Journal of Al-Azhar University Engineering Sector

Vol. 18, No. 67, April 2023, 371-385

IMPACT OF ADDITION OF MACRO FIBERS ON THE MECHANICAL PROPERTIES OF CONCRETE

Mohamed M. Badawy*, Azza I. Anan

Civil Engineering Department, High Institute for Engineering and Technology at Al-Obour, Cairo, Egypt

*Correspondence: mohamedm@oi.edu.eg

Citation:

M. M. Badawy and A.I. Anan, " Impact Of Addition Of Macro Fibers On The Mechanical Properties Of Concrete", Journal of Al-Azhar University Engineering Sector, vol. 18 pp. 372-386, 2023

Received: 07 November 2022

Accepted: 15 March 2023

ABSTRACT

Using of fibers in manufacturing concrete is one of the most important technique to overcome the brittleness behavior of concrete. In this study, the impact of addition these fibers on the mechanical properties of concrete was examined using three different types of polyolefins, polypropylene, and glass-chopped fibers. Each fiber type was tested at five different doses (2 kg/m^3, 4 kg/m^3, 6 kg/m^3, 8 kg/m^3, and 10 kg/m^3 of concrete). The fibers were randomly added to various groups, verifying that they were well mixed. Slump and compacting factor tests for new concrete were studied. The findings of the slump test show that the value of the slump dropped as the dose of fiber rose. For hardened concrete, characteristic compressive strength, splitting tensile strength, and flexural tests were identified. The compressive strength of concrete after both 7 and 28 days enhanced by about 6%, 7%, and 16% for concrete mixes with polypropylene, glass, and polyolefin fibers, respectively, this improvement was recorded for fiber dose of 6 kg/m^3. All specimens of cubes, cylinders, and concrete beams were loaded twice and had a good ability to withstand more stresses and deformations again, especially for the used fiber dose of about 4-6 kg/m^3.

KEYWORDS: Polypropylene fibers, Glass fibers, Polyolefin fibers, Slump, Splitting Strength.

تأثير إضافة الألياف الدقيقة على الخواص الميكانيكية للخرسانة

عزة ابراهيم عنان*، محمد محمود بدوي

قسم الهندسة المدنية ، المعهد العالي للهندسة والتكنولوجيا بالعبور ، القاهرة ، مصر

*البريد الاليكتروني للباحث الرئيسى: mohamedm@oi.edu.eg

الملخص

يعد إستخدام الألياف في تصنيع الخرسانة من أهم التقنيات الحديثة للتغلب على السلوك القصف للخرسانة. في هذا البحث تم إستخدام ثلاثة أنواع متغيرة من البولي فلين والبولي بروبيلين والألياف الزجاجية المصنعه لدراسة تأثير إضافة هذه الألياف على الخواص الميكانيكية للخرسانة. تم دراسة خمسة نسب لكل نوع من الألياف 2 كجم / م^3 ، 4 كجم / م^3 ، 6 كجم / م^3 ، 8 كجم / م^3 و 10 كجم / م^3. تم إجراء إختبار الهبوط ومعامل الدمك للخرسانة الطازجة. أوضحت نتائج إختبار الهبوط أن قيمة الهبوط تنخفض بزيادة كمية الألياف المضافة. تم عمل اختبارات مقاومة الضغط المميزة ، واجهاد الشد ، وإختبار اجهاد الإنحناء للخرسانة المتصلدة بعد 7 و 28 يومًا من المعالجة. كان استخدام جرعة الألياف 6 كجم / م^3 هي النسبة المئوية المثلى لجرعة الألياف للأنواع الثلاثة المختلفة. أظهرت النتائج زيادة مقاومة الضغط للخرسانة بعد 28 يوم بنسبة 6٪ و 7٪ و 16٪ للخلطات الخرسانية مع البولي بروبلين والزجاج وألياف البولي فلين على التوالي. تم تحميل جميع عينات المكعبات والأسطوانات والكمرات الخرسانية مرتين ولديها قدرة جيدة على تحمل المزيد من الضغط والتشكل مرة أخرى خاصة لجرعة الألياف المستخدمة بحوالي 4-6 كجم / م^3.

الكلمات المفتاحية: ألياف البولي بروبلين ، ألياف الزجاج ، ألياف البولي فيلين ، الهبوط ، اجهاد الانفلاق.

1. INTRODUCTION

Material technology has advanced with civil engineering. Concrete is the most widely used building material in the world. One of the primary mechanical properties of concrete is compressive strength, but it also have poor ductility and cracking strength. One of the creative ways to enhance the flexural strength, tensile splitting strength, and ductility performance of concrete is to use macro fibers in reinforced concrete structures [1, 2]. The influence of macro fibers has a minor impact on compressive strength values. Fibers reduced the workability and consistency of concrete [3, 4]. On the other hand, adding macro fibers reduces the propagation of cracks, which enhances the durability of concrete [5]. A summary of research progress on coconut fiber (natural fibers) were conducted on reinforced concrete[6]. The results of this research indicate that coconut fiber improved the mechanical performance of concrete due to crack prevention, similar to the synthetic fibers but decreased the flowability of concrete. However, coconut fibers improved flexure strength more effectively than compressive strength. An experimental study to determine the influence of secondary reinforcement on the behavior of corbels fabricated with three different types of high-performance fiber-reinforced cementitious composites, including engineered cementitious concrete (ECC); high-performance steel fiber-reinforced composite (HPSFRC); and hybrid fiber-reinforced composite (HyFRC) [7]. The secondary reinforcement is proven to significantly affect stiffness and ultimately load capacity of all three high-performance composite corbels with an aspect ratio of 0.75. However, the secondary reinforcement was more impactful for the HPSFRC corbels, with 51% increase of ultimate strength.

Changes in polypropylene fibers that vary from 0.1 to 0.4% how signficantly affect the behavior of fibrous concrete [8]. Polypropylene fibers had a major enhancement in splitting tensile strength. The largest enhancement in splitting tensile strength was achieved with polypropylene fibers at 0.3%. Consequently, the splitting tensile strength then slightly decreased as the fiber content increased [9-12]. The usage of hybrid steel fiber with polypropylene fiber in the concrete mix had a significant impact on the mechanical properties of concrete [13]. As a result, the cube's compressive strength, flexural strength, and splitting tensile strength were 6.4%, 11.4%, and 3.7% higher than ordinary concretes. A hybrid fiber concrete (HFC) composite concrete fiber material contains two or more alternative fibers donated into concrete. Simultaneously, the ductility performance and mechanical characteristics of concrete were enhanced [14-16]. Until now, it seems out that there is a gap in studying the effects of macro fibers with different ratios on the characteristics of fresh concrete, although macro synthetic fibers have a significant effect on workability and consistency of fresh concrete. Therefore, the aim of this research is to study the behavior and mechanical properties of concrete, whether fresh or hardened in case of using three different types of macro synthetic fibers with five different doses of each type.

2. EXPERIMENTAL WORK

2.1. Materials

Three types of fiber sets polyolefin, polypropylene, and glass chopped fibers were used in the current study, as presented in Fig. 1. The concrete mix was provided by the properties and strength of material laboratory of Obour Institutes. The concrete was designed to have a 28-day cube compressive strength of 25 MPa, with a 10 mm maximum aggregate size, 60% free water-cement ratio, and 384 kg/m^3 cement content. The coarse aggregate used was a crushed calcareous aggregate with a standard grading curve. Table 1 presents the mix proportions to produce one cubic meter of the concrete mix.

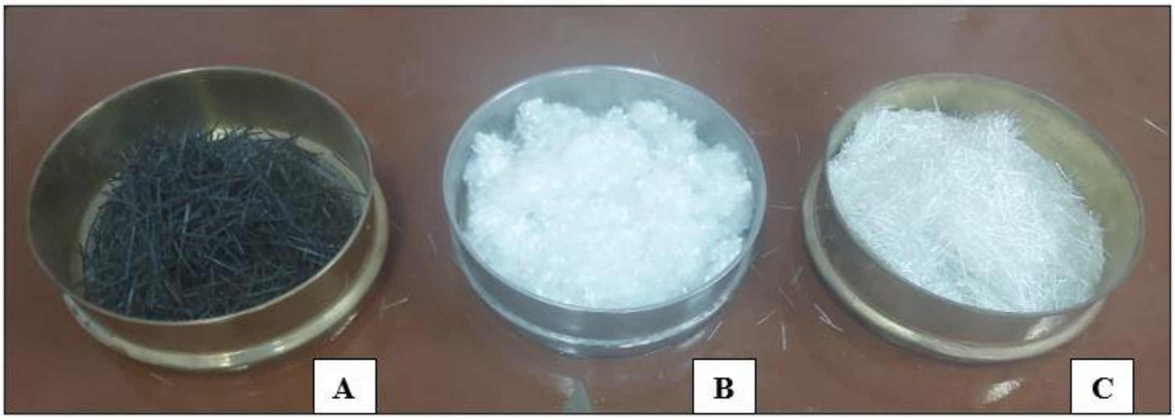

Fig. 1: Three Groups of Fibers, where A) Polyolefin, B) Polypropylene and C) Glass Chopped fibers.

Table 1: Concrete Mix Proportions

Material	Dolomite(kg)	Sand(kg)	Cement(kg)	Water (Liter)
Mix Proportion (Kg/m^3)	898	863	384	230

The grading curves for used crushed dolomite and fine sand are presented in Fig. 2 and Fig. 3 respectively. Ordinary Portland cement from Qena Factory of cement had been used in this study and the chemical composites are shown in Table 2.

Table 2: The Chemical Composites of Ordinary Portland Cement

Component	SiO_2	AL_2O_3	Fe_2O_3	Cao	MgO	SO_3	K_2O	Na_2O	CL^-
Portland cement	20.6	4.5	3.6	62.5	2.6	2.7	0.5	0.2	0.01

The technical data and mechanical properties of the three fiber types, Polyolefin, polypropylene, and glass chopped fibers in which obtained from the technical data sheet of sika EGYPT for modern building chemicals and were presented in Table 3. These fibers have a high density called compact density, which shows how close the atoms or molecules are to each other.

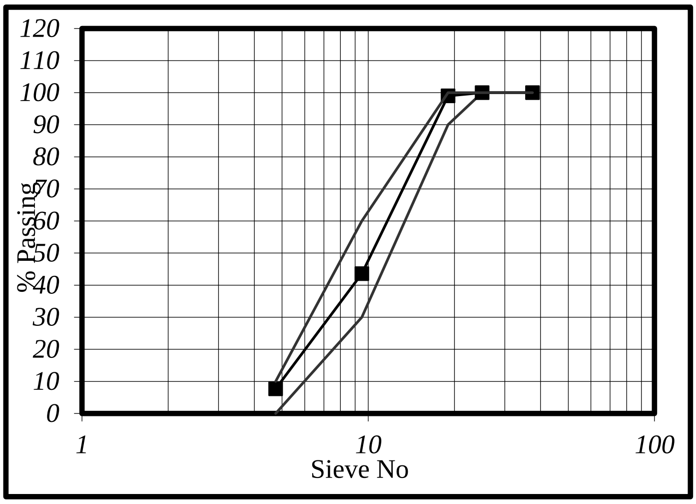

Fig. 2: The Grading Curve for Crushed Dolomite

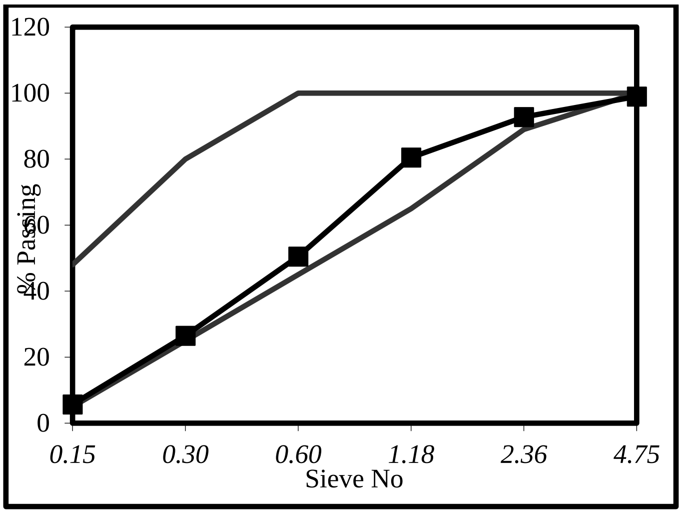

Fig. 3: The Grading Curve for Fine Sand

Table 3: Mechanical Properties of the Three Types of Fiber

Fiber Type	Polyolefin	Polypropylene	Glass
Type	100% polyolefin	Polypropylene	Glass
Color/Appearance	Black Fiber	round shape, white	Natural
Length of Fiber (mm)	48	18	18
Diameter (mm)	0.90	0.025	0.013
Compact (High) density (kg/m^3)	910	910	1180
Tensile Strength (MPa)	500	550	95
Elastic Modulus (GPa)	20	5.4	4

2.2. Methods

Experimental work was conducted to measure the compressive strength, splitting tensile strength, and flexural strength of concrete for three types of fiber sets. However, each reading was an average value of three standard concrete cubes, cylinders, and prisms. The cubic compressive strength results were measured at two different concrete ages 7 and 28 days. But, splitting tensile strength and flexural strength were measured at 28 days. Each set consisted of five different fiber doses: 2 kg/m3, 4 kg/m3, 6 kg/m3, 8 kg/m3, and 10 kg/m3. 90 cubes of 150x150x150 mm, 45 cylinders of 150x300 mm, and 45 prisms of 150x150x600 mm were examined in the present study. Test specimens without fiber additives were cast as control specimens for comparison purposes.

Fresh Concrete Testing

Five concrete mixes were designed for each of the three fiber types where all concrete components were constant for one cubic meter of concrete and the only variable was the percentage of macro fibers additions (2 kg/m^3, 4 kg/m^3, 6 kg/m^3, 8 kg/m^3, and 10 kg/m^3). Slump and compacting factor tests were conducted for each concrete mix to validate the optimum fiber dose without a negative effect on the workability and consistency of the concrete. Fig. 4 shows that the control specimen which is free from any type of fiber measured slump and compacting factor were 8 cm and 0.96, respectively. Table 4 shows the slump and compacting factor values for all other specimens classified into three groups. It could be noted that the values of slump decreased as the percentage of fibers increased. However, the values of the compacting factor follow the same trend, except in the case of concrete mixes containing polyolefin, which maintain good workability even as the polyolefin fiber content increases. The results of slump and compacting factor were presented in Fig. 5 and Fig. 6 respectively. The concrete mixes of the three types of fibers were presented in Fig. 7. Fibers had a significant impact on the slump and consistency of the concrete. For example, the effect of using 6 kg/m^3 of polyolefin fibers on the slump value of fresh concrete is presented in Fig. 8.

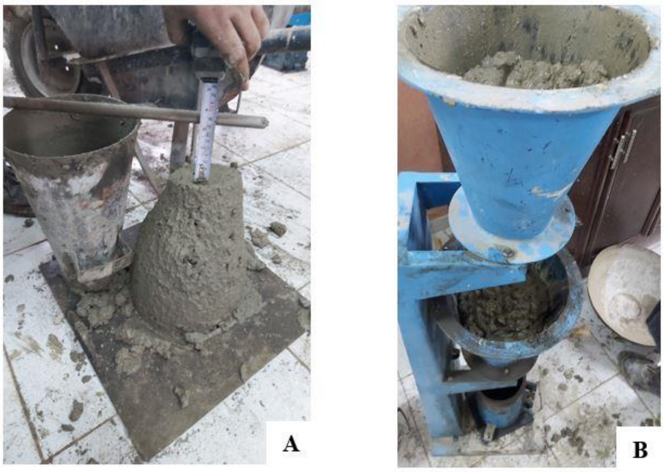

Fig. 4: Presented Slump and Compacting Factor Tests for Control Specimen, where A) Slump and B) Compacting factor

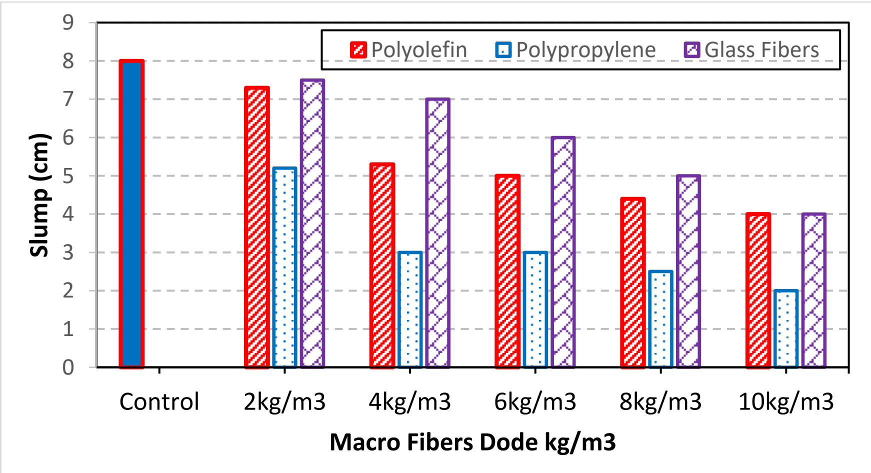

Fig. 5: Presented Slump Values for All Tested Specimens

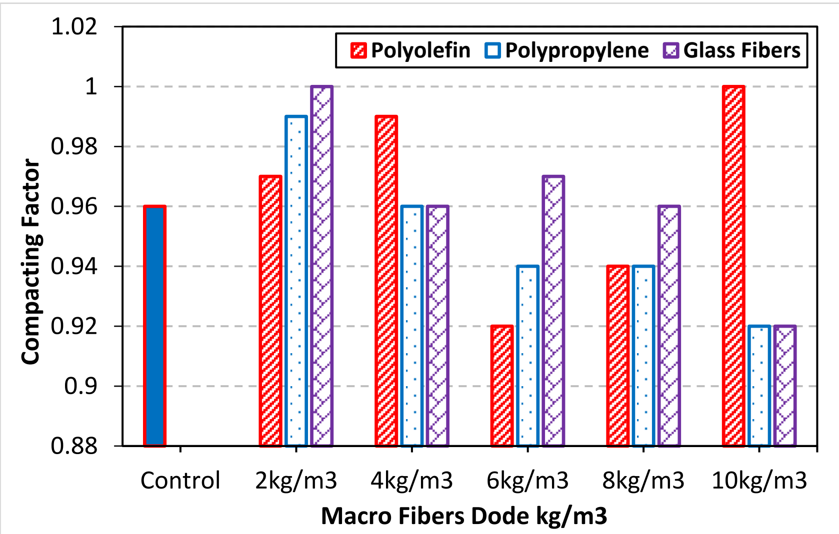

Fig. 6: presented Compacting Factor Values for All Tested Specimens

Table 4: The values of the slump and compacting factor for examined concrete mix

Group No.	**Control**	Group.1 **"Polyolefin"**					Group.2 **"Polypropylene"**					Group.3 **"Glass"**				
Mix No.	0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Percentage (kg/m^3)	0	2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
Slump (cm)	8	7.30	5.30	5.00	4.4	4	5.2	3	3	2.5	2	7.5	7	6	5	4
Compacting Factor	0.96	0.97	0.99	0.92	0.94	0.94	0.99	0.96	0.94	0.94	0.92	1.00	0.96	0.97	0.96	0.92

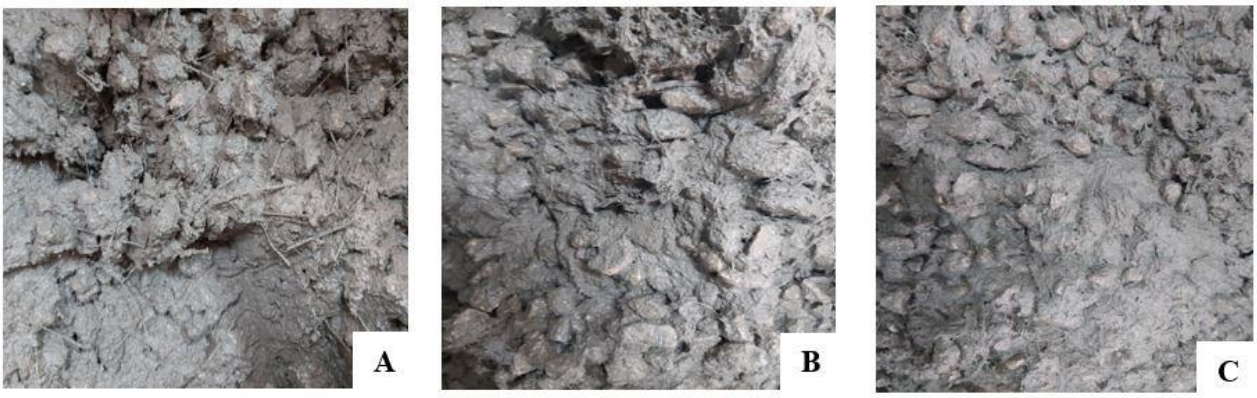

Fig. 7: Shows the Concrete Mix of the Different Types of Fibers (6 kg/m^3), where A) Polyolefin, B) Polypropylene and C) Glass Chopped

6 cubes, 3 cylinders, and 3 prisms were prepared and cast from each concrete mix with different fiber types and doses as shown in Fig. 9. After the concrete pour for all the different samples, they were placed in the treatment basin as shown in Fig. 10 until they were tested at the specified age. All the standard recommendations for tests were followed, as all cubes, cylinders, and prisms were cast and compacted 25 times in three layers.

Fig. 8: Effect of Fiber Usage on Slump Value of Concrete

Fig. 9: Preparing and Concrete Casting Process for each Concrete Mix

Fig. 10: All Samples of Different Concrete Mixes After Being Placed in the Curing Basin

2.3. Hardened Concrete Testing

2.3.1. Compressive strength

Three varied experimental tests were conducted for concrete, characteristic compressive strength, splitting tensile strength, and flexural strength. The compressive strengths for the control specimen were about 15.36 and 23.2 MPa, respectively, for 7 and 28 days. These experimental tests were conducted at the ages of 7 and 28 days for the three types of macro fibers adding, Polyolefin, Polypropylene, and Glass Chopped Fibers. Fig. 11 presents a comparison of compressive strength for group 1 at different ages. It could be noted that the compressive strength of cubes for fiber doses of 2 kg/m^3, 4 kg/m^3, and 6 kg/m^3 was gradually enhanced by 8%, 12%, and 25%, respectively, compared to control specimens. But on the other hand, the compressive strength of cubes for fiber doses of 8 kg/m^3 and 10 kg/m3 decreased by 7% and 11%, respectively, compared to the control specimen. It is important to mention that increasing the fiber doses to more than 6 kg/m^3 will negatively affect the compressive strength of concrete. A comparison of the compressive strength of concrete mixes with polypropylene fiber addition was also performed at 7 and 28 days for five doses. Compared to control specimen, Fig. 12 shows that there was a slight enhancement in the concrete compressive strength for specimens with polypropylene adding from 2kg/m^3 to 6kg/m^3 on the contrary, specimens with polypropylene adding 8kg/m^3 and 10kg/m^3 not even improved rather, the compressive strength results declined significantly. This is referring to an increase in polypropylene fibers doses more than 6kg/m^3 lead to absorb a large amount of the water intended for the cement reaction in the concrete mix.

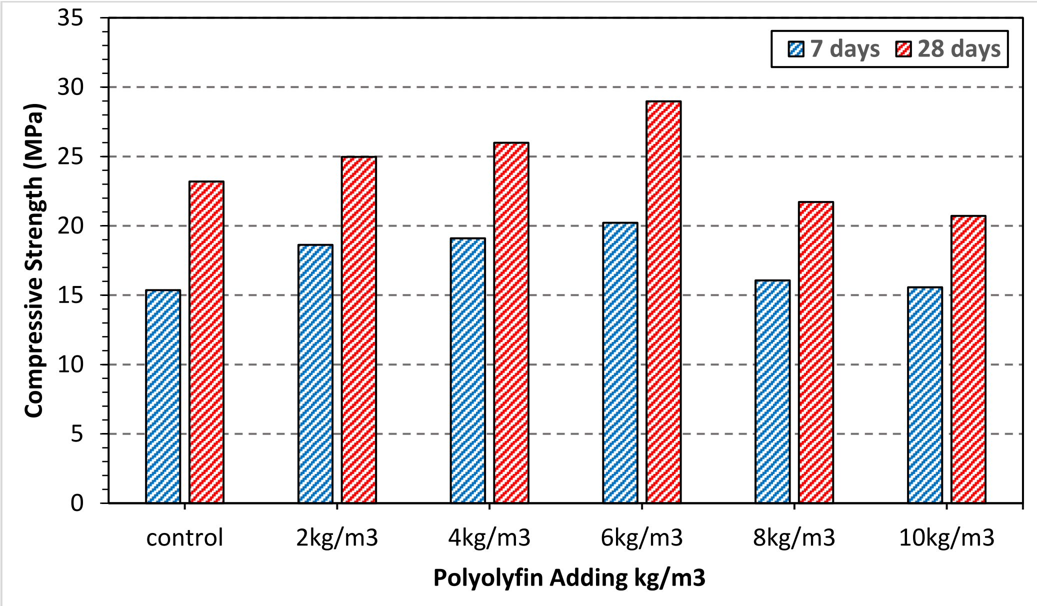

Fig. 11: Comparison of Compressive Strength for Group 1 at Different Ages

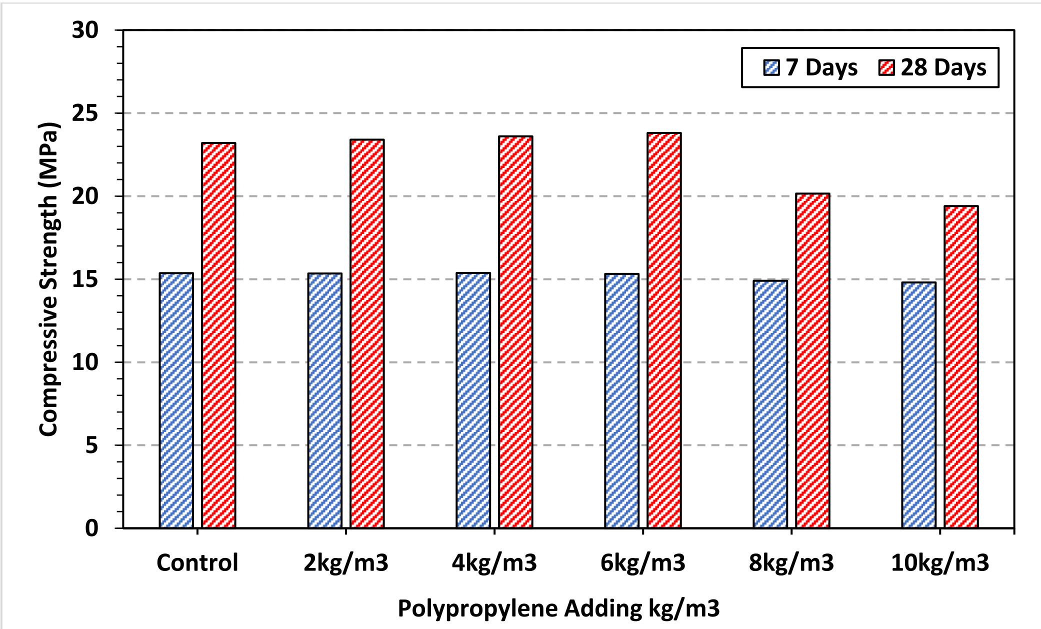

Fig. 12: Comparison of Compressive Strength for Group 2 at Different Ages

The final experimental tests for standard cubes were performed at 7 and 28 days to investigate the effect of adding glass chopped fibers. Fig. 13 presented a comparison of compressive strength for group 3 for the same five doses at different ages (7–28 days).

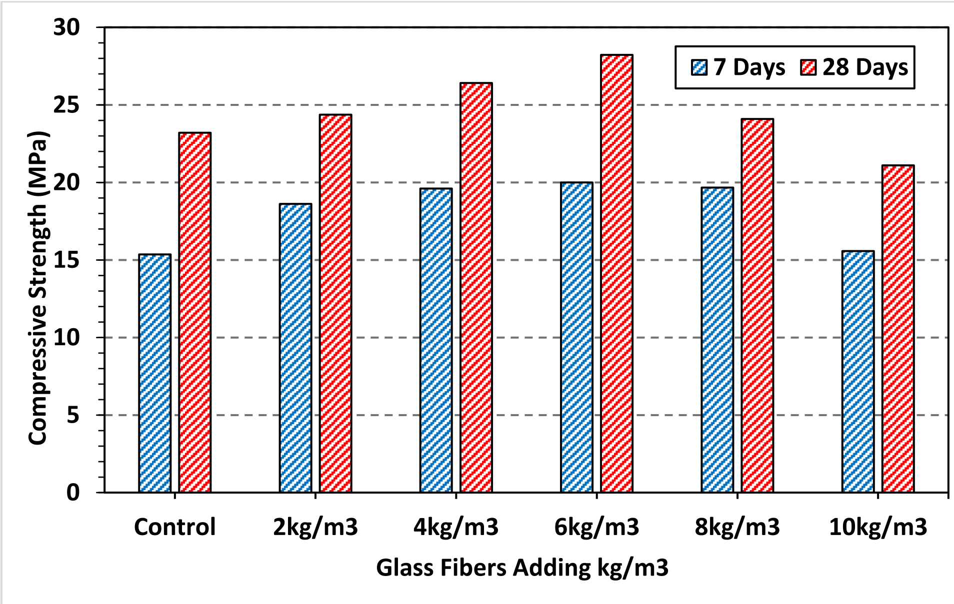

Fig. 13: Comparison of Compressive Strength for Group 3 at Different Ages

It can be noted that the optimum dose of glass fibers was 6 kg/m^3 at which compressive strength was enhanced by 22% compared to control cubes. The compressive strength was enhanced by 7% and 13% for glass fiber doses of 2 kg/m^3 and 4 kg/m^3, respectively, compared to control specimens. The addition of 8 kg of glass fiber per m^3 of concrete did not affect its compressive strength. However, the compressive strength of concrete decreased by 10% in the case of adding 10 kg/m^3 of glass fibers. Fig. 14 presents a compressive strength test for standard cubes for each type of fiber. Mode of failure for the three examined groups presented in Fig. 15, Fig. 16, and Fig. 17 at which polyolefin, polypropylene, and glass fibers were used. A comparison of the compressive strength of concrete is presented in Fig. 18.

Fig. 14: Compressive Strength Test for Standard Cubes, where A) Fiber Free, B) Polyolefin, C) Polypropylene and D) Glass Chopped.

Fig. 15: Non-explosive Failure for Cubes at which 6kg/m^{3}Polyolefin Dose Were Used

Fig. 16: Semi-explosive Failure for Cubes at which 6kg/m^{3}Polypropylene Dose Were Used

Fig. 17: Non-explosive Failure for Cubes at which 6kg/m^3 Glass Fibers Dose Were Used

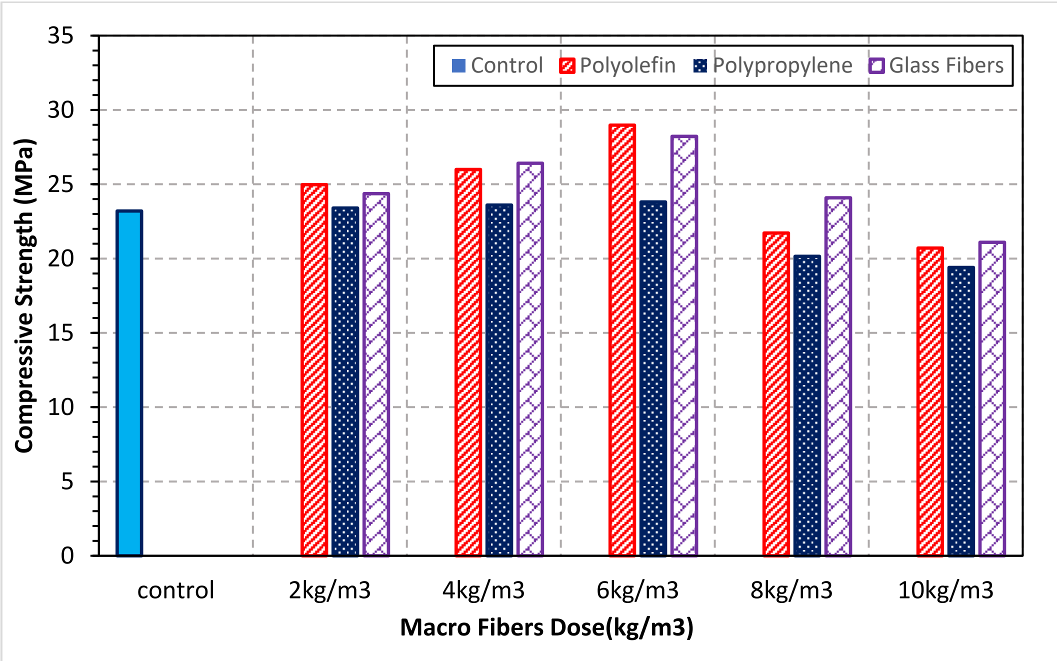

Fig. 18: Comparing the Compressive Strength of Concrete for Three Groups

2.3.2. Tensile strength

Tensile strength is one of the most important characteristics that control the mechanical properties of concrete. Consequently, the crack pattern and timing of the first crack in concrete are highly dependent on the tensile splitting strength of the concrete. As a result, the tensile splitting strength of concrete without fiber addition was investigated as a control specimen. It was also examined for all concrete specimens with alternative fiber types, including polyolefin, polypropylene, and chopped glass fibers, as presented in Fig. 19. This figure also depicts the mode of failure for cylinder specimens using 6 kg/m3 fibers.

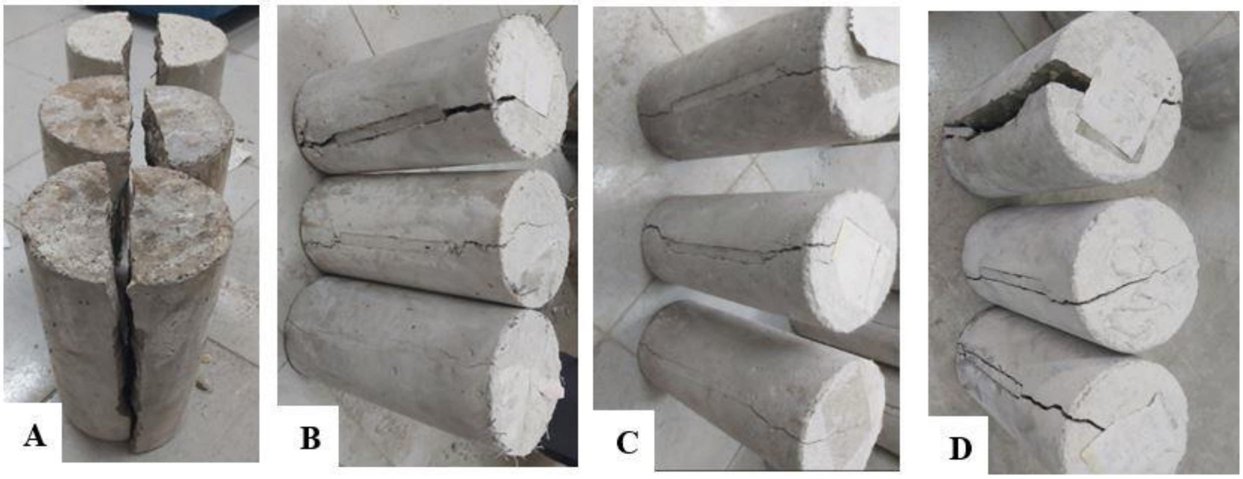

Fig. 19: Mode of Failure for Standard Cylinders at which 6kg/m^3 Fibers Dose Used, where A) Fiber Free, B) Polyolefin, C) Polypropylene and D) Glass Chopped

It should be observed that the use of polyolefin and polypropylene fibers in concrete delayed the cracks, and the mode of failure for these specimens was ductile compared to the control specimens, which had a clear brittle failure. On the other hand, concrete cylinders with glass fiber added had a semi-ductile mode of failure. Fig. 20 illustrates the values of the splitting tensile strength for cylinders at which polyolefin, polypropylene, and glass fibers were used. It should be observed that the splitting tensile strength of the control specimen, which is free from fibers was about 2.10 N/mm^2. The results of splitting tensile strength showed an enhancement of 2.4%, 16%, 24%, 13%, and 4%, respectively, for polyolefin doses of 2, 4, 6, 8, and 10 kg/m^3. Consequently, other groups of polypropylene and glass fibers had the same trend with different values. It can be noted that adding 6 kg/m^3 from the three alternative fiber types was the optimum dose for enhancement of splitting tensile strength compared to the control specimen.

The efficiency and contribution of using three types of fibers in reducing cracks are presented in Fig. 21 which shows a close-up of the cracks closing by fibers. As shown in this figure, the fibers have a good impact in eliminating and closing cracks, which improves concrete's compressive strength and optimizes its ductility.

2.3.3. Flexural strength

Flexural tests were conducted on 48 prisms with dimensions of 15*15*60 cm^3, three of which had no fibers added as control specimens. The other 45 prisms were examined for the three groups of used fibers: polyolefin, polypropylene, and chopped glass fibers. The test setup for standard prisms is presented in Fig. 22

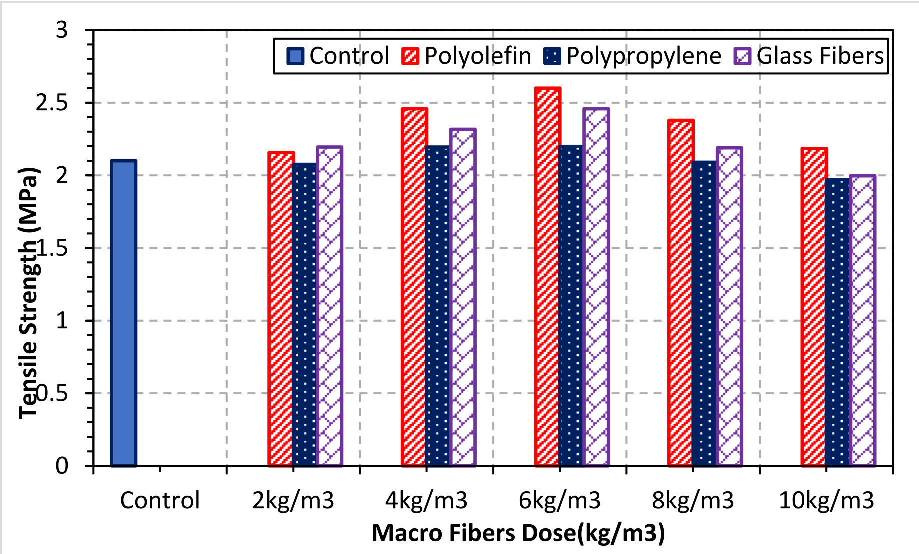

Fig. 20: Comparing Tensile Splitting Strength of Concrete for Three Groups

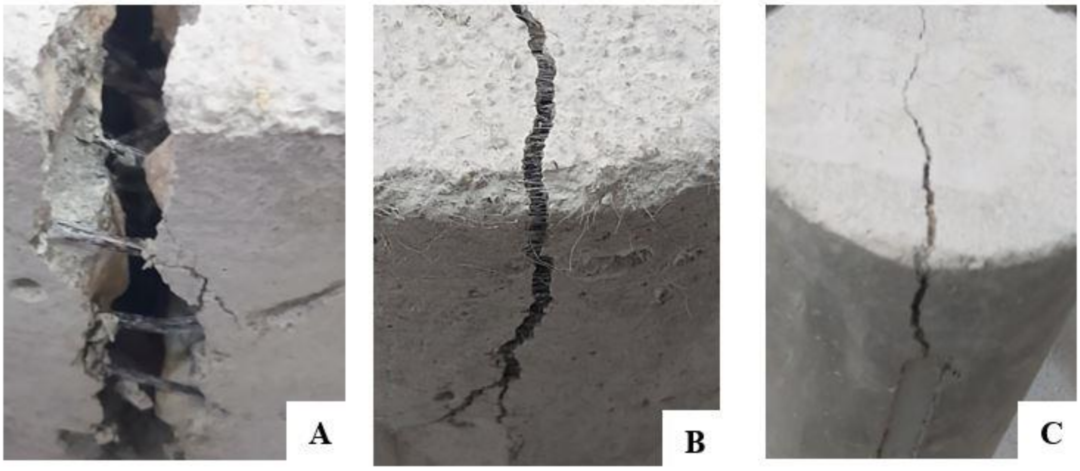

Fig. 21: The Contribution of Three Types of Fibers in Reducing Cracks, where A) Polyolefin, B) Polypropylene and C) Glass Chopped

Fig. 22: Flexural Strength Test Setup for Standard Prisms(15cmx15cmx60cm)

The crack pattern and mode of failure for control prisms are presented in Fig. 23, where the type of failure was brittle. The crack pattern, on the other hand, was ductile, and fibers were used specifically for specimens with polyolefin addition. Crack pattern and mode of failure for specimens with polyolefin, polypropylene, and glass fibers are presented in Fig. 24, Fig. 25, and Fig. 26, respectively. Fig. 27 presented a comparison of flexural strength for all tested specimens in which polyolefin, polypropylene, and glass fibers were used. It could be noted that the addition of glass fibers improves the flexural strength by 20%, 24%, 30%, 13%, and 10% compared to the control specimen, which had 17.5 MPa. Beam specimens with polyolefin addition had no significant enhancement, and flexural strength improved by 7% at most for specimens with 6 kg/m^3 polyolefin addition. On the other hand, specimens with polypropylene fibers enhanced the flexural strength of specimens by 18.4%, 20.6%, 20.9%, 18.9%, and 18.2% compared to the control specimen.

Fig. 23: The Crack Pattern and Mode of Failure for Control Prisms

Fig. 24: The Crack Pattern and Mode of Failure for Prisms with Polyolefin

Fig. 25: The Crack Pattern and Mode of Failure for Prisms with Polypropylene

Fig. 26: The Crack Pattern and Mode of Failure for Prisms with Glass Fibers

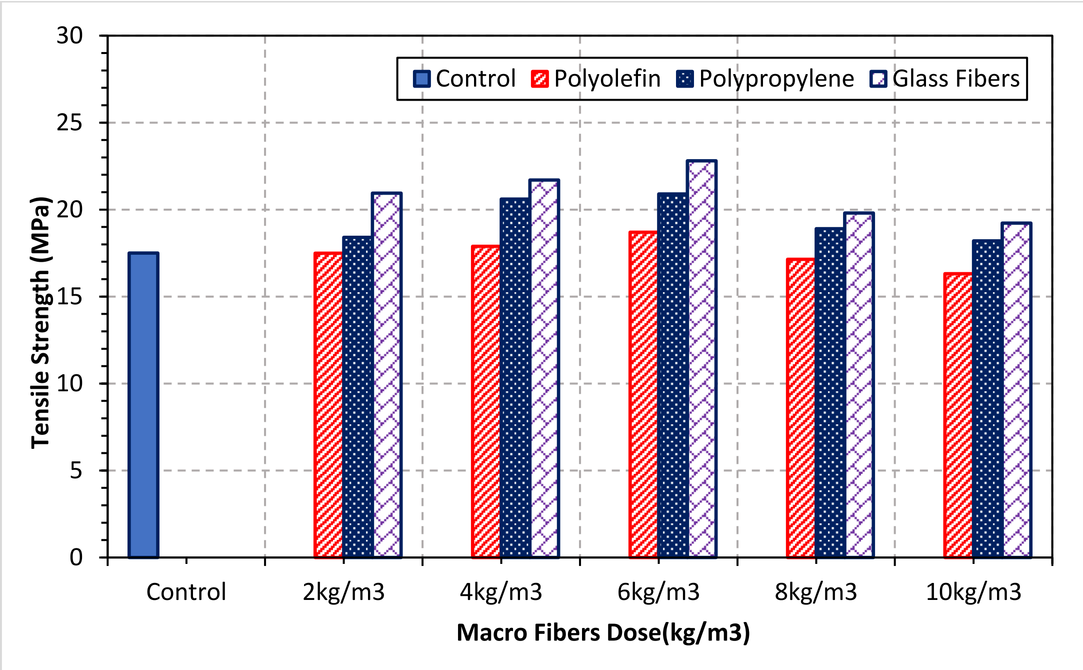

Fig. 27: Comparing the Flexural Strength of Concrete for Three Groups

CONCLUSIONS

Based on experimental investigation and analysis of results obtained, the following conclusions may be drawn:

- Increasing Fiber doses in concrete mixes by 6 kg/m^3 hurts the workability of concrete, especially for concrete mixes with polypropylene fibers added.
- Polyolefin mix improves the characteristic compressive strength of concrete by 8%, 12%, and 25% for 2 kg/m^3, 4 kg/m^3, and 6 kg/m^3 fiber doses, respectively, compared with control concrete mixes. Therefore, an increase in fiber dose content more than 6 kg/m^3 reduced the compressive strength.
- Polypropylene mix had a slight enhancement toward compressive and tensile strength of concrete while, had a good contribution in flexural strength improvement reached to 20% as a maximum value with 6 kg/m^3 fiber dose.
- The compressive strength of concrete mixes with glass chopped fibers was enhanced by 7%, 13%, and 22% respectively, for 2 kg/m^3, 4 kg/m^3, and 6 kg/m^3 fiber doses compared to control concrete mixes. Thereafter, increases in glass fibers hurt compressive strength.
- 6 kg/m3 Fiber dose was the maximum optimal fiber added to the concrete mix for all types of fibers under study and had a significant improvement on the mechanical properties of hardened concrete without a negative effect on fresh concrete.
- The use of macro fibers had a significant role in crack elimination, which is evident in the improvement of tensile splitting and flexural strength.
- The maximum gain in splitting tensile strength was achieved for 6 kg/m^3 polyolefin, polypropylene, and glass fibers. Thereafter, the increase in fiber content has marginally reduced the splitting tensile strength.
- The maximum gain in flexural strength was achieved at 6 kg/m.^{3} glass fibers, polypropylene, and polyolefin. Thereafter, an increase in fiber dosage above 6kg/m^3 marginally reduced flexural strength.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Material Lab in the Civil Engineering Department, High Institute for Engineering and Technology, Obour Institutes, Cairo, Egypt.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

REFERENCES

[1] F. Puertas, T. Amat, Fernandez-Jimenez, and T. Vazquez, "Mechanical and durable behavior of alkaline cement mortars reinforced with polypropylene fibers", Cement and Concrete Research 33 (2003), 2031–2036.
[2] Giuseppe Campione, Maria LetiziaMangiavillano, "fibrous reinforced Concrete Beam in Flexure: an Experimental Investigation, Analytical Modeling, and Design Considerations," Engineering Structures Journal 30 (2008) 2970–2980.
[3] G. Ramakrishna, T. Sundararajan, " Impact strength of a few natural fiber reinforced cement mortar slabs: a comparative study", Cement and Concrete Composites 27 (2005) 547–553.
[4] ACI Committee 544: Measurements of Properties of Fiber Reinforced Concrete, Journal of American Concrete Institute: Mar 28, 2017, Vol. 75, s. 283-289
[5] Li X and Fei Y., "Application of Fiber in Concrete: Coal Ash," (2013) No. 6, p. 42
[6] Jawad Ahmad, Ali Majdi, Amin Al-Fakih, Ahmed Farouk Deifalla, Fadi Althoey, Mohamed Hechmi ElOuni, Mohamed A-El-Shorbagy " Mechanical and Durability Performance of Coconut Fiber Reinforced Concrete: A State-of-the-Art Review" Materials 2022, 15, 3601. https://doi.org/10.3390/ma15103601
[7] Nasuha Md Zin, Amin Al-Fakih, Ehsan Nikbakht, Wee Teo, Mahmoud Anwar Gad " Influence of Secondary Reinforcement on Behavior of Corbels with Various Types of High-Performance Fiber-Reinforced Cementitious Composites" Materials 2019, 12, 4159; http://doi:10.3390/ma12244159
[8] Parveen Dangra, "Structural Behaviour of Fibrous Concrete Using Polypropylene Fibers," International Journal of Modern Engineering Research (IJMER), www.ijmer.com, Vol. 3, Issue. 3, May - June 2013, pp. 1279–1282, ISSN: 2249-6645
[9] T. Budi Aulia, "Effect of polypropylene Fibres on the properties of high strength concretes," Institutes for Massivbau and Baustoffechnologi, University Leipzig, Lacer No. 7 (2002).
[10] V M Malhotra, Carette, A Bilodeau, "Mechanical properties and durability of polypropylene fiber reinforced high-volume fly ash concrete for shotcrete applications," ACI Materials Journal, 1994, 91(5), 478–486.
[11] Waheeb Ahmed Al-Khaja, "Mechanical properties and time-dependent deformation of polypropylene fiber concrete." J.KingUniv, Vol. 7 Eng Sci. (1) pp 67-76.
[12] YeolChoia, Robert L. Yuan, "Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC", Cement and Concrete Research 35 (2005) 1587-1591.
[13] Dongqing He1 and et al., "Study on Mechanical Properties of Hybrid Fiber Reinforced Concrete"IOP Conf. Series: Earth and Environmental Science 100 (2017) 012111, doi:10.1088/1755-1315/100/1/012111
[14] XueZhi W, Jing Jing H, and Hao F: Experimental Study on Basalt-Polypropylene Hybrid Fiber Reinforced Concrete Flexural Toughness Characteristic Concrete, (2014, No. 4, p. 82–86
[15] ChoteSoranakom, BazinMobasher, "Flexure Design of Fiber Reinforced Concrete," ACI Material Journal (September 2009).
[16] C.D. Johnston, "Steel Fiber Reinforced Mortar and Concrete," A Review of Mechanical Properties in Fiber Reinforced Concrete ACI-SP 44-Detroit (1974).