and silica fume powder which can be completely dispersed into individual particles.

Table (9): Slump Flow, J-Ring and V-Funnel Test Results of SCC

Mix No.	Slump Flow		J ring		V-funnel		
	T_{50} (2-5) sec	D 650-800 mm	T_{50J} (2-5) Sec	BJ <10 mm	T_f 6-12 (sec)	T5 (sec)	T_5-T_f 0-3 (sec)
MIX 1	2.93	725	3.42	8.5	7.73	9.62	1.89
MIX 2	3.28	695	3.64	12.0	9.87	12.69	2.82
MIX 3	5.23	652.5	6.82	24.5	9.51	12.38	2.87
MIX 4	2.98	720	3.22	12.5	7.66	9.83	2.17
MIX 5	3.56	690	3.89	13.5	9.42	11.25	2.83
MIX 6	8.5	545	-	27.5	15.97	20.38	4.41
MIX 7	2.06	730	2.53	8.75	7.21	9.16	1.95
MIX 8	2.85	720	3.38	9.5	7.69	10.41	2.72
MIX 9	4.28	655	4.56	17.2	8.28	10.76	2.48

Hardened Concrete Properties

Table (10) shows the average compressive, splitting and flexural strengths of Self-compacting concrete with silica fume, clinker and limestone fillers and with and without steel and glass fibers. It can be noted from the Table (10), that there is an increase in compressive, splitting and flexural strengths with fibers addition in SCC.

Table (10): Average Compressive, Splitting and Flexural Strengths Results of SCC at 28 Days

Mix No.	Compressive Strength (MPa)	Splitting Strength (MPa)	Flexural* Strength (MPa)
Mix 1	58.86	3.87	9.01
Mix 2	61.51	4.84	11.09
Mix 3	60.92	4.62	10.22
Mix 4	48.07	2.92	6.39
Mix 5	50.13	3.52	7.29
Mix 6	48.94	3.41	6.97
Mix 7	46.60	2.91	6.06
Mix 8	47.51	3.37	6.46
Mix 9	47.12	3.27	6.21

* Using Third-Point Loading Method with Span length 270 mm

From Table (10) and Fig.(1), fiber inclusions of all types increased the compressive strength, but this increase was not significant in neither of the mixes. Highest 28-day compressive strength was obtained for Mix2 (self-compacting concrete with 0.5% steel fibers and 10% silica fume filler), whereas the lowest value was obtained in Mix9 (self-compacting concrete with 0.1% glass fibers and 10% limestone filler). The splitting and flexural strengths development for various filler and fibers contents of all mixes of self-compacting concrete are presented in Table (10) and Figs. (2) and (3). Results demonstrated that in general, all self-compacting concrete specimens exhibited continuous increase in splitting and flexural strengths with 0.5% and 0.1% steel and glass fibers. Table (10) and Figs. (2) and (4), show that the addition of 0.5% steel fibers and 0.1 glass fibers to the self-compacting concrete at 28 days containing 10% silica fume by weight of cement causes increase in the splitting strengths 25.06% and 19.37% respectively.

Also, it can be seen that the addition of 0.5% steel fibers and 0.1% glass fibers to the self-compacting concrete at 28 days containing 10% clinker powder by weight of cement causes increase in the splitting strengths 20.54% and 16.78% respectively. While, the increases of splitting strength of self-compacting concrete with of 0.5% steel fibers and 0.1 glass fibers and 10% limestone were 15.80% and 12.37% respectively. Also From Table (10) and Figs (3) and (4), it can be seen that the addition of 0.5% steel fibers and 0.1 glass fibers to the self-compacting concrete at 28 days containing 10% silica fume by weight of cement causes increases in the flexural strengths 23.08% and 13.42% respectively. Also, it can be seen that the addition of 0.5% steel fibers and 0.1 glass fibers to the self-compacting concrete at 28 days containing 10% clinker powder by weight of cement causes increase in the flexural strengths 14.08% and 9.07% respectively. While, the increases of flexural strength of self-compacting concrete with of 0.5% steel fibers and 0.1 glass fibers and 10% limestone were 6.6% and 2.47% respectively. Figs (2) and (3) shows the results of the splitting and flexural strengths. Self-compacting concretes with silica fume give better results than those with ground limestone and clinker powder. This behavior is due to the pozzolanic activity of the silica fume which increases when ground because of the higher reactivity related with the higher fineness.

This improvement in the properties of superplastized silica fume self-compacting concrete is attributed to the reduction in capillary porosity caused by the reduction of the water content of the mix. In addition to deflection or dispersion of the cement agglomerates into primary particles. Further, the dispersion system will include particles spaced at a more uniform distance from one to another. Thereby on continuing hydration there is a greater statistical chance of intermeshing of hydration product with fine and coarse aggregates surface to produce a system of higher internal integrity. Also, this improvement in properties is attributed to the pozzlanic reaction of the silica fume with calcium hydroxide, which was liberated during the hydration of cement. It contributed to the densification of concrete matrix, thereby strengthening the transition zone and reducing the micro cracking leading to significant increase in strengths.

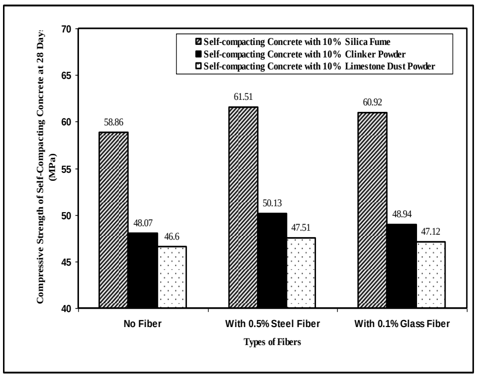

Fig. 1 :The Effect of Fillers and Fiber Types on The Compressive Strength of Self-Compacting Concrete

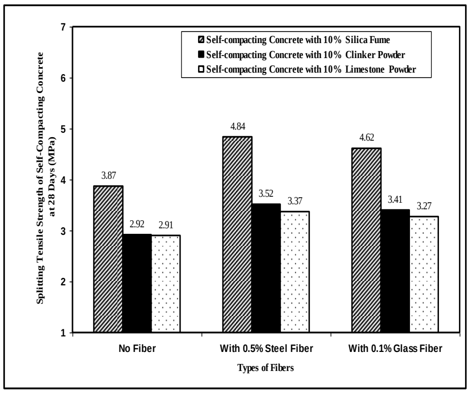

Fig. 2 The Effect of Fillers and Fiber Types on The Splitting Tensile Strength of Self-Compacting Concrete

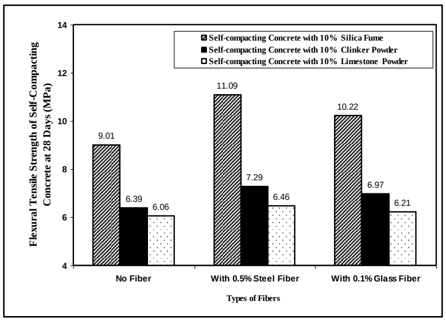

Fig. 3 The Effect of Fillers and Fiber Types on the Flexural Tensile Strength of Self-Compacting Concrete

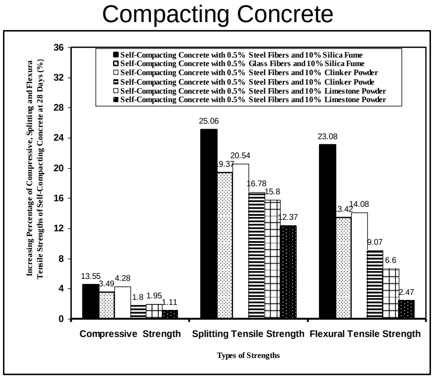

Fig. 4 Increasing Percentages of Compressive, Splitting and Flexural Tensile Strengths of Self-Compacting Concrete at 28 Days (%)

CONCLUSIONS

The study has arrived to the following conclusions:-

1- Fresh concrete properties of SCC such as (workability and flow ability) decreased while hardened properties such as (compressive strength, flexural strength and tensile strength) improved by the addition of fibers.
2- The incorporation of fibers decreases the slump flow of all concrete mixtures containing steel and glass fibers compared control mixes (0% fiber). This can be attributed to the fact that the incorporation fiber increases the internal resistance to flow. Workability tests of SCC mix seemed to be more affected by the inclusion of glass fibers with 0.1% volume fraction compared to steel fibers with 0.5% volume fraction.
3- The higher hardened properties are measured in mixes containing silica fume as a filler with steel fibers . Results demonstrated that in general, all self-compacting concrete specimens exhibited increases in splitting and flexural strengths with 0.5% steel and 0.1% glass fibers.
4- Addition of steel and glass fibers improved the 28-day compressive, splitting tensile and flexural strengths of self-compacting concrete, with steel fiber showing the best performance. The significant gain in splitting tensile/flexural strength due to steel fiber compared to glass fibers can be attributed to the better interlocking characteristics of steel fibers in the concrete matrix.
5- The addition of 0.5% steel fibers and 0.1 glass fibers to the self-compacting concrete at 28 days containing 10% silica fume by weight of cement causes increases in the splitting strengths 25.06% and 19.37% respectively. While, the increases in the flexural strengths were 23.08% and 13.42% respectively.

REFERENCES

1- Al- Mishhadani . Shakir A. , Al-Rubaie. Mays F; "A Data Base for Self-Compacting Concrete in Iraq" Eng &Tech .journal Vol., 27No.6, 2009.

2- B. Krishna Rao., V. Ravindra ; " Steel Fiber Reinforced Self Compacting Concrete Incorporating Class F Fly Ash" International Journal of Engineering Science and Technology Vol. 2 (9), 4936 - 4943. (2010).

3- Abdul Hameed , M, ; " A study of Mix Design and Durability of Self–Compacting Concrete", M.Sc Thesis, Civil Engineering ,King Fahd University of petroleum &Minerals Dhahran, Saudi Arabia , (2005).

4- H. Oucief, M.F.Habita, B.Redjel ; " Hybrid Fiber Reinforced Self-Compacting Concrete: Hardened Properties" International Journal of Civil Engineering. Vol.4, No. 2. (2006).

5- Zoran G., Iva D. and Gordana T "Properties Of Self – Compacting Concrete With Different Types Of Additives " Vol. 6, No 2, pp. 173 – 177,(2008).

6- Buquan m., jenn –chuanch ., chen –any; " Influence Of Fiber Content On Properties Self- Compacting Steel Fiber Reinforced Concrete " journal of the Chinese institute of engineers ; vol. 26,no. 4, pp .523-530(2003).

7- G. Jeenu , U. R. Reji , V. Syam Prakash ; " Flexural Behavior Of Hybrid Fiber Reinforced Self- Compacting Concrete" India. 28 – 29 August (2007).

8- EFNARC, "Specification and Guide Lines For Testing Fresh Self – Compacting Concrete" February,(2002).

9- British Standard Institution; "Method of Testing Hardened Concrete for Other Strength". B.S. 1881, Part 5, London,(1970).

10- ASTM C496-86 ;"Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", Annual Book of ASTM Standard, Philadelphia, Vol. 04-02, pp. 259-262. (1989).

11- ASTM C78-84; "Standard Test Method For Flexural Strength of (Using Simple Beam With Third-Point Loading)", Annual Book of ASTM Standard, Philadelphia, Vol. 04-02, pp.32-34, (1989).