Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Properties of Engineered Cementations Composite Concrete (Bendable Concrete)

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ARTICLE INFO

Article history:

Received 24 July 2024
Revised 24 July 2024 ,
Accepted 31 July 2024 ,
Available online 01 August 2024

Keywords:

Bendable concrete
Engineered Cementitious Composite
SECC
Self-Compacting
ECC
Compressive Strength

ABSTRACT

Bendable concrete, or Engineered Cementitious Composites abbreviated as ECC, is a class of ultra-ductile fibre-reinforced cementitious composites characterized by high ductility and tight crack width control. This material is capable of exhibiting considerably enhanced flexibility. The main object of this work was to investigate the properties of self-compacting bendable concrete (SECC) produced by different types and percentages of material and to achieve high resistance to segregation, high workability, and low yield stress such as of steel fiber that was (1,1.5 and 2) %, the percentage of silica fume that was (10,15 and 20) %, the percentage of PVA (Polyvinyl alcohol) that was (0.2,0.3 and 0.4) %. To achieve this aim, seven mixes of SECC were designed and tested. A survey of fresh and mechanical properties of different SECC mixtures was evaluated using slump flow and V-Funnel tests. The workability of all studied mixes is good, with slump flow diameter greater than or equal to (24 mm), flow times range between (7 and 7.5) sec, and the mechanical properties of hardened SCC mixes are also assessed compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity. The mechanical properties were significant when using steel fiber with 1% to 1.5% and 2%, increasing the compressive strength by about 3% and 8% and the splitting tensile strength by about 20% and 37%, respectively.

1. Introduction

Concrete is always a building material with high compressive strength but little tensile strength. If a concrete beam has no reinforcement, it will crack and fail when subjected to a relatively small load, where the failure occurs suddenly in most cases and in a brittle manner [1]. Flexible or bendable concrete is an engineered cementitious

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https://doi.org/10.61268/w4yqhe03

composite (ECC) that exhibits ductile material properties, unlike conventional concrete's brittle nature [2]. Prof. Victor Li developed flexible or bendable concrete at the University of Michigan. The coarse aggregate is eliminated in a flexible concrete mix, and more fibres are incorporated. Flexible concrete comprises cement, fibres, sand, water, and Superplasticizer [3]. Some important constituents of flexible concrete are summarised: a) Fibres in Bendable Concrete, b) Fine Aggregates in Bendable Concrete, and c) Superplasticizers in Bendable Concrete. The fibres in the bendable concrete are provided with an anti-friction coating called the slick coating. This coating helps the fibres to slip over the other. This won't create friction between the fibres, hence preventing the formation of cracks in the concrete. This also increases the flexibility of the concrete [4]. Steel fiber is now the primary material to strengthen concrete and solve brittleness [5]. The fine sand used for water treatment activities is the best fine aggregate for flexible concrete. If this is unavailable, normal sand can be used. Some replacements like silica fume, blast furnace slag and fly ash can also be used for this concrete-making [6]. Flexible concrete requires higher workability, which hence demands superplasticizers. Some superplasticizers used for flexible concrete are Lignin, Naphthalene, Melamine formaldehyde, Sulphonate, Polycarboxylate ether, and Lignosulfonates [7,8]. An engineered cementitious composite (ECC) is a key to intruding the new type of concrete, which can resist more applied load before cracking and behave as ductile material; this behaviour will help to resist more applied load before failure and give more causer before the collapse. This section briefly reviews the experimental studies investigating self-compacting bendable concrete SECC behaviour. Qian et al. 2010 [9] studied ECC self-healing and how it affects curing conditions and precaching time. ECC beams were pre-cracked at different ages and cured in air, 3% CO2, cycle wet/dry, and water. ECC beams recovered or exceeded their initial deflection capacity under all curing conditions, regardless of precaching age. After self-healing, ECC beams preserved more flexural stiffness than fresh samples, but this decreased with precaching time. Due to cementitious material hydration, pre-cracked samples at 14 and 28 days had higher flexural strength. The study also discovered that nano clay reservoirs could improve ECC self-healing without external water. Victor C Li et al2012 [10]. In a recent study, researchers changed the mixing procedure to improve fiber distribution. Fibers are introduced after solid and liquid materials are mixed in traditional mixing. Due to plastic viscosity before fiber addition, this generally results in poor fiber dispersion and poor hardened characteristics. In the modified mixing sequence, solid and liquid ingredients are mixed in two phases with fibers between. Comparing the uniaxial tensile test and fiber distribution analysis, findings showed the effects of water mixing sequences. The altered mixing sequence improved ECC's tensile strain capacity, ultimate tensile strength, and fiber distribution compared to the regular sequence. Fly ash and slag reduced compressive strength by 40% and 14%, respectively. The ternary system substituting 70% cement with fly ash and slag improved ductility and matrix strength. Fly ash with silica fume increased ECC compressive strength but decreased toughness. **Yu Zhu *et al.* 2014[11],** The study focused on investigating the mechanical properties of ECC (Engineered Cementitious Composites) made with high-volume mineral admixtures such as fly ash, slag, and silica fume. The research aimed to connect compressive strength and the parameters obtained from load-deflection curves of 12 ECC mixtures. These mixtures used binary and ternary systems of binder materials with varying levels of mineral admixtures. The water-binder materials ratio (W/B) was maintained at 0.25 for all ECC mixtures, and the replacement levels of different mineral admixtures in binary systems ranged from 50% to 80%. **Waghule 2017[12]** studied that bendable concrete deforms much more than regular concrete without failing to incorporate super fine silica sand and tiny PVA fibers. The mechanical strength test is done on the beam, and as a result, the beam can withhold a large load and a large deformation even without steel reinforcement. The flexural strength is 60% higher than normal concrete.

2. Significance of research

The primary aim of this study is to assess and analyse recent experimental findings investigating the properties of self-compacting bendable concrete (SECC) produced by different types and percentages of material. The study concentrates on the materials utilized in SECC, the recipe design, and the preparation methods. Furthermore, it highlights the key characteristics of SECC, which significantly impact concrete's structural behaviour and durability.

3. Experimental Program

The experimental program has been conducted to view the differences in self-compacting bendable concrete (SECC) behavior during the fresh and hard states. The slump flow and V-Funnel Test were performed on concrete in the fresh state while compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity were conducted for hardened SECC.

3.1 Materials

3.1.1 Cement

Ordinary Portland cement (ALsaad) is used throughout this study. Tables (1) and (2) illustrate the chemical and physical properties of the cement, respectively.

Table 1: Chemical Composition and Main Compounds of the Cement

composition	Weight%	Iraqi Specifications No. 5/2019 [12]
SiO_2	21.92	-
CaO	62.52	-
MgO	3.35	Not more than 5 %
Al_2O_3	4.0	-
Fe_2O_3	3.3	-
SO_3	2.2	Less than 2.8 %
C_3A	5.02	More than 3.5 %
Loss on Ignition (LOI)	2.65	Not more than 4 %
Insoluble Residue (IR)	0.95	Less than 1.5 %
Lime Saturation Factor	0.71	0.66-1.02

Table 2: Physical Properties of Cement

Physical Properties			
Name	Unit	No.1	Iraqi Specification No. 5/2019 [12]
Specific Surface Area	cm^2/g	2680	Not Less Than 2300
Initial Setting Time	Min	160	Not Less Than 45
Final Setting Time	Hours	6.4	Not more than 10
Compressive strength at two days	MPa	27.0	Not Less Than 20
Compressive strength at 28 days	MPa	49.8	Not Less Than 42.5
Soundness by Autoclave Method	%	0.64	Not more than 0.8

3.1.2 Fine Aggregate

The fine aggregate with rounded particle shapes and smooth textures requires less mixing water in concrete, which was preferable in SECC. This study uses natural sand as fine aggregate for concrete mixes. This sand was tested according to Iraqi Standard Specification (I.Q.S NO 45 of ١٩٨٤) [14], as shown in Table (3). According to the test, the grading zone of fine aggregate is zone 3.

Table 3: Grading of the Sand

Sieve Size	% Passing

(mm)	Fine Aggregate%	IQS No. 45/١٩٨٤ for Zone (3) [13]
10	100.00	100
4.75	92.56	100-90
2.36	82.47	100-75
1.18	70.51	90-55
600	46.49	59-35
300	14.61	30-8
150	1.86	10-0
SO3 as salt	0.34	0.5
Clay	3.5	5
Zone	3	-

3.1.3 Limestone Powder Fillers

Locally, the limestone powder "Al-Gubra" is obtained by grinding the limestones excavated from different regions in Iraq. The cement in SCC mixes is generally partially replaced by fillers like limestone powder to enhance a certain property such as: -

1-Increase the amount of powder (filler + cement) for being more
cost-effective in comparison to utilizing just the cement.

2- Improve segregation resistance, increase workability and early
strength

3- Avoid extreme generation of heat.

4- Improve fluidity and cohesiveness.

Tables (4) show the chemical composition and grading
of limestone powder utilized in a current study. The used limestone powder can be described as fine, according to Table (5).

3.1.4 Admixtures

A superplasticizer-type sulphonate melamine and naphthalene formaldehyde condensate, which is known commercially as Gleniume 51, was used in this work. Gleniume 51 differs from conventional superplasticisers based on a unique carboxylic ether polymer with long lateral chains. This greatly improves cement dispersion. Table (6) indicates the technical description of an aqueous solution of the superplasticizer used in this investigation; it is free from chlorides and complies with ASTM C494[15] types A and F.

3.1.5. Silica Fume

Silica fume, which is a by-product of the ferrosilicon industry, is a highly pozzolanic material that is used to enhance the mechanical and durability properties of concrete [16]. Densified gray-colored micro-silica, named **MEYCO MS 610,** produced by BASF Company, UAE, was used as a mineral admixture to improve the fresh and hardened properties of SCC throughout this study. Table 7 shows the properties of silica fume, which complies with ASTM C1240-03[17].

Table 4: Chemical Properties of Limestone

Oxide Composition	% by Weight
CaO	54.1
MgO	0.13
SiO_2	1.38
Fe_2O_3	0.12
Al_2O_3	0.72
SO_3	0.21
Loss on Ignition (LI)	42.56

Table 5: Grading Test of Limestone Powder

Sieve size (mm)	Accumulative Retained Ratio
10	0
4.75	0
2.36	3.9
1.18	9.5
600µm	41
300 µm	69.9
150 µm	88
Pan	
	Σ 212.3

Fineness Modulus = 212.3 / 100= 2.123

Table 6: Technical Properties of Superplasticiser

Form	Viscous Liquid
Color	Light brown

Relative density	1.06 –/+ 0.02 @ 20° C
pH	6.6
Viscosity	128μ 30 cps @ 20° C
Transport	Not classified as dangerous
Labeling	Not classified as label required
Douse	10 l/m^3

* This data was listed from a catalogue of the manufacturer

Table7: Technical properties of silica fume

Structure of the material	Densified micro silica
Color	Gray
Density	0.55 - 0.70 kg/liter
SiO2	> 15 m2/kg
Specific	weight 2300 kg/m3

Note: The data from the manufacturer catalogue.

3.1.6 Mixing Water

Drinkable water is used for mixing in this study.

3.1.7 Steel Fiber

Steel fibers SF are the most famous type used in multiple structures to improve mechanical properties such as ductility, impact, increase tensile strength, resistance to fatigue, and shear strength; adding SF reduces workability [18] [19][20][21].

Steel fiber reinforcement is used for economic benefits by lowering reinforcement in the construction without any decrease in performance, and it is used in SECC with no need for any vibration because of the high workability of concrete. Rana reported that the SF effect on workability is because of the longitudinal shape and high value of surface area/volume; the characteristics are different from cement and aggregate [22]. Microsteel fibers with a golden color, as shown in Figure (1) with an Aspect ratio equal to 100, are used in this study; Table (8) shows the properties of micro steel fibers.

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Table 8: Properties of Micro Steel Fibers

Relative Density	7860 kg/m^3
Yield strength	1130 MPa
Modulus of elasticity	200×10^3 MPa
Strain at portion limit	5650×10^{-6}
Poisson's ratio	0.28
Average length	50 mm
Nominal diameter	0.5 mm
Aspect ratio	100

* These properties were listed from a catalogue of manufacture

Figure 1 Micro Steel Fibers

3.1.8 Polyvinyl Alcohol Fibres

Polyvinyl Alcohol Fibers PVA were used in this study to create bendable concrete, and one of the extraordinary features of these fibers is their strong bonding capability with cement paste[23]. A layer of $Ca(OH)2$, known as an interfacial transition zone, is formed around the PVA fibre, which appears as a white film; this does not occur when using polypropylene and glass. Both Ca+ and OH- PVA fibers attract ions in cement slurry and create a layer of Ca (OH)2 around them; that is to say, the Ca(OH)2 layer plays an imperative role in increasing bonding strength between the fibers and the paste [24].

However, Polypropylene fibers, despite their high tensile strength, are not coated with epoxy due to the absence of surface coating. Thus, they have a high susceptibility to alkali environments [25]. The lengths of the PVA fibres used in the research were between 8 mm and 12 mm, with a diameter of 40µm. as shown in Figure (2).

Figure 2: Polyvinyl Alcohol Fibres

3.2. Concrete Mixes

To achieve the scope of this study, seven mixes based on the mix design method (EFNARC 2002) (24) were divided into three groups based on the type of variables adopted, such as different percentages of steel fibre that were (1,1.5 and 2) %, the percentage of silica fume that was (10,15 and 20) % and the percentage of PVA (Polyvinyl alcohol) that was (0.2,0.3 and 0.4) % have been prepared in this stud, PVA fibers was added by the weight of the concrete, Table (8) shows the details of mixes.

Table 8: Details of concrete mixes

Mix	Cement (Kg/m3)	Fine aggregate (Kg/m3)	silica fume %	PVA %	steel fiber %	Limestone (Kg/m3)	Super plasticizer (L/m3)	Water (L/m3)
M1	400	650	10	0.2	1	250	10	150
M2	400	650	10	0.2	1.5	250	10	150
M3	400	650	10	0.2	2	250	10	150
M4	400	650	15	0.2	1	250	10	150
M5	400	650	20	0.2	1	250	10	150
M6	400	650	10	0.3	1	250	10	150
M7	400	650	10	0.4	1	250	10	150

Concrete specimens are taken off from the molds. After 48 hours, the beams are covered with burlap and wet with water daily for seven days, as shown in Figure (3).

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https://doi.org/10.61268/w4yqhe03

Figure 3: Specimens for Hardened SECC Mix Properties

4. Results and Discussions

4.1 Fresh Concrete Properties

Tests were performed immediately after mixing to examine the filling ability, passing ability, and segregation resistance of fresh SECC. The results were found to lie with EFNARC [26] limitations with slump flow diameter greater than or equal to (24 mm) and flow times range between (7 and 7.5) sec. Figure (3) and Figure (4) show the tests were for the mixture containing a percentage of PVA fibers of 0.3%.

Figure 4 Slump Flow Test

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Figure 5 V-Funnel Test

4.2 Mechanical Properties of Hardened concrete

4.2.1 Compressive Strength (f_{cu}, f'_c)

Cubic specimens (100) mm and cylinder specimens (150×200) mm have been used to estimate the compressive strength and mix according to ASTM C39/C39M2014. [27], as shown in Figure (6).

4.2.2 Splitting Tensile Strength (f_{ct})

The indirect tensile strength test has been done for each mix according to (ASTM C496/C496-04, 2011) [28], With a cylindrical specimen (150×200) mm, as shown in Figure (6).

4.2.3 Modulus of Elasticity (E_c)

The measurement of the modulus of elasticity (E_c) of concrete for each mix specimen has been done according to (ASTM C469-87, 2002.) [29] using cylindrical specimens (150×300) mm, with a curing age of 28 days, as shown in Figure (6).

4.2.4 Flexural Strength (Modulus of Rupture) (f_r)

The flexural strength test was according to (ASTM-C78, 2003) [30] by using one prism with dimension (100×100×500) mm for each mix; the prisms tested with two points loading at age 28 days, as shown in Figure (6).

4.3 Test Result of Control Samples

4.3.1 Group A: Effect of Steel Fiber Ratio

The mechanical properties of hardened concrete for group A are listed in Table (9). The results represented Compressive Strength fcu, Modulus of Rupture fr, Splitting Tensile Strength ft, and Modulus of elasticity EC, as shown in Figure (7), Figure (8), Figure (9), and Figure (10).

Figure 6: Hardened Concrete Testing

Table 9: Mechanical Properties of Group A

MIX	Steel fibre %	fcu MPa	%	f'c MPa	%	ft MPa	%	fr MPa	%	EC GPa	%
M1	1	42.34	---	35.08	---	6.05	---	7.75	---	27837	---
M2	1.5	43.52	3	36.58	4	7.52	20	9.13	15	28426	2
M3	2	46.24	8	38.54	9	9.55	36	11.57	33	29178	5

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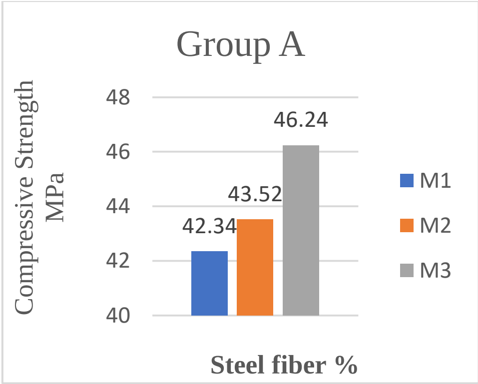

Figure 7: Compressive strength of Group A

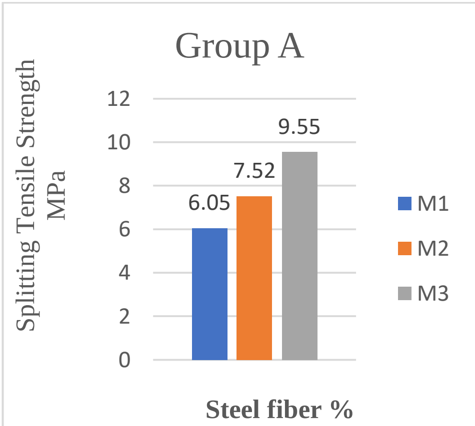

Figure 8: Splitting Tensile Strength of Group A

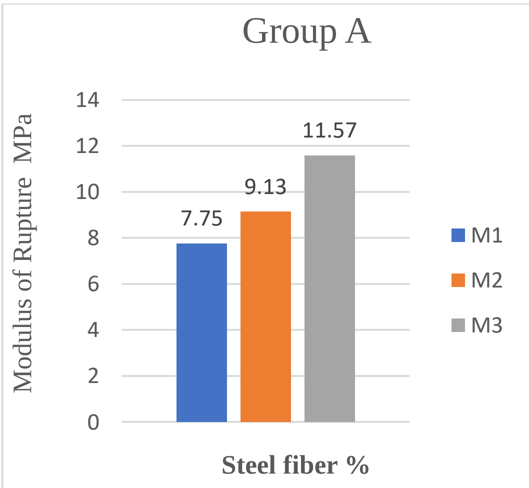

Figure 9: Modulus of Rupture of Group A

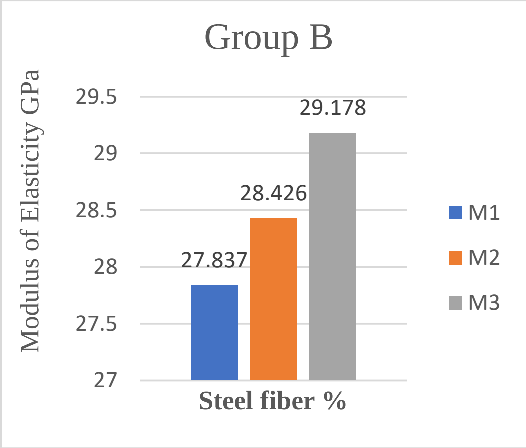

Figure10: Modulus of Elasticity of Group A

An increase in the steel fiber ratio from 1% to 1.5% and 0.2% led to an increase in the compressive strength by about 3% and 8% and the splitting tensile strength by about 20% and 37%, respectively. Also, the value of modulus of rupture and modulus of elasticity when the steel fiber ratio increases from 1% to 1.5% and 0.2% leads to an increase of about (15%, 33%) and (2%,5%), respectively, the steel fibers had a high tensile, compressive and modulus of elasticity, which could effectively stop the development of microcracks in the matrix and improve the strength of the concrete.

4.3.2 Group B: Silica Fume Ratio Content

The mechanical properties of hardened concrete for group B are listed in Table (10). The results represented Compressive Strength Fcu, Modulus of Rupture Fr, Splitting Tensile Strength Ft, and Modulus of elasticity EC, as shown in Figure (11), Figure (12), Figure (13), and Figure (14).

Table 10: Mechanical Properties of Group B

MIX	Silica Fume %	Fcu MPa	%	f'c MPa	%	ft MPa	%	**fr MPa**	**%**	**EC GPa**	**%**
M1	10	42.34	---	35.08	---	6.05	---	7.75	---	27837	---
M2	15	43.31	3	36.51	4	6.90	12	8.13	5	28399	2
M3	20	48.08	10	39.18	7	7.24	16	9.06	14	29419	5

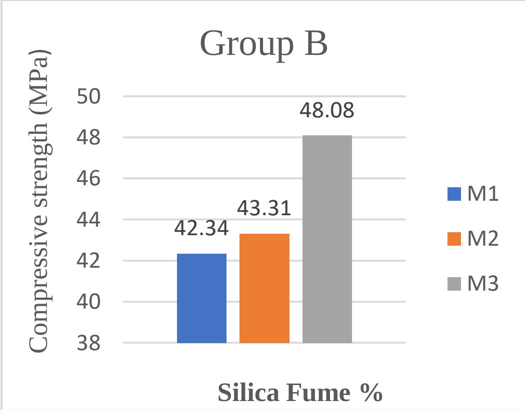

Figure 11: Compressive strength of Group B

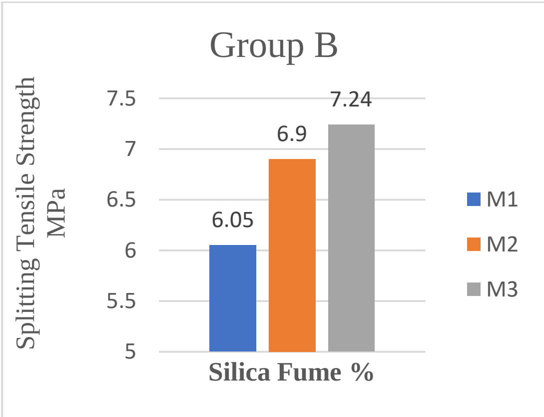

Figure 12: Splitting Tensile Strength of Group B

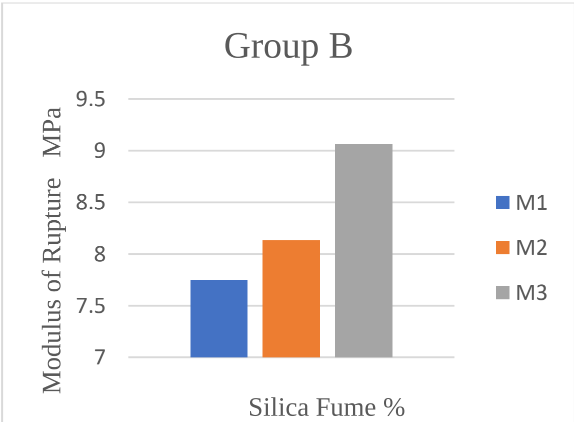

Figure 13: Modulus of Rupture of Group B

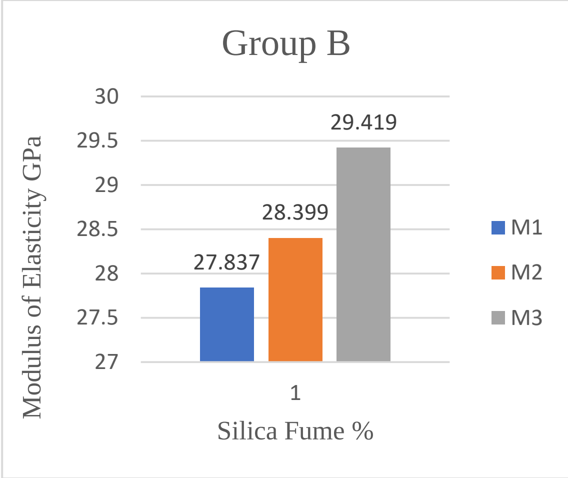

Figure 14: Modulus of Elasticity of Group B

An increase in the silica fume ratio from 10% to 15% and 20% led to an increase in the compressive strength by about 3% and 10% and the splitting tensile strength by about 12% and 16%, respectively. Also, the value of modulus of rupture and modulus of elasticity when the silica fume ratio increases from 10% to 15% and 20% leads to an increase of about (5%, 14%) and (2%,5%), respectively, the increase of the compressive strength of mixtures including silica fume demonstrated the positive effect of partial replacement of cement with fine pozzolanic powders. This participates in filling the voids and pores, which increases the density. The pozzolanic reaction between SiO2 (from powders) and calcium hydroxide, which leads to the formation of new hydrated compounds (hydrated calcium silicate), fills the microspaces and results in higher compaction and strength.

4.3.3 Group C: PVA Ratio Content

The mechanical properties of hardened concrete for group C are listed in Table (11). The results represented Compressive Strength Fcu, Modulus of Rupture Fr, Splitting Tensile Strength Ft, and Modulus of elasticity EC, as shown in Figure (15), Figure (16), Figure (17), and Figure (18).

Table 12: Mechanical Properties of Group C

MIX	PVA %	fcu MPa	%	f'c MPa	%	ft MPa	%	fr MPa	%	EC GPa	%
M1	0.2	42.34	---	35.08	---	6.05	---	7.75	---	27837	---
M2	0.3	43.11	2	35.14	0.2	6.92	13	9.25	16	27861	0.09
M3	0.4	44.25	4	36.57	4	8.1	25	12.75	40	28422	2

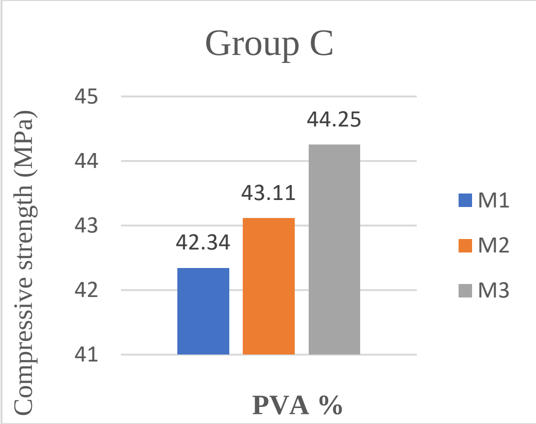

Figure 15: Compressive strength of Group C

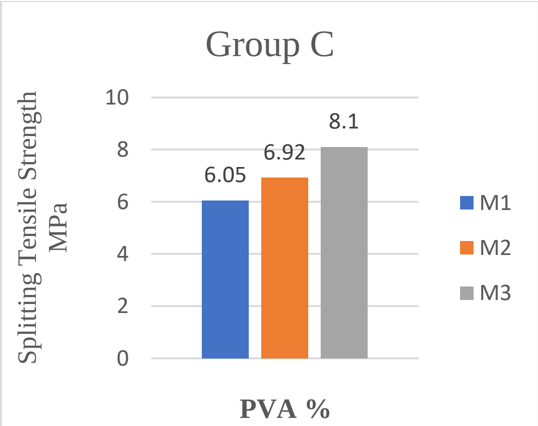

Figure 16: Splitting Tensile Strength of Group C

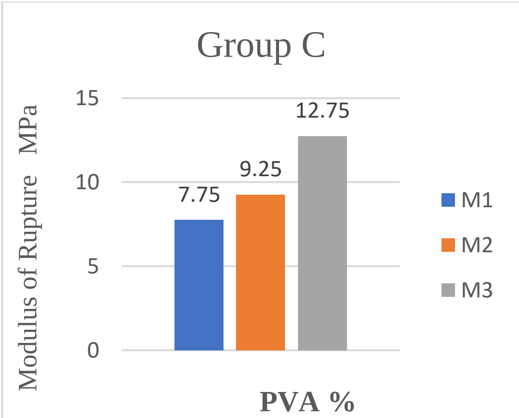

Figure 17: Modulus of Rupture of Group C

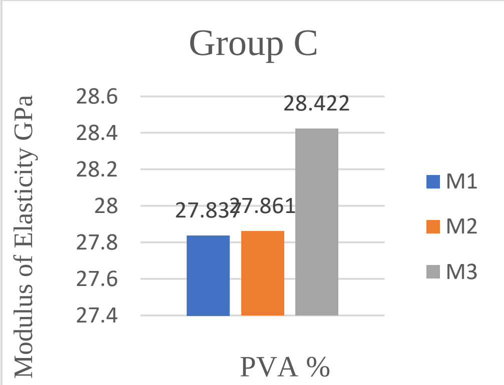

Figure 18: Modulus of Elasticity of Group C

An increase in the PVA ratio from 0.2% to 0.3% and 0.4% led to an increase in the compressive strength by about 2% and 4% and the splitting tensile strength by about 13% and 25%, respectively. Also, the value of modulus of rupture and modulus of elasticity when the PVA ratio increases from 0.2% to 0.3% and 0.4% leads to an increase of about (16%, 40%) and (0.09%,2%), respectively, the improvement in mechanical properties can be attributed to the good bonding effect of both the steel and PVA fibers, which was based on the uniform distribution of the fibers in the matrix. The hybridization of fiber reinforcement can continue to improve the mechanical behavior of composites by controlling the spread of cracks at variable stages of deformation and enhancing the strength of the concrete.

5. Conclusion

The discussions of the results reached are summarized in the following paragraphs:

1. Successfully obtaining bendable, self-compacting concrete is important for concreting areas with dense reinforcement or difficult to compact.
2. The use of bendable and self-compacting concrete has a great benefit in delaying failure, as the components of this concrete help prevent the rapid development of cracks and thus increase its capacity to resist more loading.
3. The presence of PVA fibers improves many of the mechanical properties of concrete, especially its tensile properties, as the presence of these fibers increases the ability of concrete to withstand the applied loads before reaching failure.
4. The mechanical properties were significant when using steel fiber with 1% to 1.5% and 0.2% led to an increase in the compressive strength by about 3% and 8% and in the splitting tensile strength by about 20% and 37%, respectively.
5. the value of modulus of rupture and modulus of elasticity when the PVA ratio

increases from 0.2% to 0.3% and 0.4% leads to an increase of about (16%, 40%) and (0.09%,2%), respectively.

6. The hybridization of fiber reinforcement can continue to improve the mechanical behavior of composites by controlling the spread of cracks at variable stages of deformation and enhancing the strength of the concrete.

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