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Mechanical Properties of High Performance Fiber Reinforced Concrete

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ABSTRACT

An experimental work was carried out to produce high performance concrete (HPC) using superplasticizer and silica fume reinforced with fiber. The variables studied were fibers type (steel fibers and polypropylene fibers), aspect ratio of steel fibers (60 and 100) and fiber volume fraction (0.0%, 0.5%, and 0.75%). The effect of fibers on the mechanical properties (compressive strength, splitting tensile and flexural strength, static modulus of elasticity, toughness, and resilience) of normal strength and high performance concrete was also studied. The results show that the optimum dosage of silica fume is 5% as addition by weight of cement with superplasticizer dosage 2 liter/100kg of cement. This dosage of silica fume improves the compressive strength of concrete by about 25% relative to concrete mix without silica fume. The addition of steel fibers causes a slight increase in compressive strength of HPC as fiber volume fraction increases, while the compressive strength decreases as fiber aspect ratio increases. Both splitting tensile and flexural strengths show a significant increase as the fiber volume fraction and aspect ratio increases. The percentage increase in compressive, splitting tensile and flexural strengths for HPC with steel fiber volume fraction 0.75% and aspect ratio 100 at age 60 days is about 9%, 75%, 64%, while for HPC containing polypropylene fiber with volume fraction 0.5% is about 8.5%, 2%, 0% respectively relative to non fibrous HPC.

Keywords: High performance concrete, Steel fibers, polypropylene fibers, Silica fume, Superplasticizer.

الخواص الميكانيكية للخرسانة العالية الاداء المسلحة بألالياف

الخلاصة

يشمل البحث دراسة الخواص الميكانيكية للخرسانة العالية الاداء المسلحة بألالياف. يتضمن البرنامج العملي انتاج خرسانة عالية الاداء بأستخدام الملدن المتفوق وابخرة السيلكا المكثفة والمسلحة بالالياف. المتغيرات التي تم

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دراستها هي نوع الالياف (الالياف الفولاذية والياف البولي بروبلين) , النسبة الباعية للالياف الفولاذية (٦٠, ١٠٠) والنسبة الحجمية للالياف (٠%, ٠،٥%, ٠،٧٥%). تم دراسة تأثير اضافة الالياف على الخواص الميكانيكية (مقاومة الانضغاط, مقاومة الشد الانشطاري, مقاومة الانثناء, معامل المرونة الستاتيكي, الصلابة, الرجوعية) للخرسانة الاعتيادية والعالية الاداء. اظهرت النتائج ان الوزمة المثالية لابخرة السيلكا المكثفة كانت ٥% كأضافة من وزن الاسمنت والوزمة المثالية للملدن المتفوق هي ٢لتر لكل ١٠٠ كغم من الاسمنت . الوزمة لابخرة السيلكا المكثفة ساعدت في تطوير مقاومة الانضغاط للخرسانة حوالي ٢٥% بالمقارنة مع الخلطة الخرسانة بدون ابخرة السيلكا.بينت النتائج ان اضافة الالياف الفولاذية تسبب زيادة طفيفة في مقاومة الانضغاط للخرسانة عالية الاداء عند زيادة النسبة الحجمية للالياف, بينما تقل مقاومة الانضغاط بزيادة النسبة الباعية للالياف. كذلك تبين بأن مقاومة الشد الانشطاري ومقاومة الانثناء تزداد بشكل واضح بزيادة النسبة الحجمية والنسبة الباعية للالياف. حيث كانت نسبة الزيادة في مقاومةالانضغاط والشد الانشطاري ومقاومة الانثناء للخرسانة عالية الاداء الحاوية على نسبة حجمية ٠،٧٥% ونسبة باعية ١٠٠ بعمر ٦٠ يوم حوالي ٩% و ٧٥% و ٦٤% اما بالنسبة للخرسانة عالية الاداء الحاوية على الياف البولي بروبلين بنسبة حجمية ٠،٥% فكانت نسبة الزيادة ٨،٥%و٢% و٠% على التوالي بالمقارنة مع الخرسانة عالية الاداءغير حاوية على الياف.

INTRODUCTION

High Performance Concrete (HPC) is defined as a concrete meeting special combination of performance and uniformity requirements that cannot be achieved routinely using conventional constituents and normal mixing, placing and curing practices[1]. HPC is achieved by using superplasticizer to reduce water-binder ratio and by using supplementary cementing materials, such as silica fume, which usually combines high–strength with high durability[2]. HPC is more brittle than conventional concrete. This problem of brittleness can be solved by adding fibers, the inclusion of short discrete fibers into the concrete mixture can increase HPC compressive strength and durability and makes it more homogeneous and isotropic, since the randomly oriented fibers arrest a micro cracking mechanism and limit crack propagation, thus improving strength and ductility [3]. The addition of steel fibers to concrete not only improves the compressive strength and ductility of concrete, but also improves tensile strength, flexural strength, impact strength and toughness. The improved toughness in compression imparted by fibers is useful in preventing sudden and explosive failure under static loading and in absorption of energy under dynamic loading [4]. Polypropylene fibers are synthetic fiber with low density, fine diameter and low modulus of elasticity. It has some special characteristics, such as high strength, ductility and durability, abundant resources, low cost, and easily physical and chemical reformations according to certain demands[5].

The experimental results for steel fiber reinforced concrete specimens were compared with the results from analytical models based on the regression analysis by other researchers [6]. The variables considered were, the grade of concrete [normal strength (35 MPa), moderately high strength (65 MPa), and high strength concrete (85 MPa]; volume fractions of the steel fibers (0.0, 0.5, 1.0, and 1.5%). They concluded that the addition of steel fibers caused a small increase (less than 10%) in the compressive strength, modulus of elasticity and Poisson's ration for various grades of concrete (35, 65 and 85 MPa), while there was a significant increase in the tensile strength, (splitting tensile strength and modulus of rupture) due to the addition of steel fibers by about 40%, also the post – cracking response significantly enhanced with fiber dosages. They also found that the proposed strength prediction models can be used for assessment of strength properties of steel fiber reinforced concrete based on the grade of concrete and fibers.

Other researchers [7] carried out an experimental study on tensile strength and durability characteristics of high performance fiber reinforced concrete. The variables investigated were fiber volume fraction (V_f) (0%, 0.5%, 1% and 1.5% with an aspect ratio of 80), silica fume replacement level (5% and 10% by weight of cement) and matrix composition (water/cement ratios ranging from 0.25 to 0.40). It was found that the addition of steel fibers to HPC improves its ductility, post-cracking load carrying capacity, and energy absorption capacity. They also concluded that using steel fibers up to 1.5 percent volume fraction resulted in an increase of about 38% and 56% in flexural tensile strength, and splitting tensile strength, respectively compared with a plain concrete matrix.

EXPERIMENTAL WORK

Materials:

Cement

Ordinary Portland local cement from Tasluja factory was used in all mixes throughout this research. The physical and chemical properties of this cement are presented in Tables (1) and (2) respectively. The test results indicate that the cement conforms to the provisions of Iraqi specification No.5/1984.

Fine Aggregate

AL-Ukhaider natural sand of maximum size 4.75 mm was used. Its gradation lies in zone (2), as shown in Table (3).The gradation and sulfate content results of fine aggregate were within the requirements of the Iraqi specification No. 45/1980.

Coarse Aggregate

Normal weight, crushed aggregate of maximum size 10 mm was used. It was brought from AL-Nabai region. The grading and sulfate content of coarse aggregate conform to the requirements of Iraqi specification No. 45/1980, as shown in Table (4).

Admixtures

Two types of concrete admixtures were used in this work:

a) Superplasticizer

A high range water reducing admixture (HRWRA) was used to produce the HPC mix. It is commercially known as TopFlow SP 703. The dosage recommended by the manufacturer was (0.75-2) liters/100 kg of cementations material. This type of admixture conforms to the ASTM C494-04[8]. Table (5) shows the main properties of the superplasticizer.

b) Silica Fume

Silica fume produced by Sika company was used as pozzolanic admixture. The ACI committee 234 [9] instructions were followed to determine the optimum dosage of silica fume. The physical requirement and pozzolanic activity index are given in Table (6), while the chemical oxide compositions of silica fume is given in Table (7). The results show that silica fume used in this investigation conforms to the requirements of ASTM C1240-05[10] specifications.

Fibers

Two types of fibers were used in this investigation:

a) Steel Fibers

Hooked end steel fibers which are known commercially as Dramix-Type ZC, was used in this work. These fibers were 50 mm long and 0.5 mm diameter (aspect ratio, l/d = 100). The density of the steel fibers is 7850 kg/m^3, and the ultimate tensile strength for individual fibers is 1117 MPa.

Another type of hooked steel fibers which are commercially known as Sika Fiber SH 60/30, were also used. These fibers were 30 mm long and 0.5 mm diameter (aspect ratio, l/d = 60) with ultimate tensile strength for individual fibers of 1180 MPa. The density of the steel fibers is 7800kg/m^3.

b) Polypropylene Fibers

High performance monofilament polypropylene fibers were used in this work. Table (8) indicates the typical properties of the used polypropylene fibers.

Mixing Water

Ordinary potable water was used for mixing and curing all concrete mixes in this investigation.

Concrete Mixes

Reference concrete mix was designed in accordance with ACI 211.1-9[11] to obtain a minimum compressive strength of 40MPa at 28days without any admixtures. The mix proportions are 1: 1.19: 1.8 by weight with w/c ratio of 0.43 to obtain a slump of 100±5 mm. Several trail mixes were carried out to determine the optimum content of silica fume and the optimum dosage of superplasticizer with the same workability (slump 100 ±5) in order to have a mix with compressive strength higher than 70 MPa. Finally, discrete steel fibers with different aspect ratios (100 and 60) and volume fractions (0.5% and 0.75%) were added to the concrete mixes. Polypropylene fibers with volume fraction 0.5% were also used.

Mixing of Concrete

The mixing process was performed in a pan type mixer of (0.1m^3) capacity. The dry constituents of the reference concrete mix (without superplasticizer and silica fume) were placed in the mixer and mixed for about 1.5 minutes. Then, the required quantity of water was added, the whole mix ingredients were mixed for about 2 minutes until a homogenous concrete mix was obtained. For high performance concrete, the required quantity of silica fume was mixed with the cement before the addition to the mixer to ensure homogeneous dispersion of silica fume. The dry constituents (cement, silica fume, sand, gravel) were placed in mixer and mixed for about 1.5 minutes to attain a uniform dry mix. The water content of the superplasticizer was deduced from the required quantity of water. Seventy percent of the required amount of water was added to the mixer and mixed for about 1minute, while 30% of the mixing water was added to the HRWRA and added gradually to the mix. The whole constituents were mixed for further 2 minutes. The same procedure of mixing was carried out for the fiber reinforced concrete mixes, except that the fibers were added by hand after all mix ingredient was thoroughly mixed, and the mixing was then continued for (2-3) minutes to obtain a uniform distribution of fibers throughout the concrete mix.

Preparation of Specimens

A number of specimens were prepared, cured for 60 days then tested to study some properties of high performance and normal strength fiber reinforced concrete in comparison to non fibrous high performance and normal strength concrete. These properties are workability, compressive strength (using cubes of 100 mm) , splitting tensile strength (using cylinders of 100 x 200 mm), modulus of elasticity (using cylinders of 150 x 300mm) , modulus of rupture, toughness and resilience (using prisms of 100 x 100 x 400 mm).

Curing

After demolding the specimens, they were continuously cured by water. The specimens were cured for 60 days and after that, they were kept in the laboratory to be normally dried until the time of testing.

RESULTS AND DISCUSSIONS

Selection of Mix Proportions for HPC

The results of designed reference concrete mix with mix proportions 1:1.19:1.80 by weight of cement with cement content 525 kg/m^3, w/c=0.43 containing different dosages of superplasticizer are shown in Table (9) and Figures (1). The water/cement ratio was adjusted to obtain the same workability of reference mix (100±5 mm). It can be observed that the HRWRA leads to a considerable improvement in both 7 and 28 days compressive strength and allows a reduction in water cement ratio in comparison with the reference mix. This may be attributed to the mode of action of the superplasticizer(12). The results indicated that the optimum dosage of HRWRA is 2liters per 100 kg of cement which led to water reduction of about 34% and maximum compressive strength of 56MPa at 28 days. Table (10) and Figure (2) show the details of concrete mixes with mix proportions (1:1.19:1.80) containing silica fume used as an addition by weight of cement with 5% and 10% dosages and for both dosages of HRWRA (1.5 and 2 liter/100 kg cement). The results show that the compressive strength increases with the addition of silica fume. This is due to the physical and chemical effect of silica fume on the strength of concrete (13, 14). The maximum compressive strength obtained is for mixe with 5% silica fume as addition by weight of cement and HRWRA 2 liter/100kg of cement, so the optimum dosage of silica fume is 5% as addition by weight of cement. This is because when the silica fume percentage in the concrete is increased gradually, it reaches a point called an optimum point, where the silica fume content is exactly required for reacting with the present calcium hydroxide, or it may be because of more and dense C-S-H gel acts as an impervious layer which may prevent the water to enter through it and, thereby, preventing further hydration. Therefore, the excess silica fume added beyond this limit remains as it is and does not act as a binder; hence it will cause a reduction in strength (15).

Mechanical Properties of High Performance Fiber Reinforced Concrete
a) Compressive Strength

The compressive strength test results for the selected NSC mix (1:1.19:1.80 by weight, w/c=0.43) and HPC mix (1:1.19:1.80 by weight, w/c=0.295, HRWRA 2 liter/100 kg of cement and SF 5% as addition by weight of cement) with different type, volume fractions, aspect ratio of fiber are presented in Table (11 and 12) and Figures (3 and 4). Generally, the results illustrate that the inclusion of fibers with different types, volume fractions and aspect ratios, especially in HPC mix, causes a slight increase in the compressive strength of concrete for all ages (7, 28 and 60 days). At constant aspect ratio (100), the compressive strength increases with the increase in steel fiber volume fraction from 0.5% to 0.75%, whereas the workability decreases when steel fiber content is increased to 1%, the workability and compressive strength decreased in comparison with concrete mix containing fiber content 0.75%, and the mixture become very difficult to mix and cast. It can be also observed that for constant fiber volume fraction (0.75%), the workability and the compressive strength of the mix increase as the aspect ratio of fibers decreases from 100 to 60. This is because that short fibers become active earlier than the longer fibers to control the initiation and propagation of initial micro-cracks. Thus, short fibers influences to a great degree the early part of matrix cracking, thereby enhancing the strength of the composit as compared to longer fibers(16). It can be noticed that the compressive strength of polypropylene fibers increases relative to non fibrous mixture.

Thomas and Ramaswamy(6)proposed the following equation to calculate the compressive strength of hooked steel fiber reinforced concrete with different volume fractions, the compressive strength ranged from 35MPa to 85MPa.

$$f_{cuf}=f_{cu}+0.014* f_{cu} *RI_v+1.09*RI_v \quad ..... (1)$$

Where : f_{cu} , f_{cuf} : cube compressive strength of non fibrous concrete and fibrous reinforced concrete, respectively, (MPa).
RI_v : fiber reinforcing index expressed as follows:

$$RI_v=V_f * L_f /D_f \quad ….. (2)$$

where: V_f , L_f , D_f are fiber volume fraction, fiber length in (mm) and fiber diameter in (mm)respectivily.
Ezeldin and Balaguru(17) suggests the following equation to calculate the compressive strength of steel fiber concrete containing hooked steel fibers with different volume fractions and aspect ratios. The compressive strength range from 35MPa to 85MPa.

$$f'_{cf} = f'_c + 3.51 * RI_w \qquad \text{.... (3)}$$

where:

f_c', f_{cf}' : cylinder compressive strength of non fibrous concrete and fibrou reinforced concrete, respectively, (MPa).

RI_w : fiber reinforcing index which can be expressed as follows:

$$(RI_w) = w_f * (L_f / D_f) \qquad \text{... (4)}$$

where:

W_f : weight fraction of fiber calculated as following:

$$w_f = \frac{\gamma_f}{\gamma_{cf}} * V_f \qquad \text{...(5)}$$

γ_f = density of fiber and γ_{cf} = density of fibrous concrete.

Nataraja (cited by reference [18]) carried out an experimental research on the compressive strength of steel fiber concrete containing crimped steel fibers with reinforcing index (RI_w) ranged from 0.28 to 0.82 and compressive strength ranging from 29 MPa to 43 MPa. From this study, the following equation was gained:

$$f_{cuf} = f_{cu} + 2.1604 * (RI_w) \qquad \text{..... (6)}$$

where:

f_{cu} , f_{cuf} : cube compressive strength of non fibrous concrete and fibrous reinforced concrete, respectively, (MPa).

RI_w : fiber reinforcing index calculated from Eq.(4).

The following equation obtained by **Carreira and chu (**cited by references [18]) to calculate the compressive strength of fiber reinforced concrete:

$$f_{cuf} = f_{cu} + 2.35 * (RI_v) \qquad \text{... (7)}$$

where:

f_{cu} , f_{cuf} : cube compressive strength of non fibrous concrete and fibrous reinforced concrete, respectively, (MPa).

RI_v : fiber reinforcing index calculated from Eq.(2).

The results presented in Table (14) show that there is a good agreement between the experimental compressive strength results and the calculated results using proposed equation of Ezelden and Balaguru[17]. This is because Ezelden and balaguru[17] studied steel fiber concrete containing hooked steel fibers with different volume fractions and aspect ratios.

b) Splitting Tensile Strength

Table (13) and Figure (5) illustrate the splitting tensile strength results for different concrete mixes used throughout this work. Generally, the addition of steel fibers to all concrete mixes improves the splitting tensile strength significantly relative to the reference specimens (without fiber). It can be seen that the percentage increase in splitting tensile strength for HPC increases as the fiber volume fraction and aspect ratio increase. The percentage increase for HPC containing steel fibers with aspect ratio 100 is about 56% and 75% for volume fractions 0.5% and 0.75%, respectively relative to non fibrous HPC. For fiber volume fraction 0.75%; the percentage increase is about 59% and 75% for fiber aspect ratio 60 and 100, respectively relative to non fibrous HPC. The results also indicated that the polypropylene fiber has less effect on the splitting tensile strength of HPC in comparison with steel fibers.
Thomas and Ramaswamy[6] suggested the following equation to calculate the splitting tensile strength for fiber reinforced concrete:

where:

$$F_{tf} = 0.63 * (f_{cu})^{0.5} + 0.288 * (f_{cu})^{0.5} * RI_v + 0.052 * RI_v \quad .. (8)$$

F_{tf} , f_{cu} are splitting tensile strength for concrete with steel fibers in (MPa) and cube compressive strength for non fibrous concrete in (MPa). RI_v fiber reinforcing index calculated from Eq.(2)
Ramadoss and Nagamani[7]proposed the following equation inorder to calculate the splitting tensile strength of HPC containing crimped steel fibers with aspect ratio 80 and different volume fractions.

Where:

$$F_{tf} = F_t + 0.638 * (RI_w) \quad .... (9)$$

F_{tf}, F_t are splitting tensile strength for fibrous and non fibrous concrete respectively in (MPa). RI_w : fiber reinforcing index calculated from Eq.(4).
Table (13) indicates that the experimental results are in a good agreement with the calculated values predicted by Thomas and Ramaswamy [6].

c) Flexural Strength (Modulus of Rupture)

The flexural strength test results for all type of concrete mixes are presented in Table (15) and Figure (6). The results demonstrate that using steel fibers significantly improves the flexural strength of all concrete mixes (NSC and HPC). Flexural strength significantly increases with the increases in fiber volume fraction and aspect ratio. The percentage increase for NSC containing 0.5% steel fibers with aspect ratio 100 was about 52% relative to non fibrous NSC. The percentage increase for HPC containing steel fibers with aspect ratio 100 was about 22% and 64% for fiber volume fractions 0.5% and 0.75%, respectively. For fiber volume fraction 0.75%, the percentage increase was about 12% and 64% for fiber aspect ratios 60 and 100, respectively relative to nonfibrous HPC.

Thomas and Ramaswamy[6] suggested the following equation to calculate the flexural strength for fiber reinforced concrete:

$$F_{flf} = 0.97*(f_{cu}')^{0.5}+0.295*(f_{cu}')^{0.5}RI_v+1.117*RI_v \quad \ldots (10)$$

where:
F_{flf} : flexural strength for concrete with steel fibers,(MPa), f_{cu}' : cube compressive strength for non fibrous concrete, (MPa), RI_v : fiber reinforcing index calculated from Eq.(2).

The flexural strength for high performance fiber reinforced concrete was calculated by **Ramadoss and Nagamani** [7] as follows:

$$F_{flf} = F_{fl} + 0.604 * (RI_W) \quad \ldots (11)$$

Where:
F_{flf} : flexural strength for concrete with steel fibers, (MPa), F_{fl} : flexural strength of non fibrous concrete, (MPa) , RI_w : fiber reinforcing index calculated from Eq.(4).
It can be concluded from Table (15) that the experimental results are in a good agreement with the calculated values using equation of Thomas and Ramaswamy[6]. This is because Thomas and Ramaswamy [6] used hooked steel fiber.

d) Static Modulus of Elasticity

Table (16) and Figure (7) show the results of static modulus of elasticity for all concrete mixes used in this work. Generally, it can be concluded that the addition of fibers to concrete slightly increases the static modulus of elasticity. This may be because the modulus of elasticity was calculated to the stress corresponding to 40% of the ultimate load, so it is determined prior to concrete cracking; therefore, the fibers were not activated [18].

e) Toughness Indices

The values of toughness indices for all tested prism specimens are presented in Table (16) and Figures (8, 9, and 10). The results show that toughness indices of fiber reinforced concrete significantly enhanced in comparison with non fibrous concrete. Also, toughness indices increase as fiber volume fraction and aspect ratio increase. This may be attributed to the fact that under increasing loads, once the cracks become quite wide in the post-peak region, the short fibers are pulled out, and their structural role is relatively diminished compared to the longer fibers. The longer fibers can, however, arrest the propagation of these macro-cracks and, by their gradual pull out mode of failure, substantially improve the toughness of composite [16]. High performance concrete prism reinforced with polypropylene fibers failed suddenly, thus its toughness is similar to that of non fibrous concrete. This may be attributed to the short length of fibers used in this research.

f) Resilience

The values of resilience for all tested prism specimens are presented in Table (16) and Figure (11). The results show that the addition of steel fibers increases the resilience as volume fraction and aspect ratio of fibers increase. The percentage increase for HPC containing long steel fibers (aspect ratio 100) with volume fraction 0.5% and 0.75% is about 6% and 39%, respectively, whereas the percentage increase for HPC with 0.75% fiber content is 1.5% and 39% for fiber aspect ratios 60 and 100, respectively relative to non fibrous HPC.

CONCLUSIONS

From the experimental results presented in this study, the following conclusions can be drawn:

1- The optimum dosage of silica fume is 5% as an addition by weight of cement with HRWRA dosage 2 liter/100kg of cement. This dosage of silica fume improves the compressive strength of concrete by about 25% relative to concrete mix without silica fume.
2- The addition of fibers to both NSC and HPC causes a reduction in the workability of concrete mix. The reduction in workability increases as the fiber volume fraction and aspect ratio increase. The percentage of reduction in workability is about 38% for concrete mix containing steel fibers with volume fraction 0.75% and aspect ratio 100.
3- The addition of steel fibers causes a slight increase in the compressive strength and modulus of elasticity of HPC as the fiber volume fraction increases, while these properties decrease as the fiber aspect ratio increases. Both splitting tensile and flexural strengths show a significant increase as the fiber volume fraction and aspect ratio increase. The percentage increases in compressive, modulus of elasticity, splitting tensile and flexural strengths for HPC with fiber volume fraction 0.75% and aspect ratio100 at age 60 days is about 9%, 3%, 75%, 64%, respectively relative to non fibrous HPC.
4- The toughness indices of all fiber reinforced concrete are considerably enhanced over that of non fibrous concrete. Toughness indices increase as fiber volume fraction and aspect ratio are increased
5- The resilience of non fibrous HPC and NSC improved with the addition of fiber. The resilience increases as the fiber volume fraction and aspect ratio are increased. The percentage increase for HPC containing long steel fibers (aspect ratio 100) with volume fraction 0.5% and 0.75% at age 60 days is about 6% and 39%, respectively, while the percentage increase for HPC with 0.75% fiber content is 1.5% and 39% for fiber aspect ratios 60 and 100, respectively relative to non fibrous HPC.

REFERENCES

[1].Mehta, K.P., and Monteiro, P.J.M., “Concrete Microstructure, Properties and Material”, Third Edition, Mc Graw-hill, London, 2006, pp.471 and 480.

[2].Ramadoss, P., and Nagamani, K., “Durability Characteristics of High-Strength Steel Fiber Reinforced Concrete”, New Building Materials and Construction World, Nov. 2008.
http://www.nbmcw.com/articles/concrete/495-durability-characteristics-of-high-strength-steel-fiber-reinforced-concrete.html

[3].Sarsam, K., and Al-Azzawi, Z.M., "Mechanical Properties of High-Strength Fiber Reinforced Concrete", Engineering & Technology Journal, Vol. 28, No.12, 2010, pp. 2442-2453.
[4].Ramadoss, P., Prabakaran, V., and Nagamani, K., "Toughness of Steel Fiber Reinforced Silica Fume Concrete Under Compression", International Journal of Applied Engineering Research, Report, Vol.4, No.2, Feb. 2009, PP.295-308.
[5].Mtasher, R.A., Abbas, M.A., and Ne'ma, N.H., "Strength Prediction of Polypropylene Fiber Reinforced Concrete", Engineering & Technology Journal, Vol.29, No.2, 2011, pp. 305-311.
[6].Thomas, J. and Ramaswamy, A., "Mechanical Properties of Steel Fiber-Reinforced Concrete", Journal of Materials in Civil Engineering, Vol. 19, No. 5, May 2007, pp.385-392.
[7].Ramadoss, P., and Nagamani, K.,"Tensile Strength and Durability Characteristics of High-Performance Fiber Reinforced Concrete", The Arabian Journal for Science and Engineering, Vol. 33, No. 2B , Oct. 2008, pp.307-319.
[8].ASTM C494-04, "Standard Specification for Chemical Admixtures for Concrete", Annual Book of ASTM Standards, American Society for Testing and Materials, Vol. 04-02, 2007, pp.1-9.
[9].ACI committee 234(ACI-234R-06), "Guide For Use of Silica Fume in Concrete", ACI Manual of Concrete Practice, Part1, 2006.
[10].ASTM C 1240 – 05, "Standard Specification for Silica Fume Used in Cementitious Mixtures", Annual Book of ASTM Standards, American Society for Testing and Materials, Vol. 04-02, 2007, pp.1-8.
[11].ACI Committee 211.1-91, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete", Reapproved 2002.
[12].Neville, A.M., "Properties of Concrete", Longman Group, Ltd., 4th and Final Edition, 2005, p. 257, 669, 670.
[13].Vaske, N.R., Campagnolo, J.L., and Dal molin, D.C.C., "Relationship between the Compressive Strength of Silica Fume Mortar Applied to the Substratum and the One Obtained in Standardized Cylindrical Test Specimens", IBRACON Structures and Materials Journal , Vol. 3 , No. 3, Sep. 2010 , pp. 322-345.
[14].Yazıcı, H.,"The Effect of Curing Conditions on Compressive Strength of Ultra High Strength Concrete with High Volume Mineral Admixtures", Building and Environment Vol.42, 2007, pp. 2083–2089.
[15].Muthupriya, P., Subramanian, K., Vishnuram, B.G.,"Experimental Investigation on High Performance Reinforced Concrete columns with Silica Fume and Fly Ash as Admixtures", Asian Journal of Civil Engineering (Building and Housing), Vol. 12, No. 5, 2011, PP. 597-618.
[16].Bhargava, P., Sharma, U., and Kaushik, S.,"Compressive Stress-Strain Behaviour of Small Scale Steel Fiber Reinforced High Strength Concrete Cylinders", Journal of Advanced Concrete Technology, Vol. 4, No.1, Feb. 2006, pp.109-121.
[17].Ezeldin, S., and Balaguru, P.N.," Normal- and High-Strength Fiber-Reinforced Concrete Under Compression", Journal of Materials in Civil Engineering, Vol. 4, No. 4, Nov. 1992, pp. 415-429.

[18].Yu-Chen Ou, Mu-Sen Tsai, Kuang-Yen Liu and Kuo-Chun Chang; "Compressive Behaviour of steel –Fiber- Reinforced Concrete With a High Reinforcing Index", Journal of Materials in Civil Engineering; Vol. 24, No. 2, Feb. 2012, pp.207-215.

Table (1) Physical properties of cement*.

Physical properties	Test results	Limits of Iraqi Specification No.5/1984
Specific surface area (Blaine method), m2/kg	372	≥ 230
Soundness (Auto clave), %	0.01	≤ 0.8
Setting time (Vicat's apparatus) Initial setting time, hrs: min. Final setting time, hrs: min.	 3:58 4:50	 ≥ 45 min ≤ 10 hrs
Compressive strength 3days, N/mm2 7days, N/mm2	 29.80 34.84	 ≥ 15 ≥ 23

***** Physical tests were carried out by the National Center for Construction Laboratories and Researches (NCCLR).

Table (2) Chemical composition and main compounds of the cement used throughout this investigation*.

Oxide composition	Abbreviation	Content (percent)	Limit of Iraqi Specification No.5/1984
Lime	CaO	62.44	---
Silica Dioxide	SiO_2	20.25	---
Alumina Trioxide	Al_2O_3	4.73	---
Iron Oxide	Fe_2O_3	4.32	---
Magnesia oxide	MgO	1.5	≤5.0%
Sulphate	SO_3	1.88	≤ 2.8% If C_3A > 5%
Loss on Ignition	L. O. I.	3	≤4.0%
Insoluble residue	I. R.	0.8	≤ 1.5%
Lime saturation factor	L. S. F.	0.93	0.66- 1.02
Main compounds (Bogue's equations)			
Tricalcium Silicate	C_3S	56.90	---
Dicalcium Silicate	C_2S	15.21	---
Tricalcium Aluminate	C_3A	5.23	---
Tetracalcium alumino-Ferrite	C_4AF	13.13	---

*Chemical tests were carried out by the National Center for Construction Laboratories and Researches (NCCLR).

Table (3) Fine aggregate properties* .

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No. 45/1980
14	100	100
10	100	85-100
5	15.3	0-25
2.36	0.53	0-5
Specific gravity = 2.66		
Sulfate content = 0.08% (Iraqi specification requirement ≤ 0.1%)		
Absorption = 0.52%		

* Properties of fine aggregate were performed by the National Center for Geological Survey and Mines

Table (4) Coarse aggregate properties*.

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No.45/1980, zone 2
4.75	100	90-100
2.36	90.15	75-100
1.18	74.22	55-90
0.60	51.37	35-59
0.30	19.3	8-30
0.15	3.79	0-10
Fineness modulus = 2.61		
Specific gravity =2.65		
Sulfate content =0.08% (Iraqi specification requirement ≤ 0.5%)		
Absorption = 0.75%		

* Properties of coarse aggregate were performed by (NCCLR)

Table (5) Technical data of the superplasticizer used in this investigation*.

Technical description	Properties
Appearance	Dark Brown/Black liquid
Specific gravity	1.235 at 25±2°C
Chloride content	Nil.

Storage life	**Up to 1 year in unopened containers.**

*According to manufacturer.

Table (6) Physical requirements and pozzolanic activity index for condensed silica fume(SF)*.

Physical properties	SF	ASTM C1240-05 limits
Specific surface area, min, (m^2/g)	20	≥ 15
Strenght activity Index with Portland cement at 7days, min. percent of control.	122	≥ 105
Percent retained on 45µm (No.325), max, %	9	≤ 10

*Tests were carried out by Building Research Center

Table (7) Chemical composition for silica fume * .

content(%)	ASTM C1240-05 limitations
90.51	≥ 85
0.60	–
2.32	–
0.15	–
0.58	–
0.3	–
0.01	–
1.26	–
0.10	–
0.35	≤ 4
3.82	≤ 6

*Test was carried out at by the National Center for Geological Surveyand Mines

Table (8) Properties of the used polypropylene fibers.

Chemical Base	100 % Polypropylene Fibers
Specific gravity	0.91 g/cm^3
Fiber length	12 mm
Fiber Diameter	18 micron
Water Absorption	Nil
Melting point	160 ^{o}C
Ignition point	365 ^{o}C
Acid Resistance	High
Alkali Resistance	100 %
Tensile strength	(300-400) MPa

Chloride content	Nil
Young's modulus	(3500-3900) MPa
Surface area	250 m^2/kg

*According to manufacturer

Table (9) Details of trail mixes for various dosages of HRWRA.

Mix proportions by weight	Dosage of HRWRA of (liter/100kg cement)	w/c ratio	Slump (mm)	Water reduction (%)	Compressive strength (MPa)		Increase in strength with respect to reference mix (%)	
					7days	28days	7days	28days
1:1.19:1.8	0	0.43	105	-	27.73	39.26	-	-
	1	0.32	103	25.6	37.62	51.25	35.66	30.53
	1.5	0.31	100	28.0	45.44	54.90	63.86	39.83
	2	0.285	95	33.7	40.10	55.60	44.60	41.62
	2.5	0.29	*	32.6	-	-	-	-

* Stiff mix

Table (10) Details of trial mixes for various dosages of silica fume as addition by weight of cement.

Mix proportions by weight	HRWRA of (liter/100kg cement)	Silica fume (% as addition by weight of cement)	w/c ratio	Slump (mm)	Compressive strength (MPa)		Increase in strength with respect to reference mix(%)	
					7days	28days	7days	28days
1:1.19:1.8	1.5	0	0.31	100	45.44	54.90	-	-
	1.5	5	0.32	96	59.17	67.2	30.21	22.40
	1.5	10	0.33	98	53.49	56.10	17.71	2.185
	2	0	0.285	95	40.10	55.60	-	-
	2	5	0.295	105	64.68	69.44	61.29	24.89
	2	10	0.305	105	44.62	59.46	11.27	6.94

Table (11) Details of the selected HPC mix with various volume fraction, aspect ratios and types of fiber.

Mix proportions by weight	HRWRA (liter/ 100 kg of cement)	Silica fume (% as addition by weight of cement)	W/C ratio	Type of fiber	aspect ratio	Fiber volume fraction	Slump (mm)	Slump reduction (%)	Compressive strength (MPa)		Increase in strength with respect to reference mix(%)	
									7days	28days	7days	28days
1: 1.19: 1.8	2	5	0.295	-	-	-	105	-	64.68	69.44	-	-
				Steel	100	0.5	75	28.5	67.85	73.5	4.901	5.846
				steel	100	0.75	65	38.1	68.5	75.25	5.9	8.36
				Steel	100	1	40	61.9	65.5	71.3	1.26	2.67
				Steel	60	0.75	85	19	69.8	78.86	7.91	13.56
				PPF*		0.5	95	9.5	68	74.1	5.13	6.71

*Polyproplene fiber

Table (12) Compressive strength test results for various concrete Mixes at age 60 days.

Mix symbol	Mix proportions	w/c or w/cm ratio	Type of fibers	aspect ratio of fibers	Vf * (%)	Fcu' (MPa)
NSC	1: 1.19: 1.8 by weight	0.43	-	-	-	55
0.5SF100-NSC			Steel fiber	100	0.5	62.6
HPC	1: 1.19: 1.8 byweight, 2Liter/100kg HRWRA, silica fume 5% as addition by weight of cement	0.295	-	-	-	72.6
0.5SF100-HPC			Steel fiber	100	0.5	75
0.75SF100-HPC				100	0.75	79.1
0.75SF60-HPC				60	0.75	83.3
0.5PP-HPC			PPF**		0.5	78.8

* Volume fraction of fibers. ** Polypropylene fiber

Table (13) Splitting tensile strength test results for various concrete mixes at age 60 days.

Mix symbol	F_t (MPa)	Theoretical splitting tensile strength (MPa)		Experimental / Theoretical ratio	
		Thomas and Ramaswamy	Ramadoss and Nagamani	Thomas and Ramaswamy	Ramadoss and Nagamani
NSC	3.88	4.67	3.88	0.83	1

0.5SF100-NSC	**6.27**	**5.76**	**4.92**	**1.08**	**1.27**
HPC	**5.1**	**5.36**	**5.1**	**0.94**	**1**
0.5SF100-HPC	**7.96**	**6.62**	**6.14**	**1.2**	**1.29**
0.75SF100-HPC	**8.9**	**7.24**	**6.66**	**1.22**	**1.33**
0.75SF60-HPC	**8.1**	**6.49**	**6.04**	**1.24**	**1.34**
0.5PP-HPC	**5.2**			**-**	**-**
average				**1.09**	**1.207**
Standard deviation				**0.169**	**0.162**

Table (14) Experimental /theoretical ratio of compressive strength for various concrete mixes used in this investigation.

Mix symbol	Experimental Compressive strength (MPa)	Experimental/theoretical ratio			
		Thomas and Ramaswamy	Ezeldin and Balaguru	Nataraja	Carreira and chu
NSC	**55**	**1**	**1**	**1**	**1**
0.5SF100-NSC	**62.5**	**1.12**	**1.02**	**1.069**	**1.114**
HPC	**72.65**	**1**	**1**	**1**	**1**
0.5SF100-HPC	**75**	**1.017**	**0.95**	**0.984**	**1.016**
0.75SF100 -HPC	**79.1**	**1.065**	**0.97**	**1.015**	**1.063**
0.75SF60 -HPC	**83.35**	**1.13**	**1.07**	**1.099**	**1.131**
average		**1.055**	**1.005**	**1.028**	**1.054**
Standard deviation		**0.059**	**0.041**	**0.045**	**0.058**

Table (15) Flexural strength test results for various concrete mixes at age 60 days.

Mix symbol	F_{fl} (MPa)	Theoretical flexural strength (MPa)		Experimental / Theoretical ratio	
		Thomas and Ramaswamy	Ramadoss and Nagamani	Thomas and Ramaswamy	Ramadoss and Nagamani
NSC	5.94	7.19	5.94	0.82	1
0.5SF100-NSC	9.06	8.84	6.98	1.024	1.29
HPC	9.0	8.26	9	1.08	1
0.5SF100-HPC	11.01	10.08	10.04	1.09	1.096
0.75SF100-HPC	14.8	10.99	10.56	1.34	1.4
0.75SF60-HPC	10.11	9.9	9.94	1.02	1.017
0.5PP-HPC	9.0			-	-
average				1.06	1.13
Standard deviation				0.168	0.172

Table (16) Static modulus of elasticity, Toughness indices and Resilience for various concrete mixes at age 60 days.

Mix symbol	E_c (GPa)	Toughness indices			Resilience* (N.mm)
		I_5	I_{10}	I_{20}	
NSC	32.54	1	1	1	3168
0.5SF100-NSC	34.34	5.8	11.8	18.8	4977
HPC	43.27	1	1	1	5550
0.5SF100-HPC	43.69	5.6	10.2	15.3	5908
0.75SF100-HPC	44.63	5.9	12.4	20.5	7707
0.75SF60-HPC	45.27	5.5	8.0	10.2	5637
0.5PP-HPC	44.01	1	1	1	6187

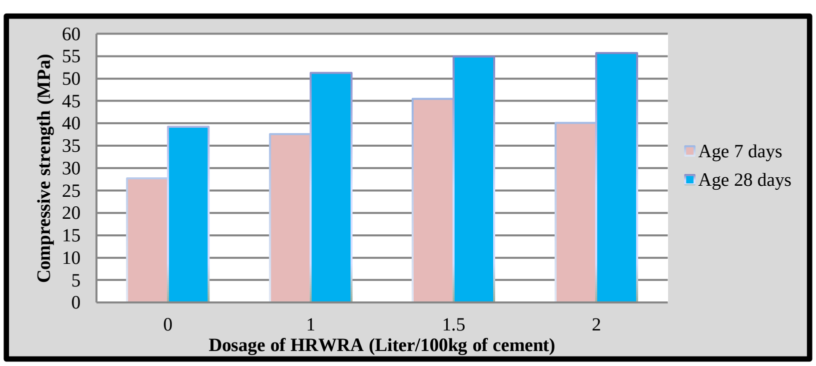

Figure (1) Effect of dosage of HRWRA on the compressive strength of concrete.

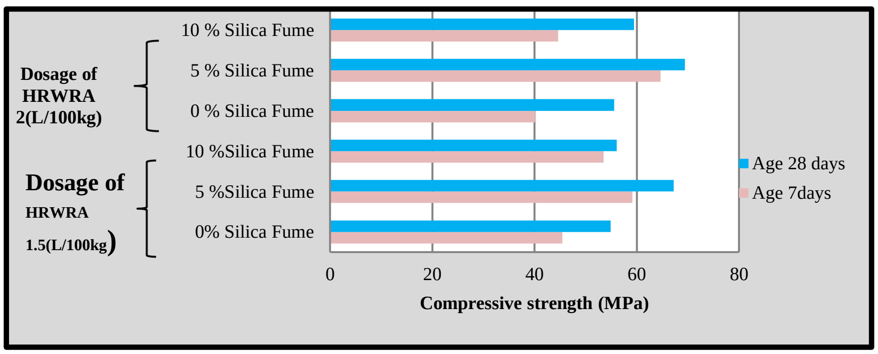

Figure (2) Effect of dosage of silica fume on the compressive strength of concrete.

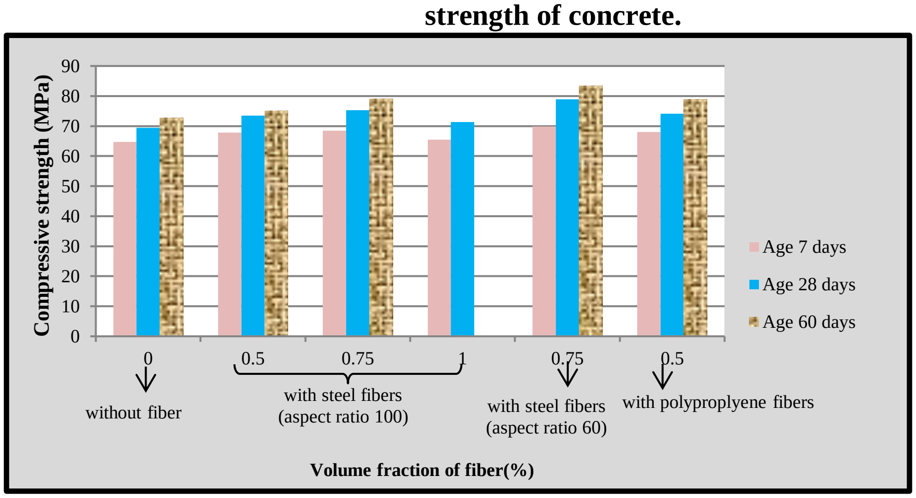

Figure (3) Compressive strength at different ages for HPC mixes with various types, volume fractions and aspect ratios of fibers.

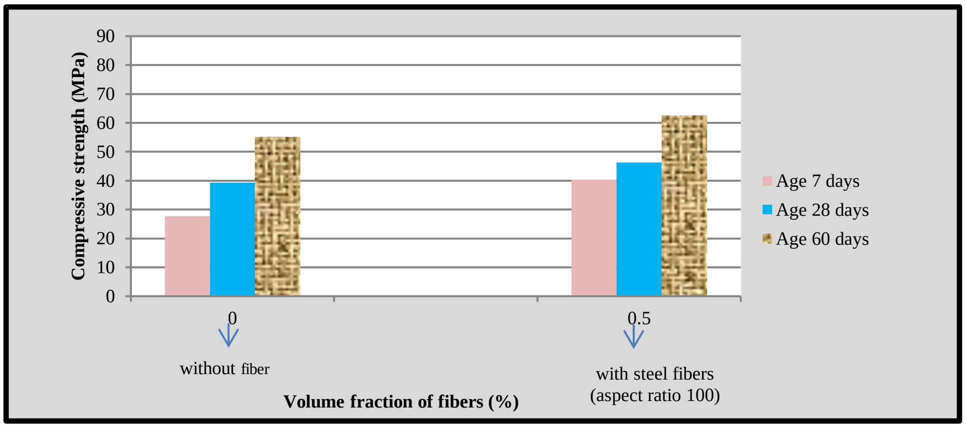

Figure (4) Compressive strength at different ages for normal strength Concrete mixes (not containing HRWRA and silica fume) with and without steel fibers.

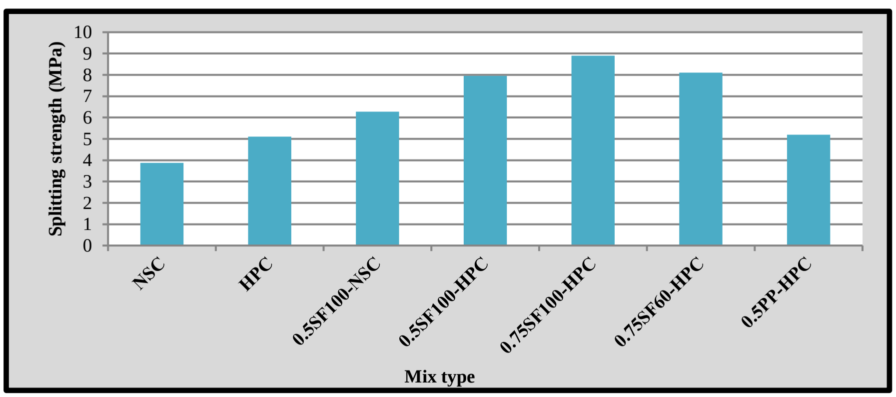

Figure (5) Splitting tensile strength for all types of concrete at 60 days age.

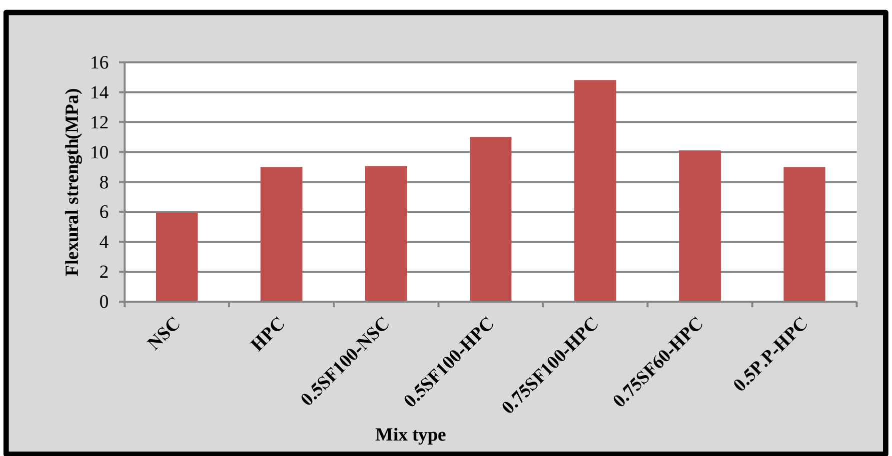

Figure (6) Flexural strength for all types of concrete at 60 days. age

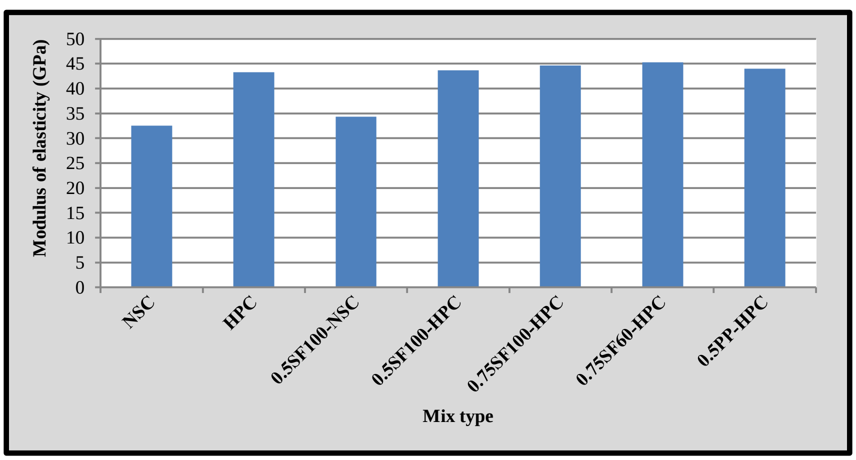

Figure (7) Static modulus of elasticity for all types of concrete mixes at age 60 days age

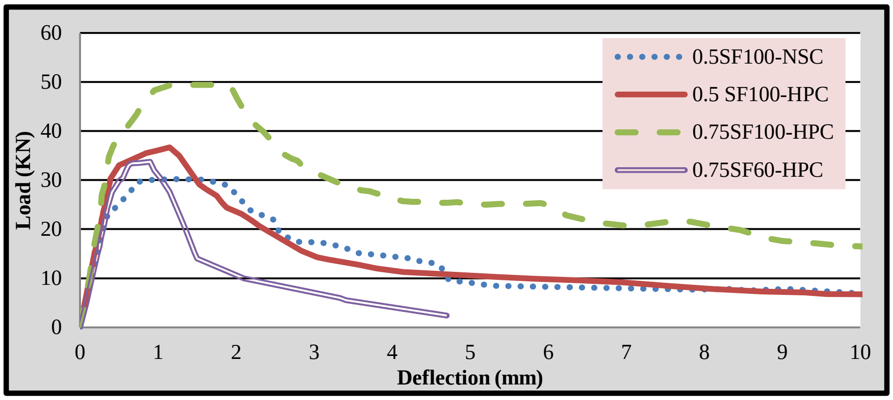

Figure (8) Load-deflection relationship for all types of concrete with various steel fiber contents and aspect ratios at age 60 days age.

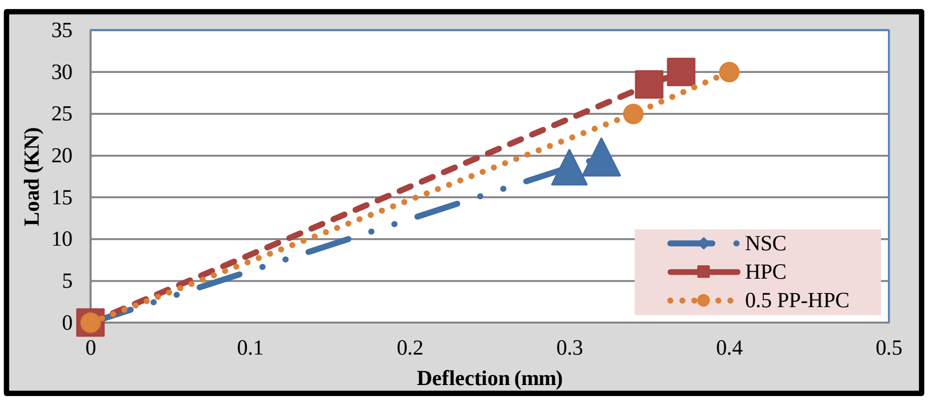

Figure (9) Load-deflection relationship for all types of concrete without steel fibers and concrete with polypropylene fibers.

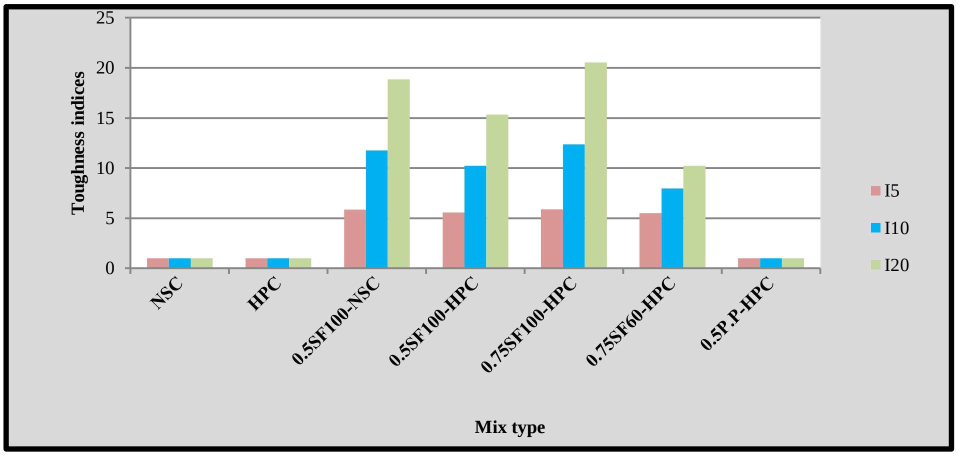

Figure (10) Toughness indices for all types of concrete mixes.

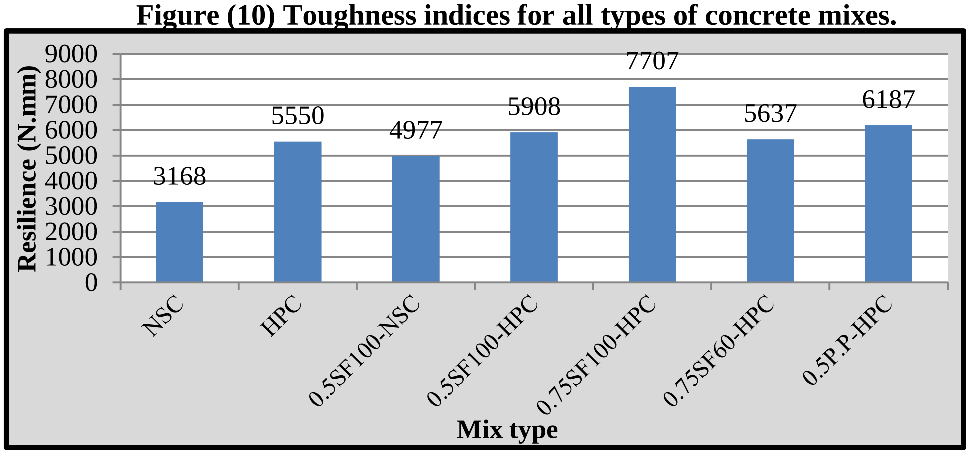

Figure (11) Resilience for all types of concrete mixes.