

Review on the Parameters Affecting the Relative Fiber-Matrix Stiffness of Fiber-Reinforced Concrete (FRC)

Arif Iskandar Mohd Shaharin¹, Masni A. Majid^{1*}

¹Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, 86400, MALAYSIA

²Jamilus Research Centre, Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, 86400, MALAYSIA

*Corresponding Author Designation

DOI: <https://doi.org/10.30880/rtcebe.2022.03.01.064>

Received 4 July 2021; Accepted 13 December 2021; Available online 15 July 2022

Abstract: Fiber-reinforced concrete (FRC) is an innovation that has been gaining interest by many researchers and those affiliated with the construction industry regarding ways on how to improve the strength of conventional concrete to sustain loads over time. Fiber-reinforced concrete is defined as concrete that contains fibers which can boost the tensile strength of the structure. Steel fibers, synthetic fibers, glass fibers, and natural fibers are some of the most well-known fibres, and each type of fibre imparts different qualities to concrete. Furthermore, different type of concretes, fibre types, geometries, densities, distribution and orientation of the fibers affect the properties of fiber-reinforced concrete. Despite the different type of materials of fiber, there are five types which is differentiate by its physical features such as hooked-end fibers, flat-crimped fibers, flat-end fibers, round-crimped fibers and double-anchored fibers. The problem that is issued is the parameters that can either increase or not in increasing the structural strength of fiber-reinforced concrete. The goal of this research is to study into the elements that influence fiber-reinforced concrete, as well as the variables that determine one of those aspects, relative fiber-matrix stiffness. According to studies, the hooked-end type of fiber gives the highest strength towards fiber-reinforced concrete depending on the materials among those five types of fiber which is flat-crimped fibers, flat-end fibers, hooked-end fibers, round-crimped fibers and double-anchored fibers. It was found that the hooked-end type of fibers has the highest strength when being studied in each parameter with toughness of 210 Nmm.

Keywords: Fiber Reinforced Concrete, Reinforced Concrete Beam, Relative Fiber-Matrix Stiffness

1. Introduction

Concrete is a necessary construction material, whether for structures or pavements. Formability is one of the primary advantages of concrete over other traditional building materials, although it has significant disadvantages, notably strain capacity and low tensile strength [1]. Nevertheless, every day innovations are produced to solve problems and issues for customers. Because of this, there has been a lot of changes added. Fibers are commonly used in concrete to avoid plastic shrinkage and shrinkage. Reduces concrete permeability, lessening water leakage. Resistant to impact, abrasion, and shattering. Steel or synthetic fibers may totally replace rebar or steel in some instances. As far as tunnels are concerned, reinforced concrete is a much more popular material. This means that some fibers lower concrete's compressive strength. Short steel-reinforced concrete uses shortened linear fibers for reinforcement. The fibers can be created from several substances. Strength of different types of fibers differs.

Steel reinforcement is protected with nearly half of the concrete in typical building elements. Concrete's decreasing strength has become a significant problem for the building industry because of the costs of materials, sustainable construction, and increasing population. Constant research has been done on efficient ways to boost concrete strength. This concrete reinforced with fiberglass gives designers and engineers more flexibility. But using fiber-reinforced concrete in building is a considerable challenge. The building business lacks vital information. Conform to findings from previous studies regarding fiber-reinforced concrete [2]. Developers have not taken fiber-reinforced concrete seriously because it costs more and is still underutilised. Using fiber-reinforced concrete in building construction results in sustainable building. Several studies suggest that concrete failure is remedied by introducing short steel fibers of tiny diameter into the concrete mix [3].

The objective of this study is to identify types of fiber-reinforced concrete, the factors affecting on fiber-reinforced concrete and to determine the parameters affecting the relative fiber-matrix stiffness on fiber-reinforced concrete. This study compares the data reviewed by past studies on the strength of each types of fiber. This review study can be used for future references on the effects of relative fiber-matrix stiffness towards fiber-reinforced concrete.

2. The Factors Affecting the Relative Fiber-Matrix Stiffness of Fiber-Reinforced Concrete (FRC)

The different sorts of fibers that we have in our natural resources can be incorporated into the concrete because of their abundance. Interlinking fibers in fiber-reinforced concrete prevent the structure from cracking, but speed up the process. The interlocking threads are the bond in the concrete, which is dispersed over it to create a stronger structure. Fiber form could be round or flat. The aspect ratio of fibers in concrete might vary based on the type and strength of the fibers. Thus, this differentiates the way it controls the structure's fracture. Plastic shrinkage and drying shrinkage cause concrete to employ concrete sealants frequently. Reducing concrete permeability reduces water leakage [1].

Costs of making fiber-reinforced concrete will be affected by its solidity properties, harsh conditions, and the best aspect ratio of the fibers. For the aspect ratio of the fibers, it is necessary to include a combination of weight, materials, and use [1]. It should also be worried in addition to the fibers that the aspect ratio of the fibers needs to conform with the intended load of the concrete and the types of fibers being utilised. Physical and mechanical behavior of fiber-reinforced concrete is complimented by standardised test protocols, such as C1399, C1609, C1550, and C1579. In this case, it's customary to base the specifications on these criteria [3].

Fibers may be categorised into two categories based on their flexibility. Built on their elasticity module, fibres can be divided into two types: those with a bigger elastic module than the concrete mix, known as hard intrusion, or those with a lower module known as soft intrusion. Steel, carbon and glass

have higher elastic modules than cement mortar. Polypropylene and vegetable fibres have lower elasticity modules. High elastic module fibres can enhance flexural and shock resistance while low elastic module fibres can improve shock, but not flexural resistance [4].

2.1 Factors Affecting Fiber-Reinforced Concrete Properties

Fiber-reinforced concrete (FRC) is a composite material that incorporates fibers in a cement matrix that is either ordered or randomly distributed. Its qualities would obviously be determined by how well stress is transferred between the matrix and the fibers.

2.1.1 Relative Fiber-Matrix Stiffness

For a successful stress transfer the modulus of elasticity of the matrix must be much lower than that of the fibre. Low modular fibres, like nylon and polypropylene, will not increase strength, but may be able to absorb a great deal of energy and thus provide more resistance and toughness. The HDPE fibers, which were employed at a volume of 0.25%, had a diameter of 0.25mm and 0.40% [5]. The results have demonstrated that HDPE fibers have not improved the compressive strength and modulus of elasticity and even a little additional HDPE fiber resulted in the early reduction of plastic shrinkage cracking of concrete that reduces the crack width by more than 50 percent by a volume fraction of 1.25 percent of HDPE fibers, which is 0.40mm diameter.

Table 1: Compressive Strength and Tensile Strength Result [5]

Concrete Property	Units	Age (days)	Plain	Ø0.25 mm fibers				Ø0.40 mm fibers		
			C1	C2	C3	C4	C5	C6	C7	
Elastic modulus										
E_c	GPa	28	24.2	24.5	24.9	25.2	24.2	25.9	25.5	
Compressive Strength										
$f_{ck} (cube)$	MPa	28	33.2	34.3	31.1	32.3	31.0	31.0	30.5	
$f_{ck} (cube)$	MPa	90	38.1	40.1	38.4	37.7	37.2	37.7	38.7	
$f_{ck} (cyl)$	MPa	28	23.3	26.2	24.1	23.4	24.1	26.6	23.5	
Tensile Strength										
$f_{ct} (cyl)$	MPa	28	2.79	3.08	2.95	2.96	3.03	2.93	2.88	
$f_{ct} (cyl)$	MPa	90	3.32	3.47	3.49	3.43	3.40	3.47	3.53	
f_{ctm}	MPa	28	3.84	4.35	4.14	4.37	4.01	4.05	3.96	

2.1.2 Volume of Fiber

In regards of experimenting the strength properties of concrete, J.M. Irwan [6] studies the concrete with PET fiber content in sequences of 0.5%, 1.0%, and 1.5% from the volume of the split. From their experiment, they found that the solidity of the concrete is affected by the fiber content. They also showed that strong fibers helps in contribute to an improvement in concrete strength and ductility. However, due to the inclusion of excessive fiber dosages, their large surface area causes challenges in terms of workability.

Table 2: Mix proportions [6]

Specimens	W/C ratio	Unit weight [kg/m^3]				Fiber volume fraction [%]	Density of PET [kg/m^3]
		C*	FA*	CA*	W*		
NC*						0	0
PET FRC 0.5	0.65	290	900	982	185	0.5	0.9
PET FRC 1.0						1.0	1.8
PET FRC 1.5						1.5	2.7

*NC = Normal concrete, C = Cement, FA = Fine aggregate, CA = Course Aggregate. W = Water

Table 3: Result of compressive strength and modulus of elasticity (MOE) test [6]

PET content [%]	Compressive Strength [MPa]			MOE [GPa]
	7 days	14 days	28 days	
0	16.43	19.73	22.00	24
0.5	15.70	16.45	24.00	26
1.0	16.06	18.79	21.90	22
1.5	14.44	16.29	20.93	19

2.1.3 The Aspect Ratio of Fiber

Naaman [7] tried to test the strength characteristics of reinforced concrete in high-gravity polyethylene fibers with different fiber content from 0% to 6% and showed a 10.63% increase in Compressive strength by 15.76% in Split strength Flexible strength by 13.9%. Since HDPE is a non-bio-degradable substance, it is of great utility for concrete construction, as it gradually improves the strength of 11.25% in 7 days and increases 10.63% after 28 days. The results of this comparison were compared with simple concrete and Shi Yin [8], who used virgin and recycled polypropylene fibers with 0.67% and 0.45% volume fractions in M40 and M25, respectively. They concluded that the addition of these Polypropylene fibers did not affect compressive strength, but a significant improvement in residual flexural strength was made.

Table 4: Concrete mix proportions [8]

Material	40MPa Concrete	25 MPa Concrete
0.6-4.75 mm Coarse sand (kg/m^3)	350	410
6.7-9.5 mm Concrete aggregate (kg/m^3)	950	260
0.3-5 mm Crusher dust (kg/m^3)	220	200
0.075-0.3 mm Fine sand (kg/m^3)	290	350
9.5-19 mm Concrete aggregate (kg/m^3)	-	690
Fly ash (kg/m^3)	130	134
Cement (kg/m^3)	256	186
Polyheed 8190 admixture (ml/100 kg cementitious materials)	337	281
Air entrainment admixture (ml/100 kg cementitious materials)	-	22
Water (l/m^3)	105	116
PP fiber (kg/m^3)	6	4

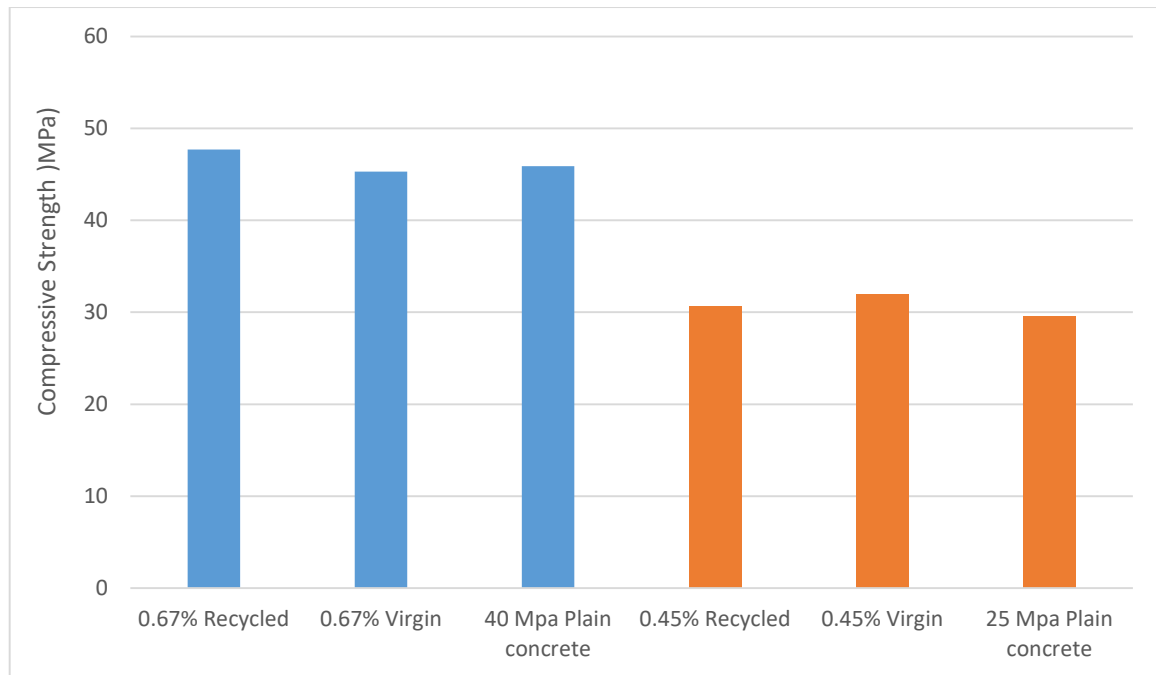


Figure 1: Result of Compressive strength of 0.67% fibre reinforced 40 MPa concrete and 0.45% fibre reinforced 25 MPa concrete cylinders [8]

3. Parameters Affecting the Relative Fiber-Matrix Stiffness of Fiber Reinforced Concrete

Fiber and matrix variables determine the connective strength of the FRC fibre matrix interaction. So far, a lot of fibre matrix pull-out behaviour has been researched. Factor that were most attractive in these researches are the type and shape of Fiber, Fiber Alignment (orientation), Fiber Surface treatment, Matrix strength and Composite, and loading rate. However, only a few researches have considered the length and size of the embedded fibre. The pull-out behaviour of hook-end fibres with embedding lengths below 10 mm seems to be little informed according to the findings [9].

3.1 Types of Fiber

The most extensive study on the effect of fiber type on the fiber-matrix connection was undertaken by Chin and Xiao [10] conducted the most comprehensive study how fiber types are affecting the fiber-matrix connection. All flat-crimped, flat-end, hooked-end, round-crimped, and double-anchored steel fibers were explored in this research. With the highest pull charge is the flat-crimped fiber (approximately 1.2 kN for fibers with 50 mm length and 1.14 mm equivalent diameter). The pullout strength of flat-end steel fiber (10.8 Nm for fibers with 50 mm length and 1.00 mm equivalent diameter) was the highest. Increasing the size, quantity, severity, or grade of fiber deformation improves ultimate pull load while lowering pullout strength. The fiber-matrix connection of hooked-end steel fibers and 3D steel fibers was similar [11]. The fibre strength in 3D fibres was more than three times that of crochet steel fibre when the contact of the matrix of fibre was investigated. Crooked fibres have been found to be stronger than 3D fibres.

3.2 The Fiber Alignment

According to Naaman [7], increasing fiber alignment in the loading direction improves fiber pullout load and ultimate load response. However, Robins [12] observed that the strength of crimped-end fibers and rounded-end fibers decreases as the alignment angle of the fiber increases. Table 2.2 illustrates the findings. Furthermore, these researchers noted that increasing fiber orientation enhances pullout toughness unless fiber breakage occurs, with maximal toughness occurring at 10° - 20° angles of fiber

orientation. By, modifying the fiber orientation, the ultimate pullout load measured from straight fibers might be raised by 50%.

Table 5: Mix proportions and mix properties [12]

Constituents	Mix Preferences		
	A	B	C
Cement (kg/m^3)	540	515	490
Silica Fume (kg/m^3)	0	25	50
Water (kg/m^3)	245	245	245
Aggregate (kg/m^3)	1510	1510	1510
Superplasticiser (% by weight of cementitious material)	0.65	1.0	1.5
Properties	A	B	C
Slump (mm)	80	90	90
Compressive Strength (MPa)	60	68	72
Density (kg/m^3)	2240	2225	2230

A study suggest ultimate fiber orientation load for hooked fibers is interdependent. Due to the increase in bridging effect of the fiber and the orientation of the fiber and matrix spalling, Lee [16] concluded that the optimal range of fiber orientation is 30° - 45° which yields the maximum bridging performance. Increased fiber orientation increases the likelihood of fiber tensile failure or matrix spalling, according to experts [14].

3.3 Matrix Strength and Composition

The final load of pull is often raised by raising the strength of the matrix. Further, with the increasing strength of the matrix but not to the extent that the fiber tensile failure is possible the general performance of the fiber-matrix interactions improves. Robins [12] have found that increasing the matrix strength also increases the tightness and the ultimate response of hooked-end steel fibers that are orientated to the loading direction. On the other hand, the fiber orientation angle increases, and the rate of growth decreases. Increased matrix strength increases the likelihood of failure of the fiber and/or matrix [14]. It should be emphasized that increasing matrix strength enhances the maximum lift load and toughness for only deformed fibers, Abu-Lebdeh [15] says; but matrix strength has little effect on some straight fibers' pull-out behavior. Moreover, the increasing strength of the pullout is greater than the ultimate rise of load in high-strength concrete. The final load of pull is often raised by raising the strength of the matrix. Further, with the increasing strength of the matrix but not to the extent that the fiber tensile failure is possible the general performance of the fiber-matrix interactions improves. Robins [12] have found that increasing the matrix strength also increases the tightness and the ultimate response of hook-end steel fibers that are orientated to the loading direction. On the other hand, the fiber orientation angle increases, and the rate of growth decreases. Increased matrix strength increases the likelihood of fiber tensile failure and/or matrix spread [14].

Slurry Infiltrated Fiber Concrete (SIFCON) mixing proportions were studied by Tuyan & Yazici [16] using the single fiber pullout test for the fiber-matrix bond. It was noted that increasing SIFCON's strength increases the interaction between the fiber-matrix. For SIFCON, during normal water and steam curing a connection was established between the fiber-matrix bond and the matrix strength, but this did not occur during autoclave curing. The effect of conventional aging on fiber-matrix interfacial relationships was investigated [14]. Following two days of cure, the maximum interfacial fiber-matrix

bond was found (Figure 2). Although water treatment increased the strength of the matrix for more than two days,

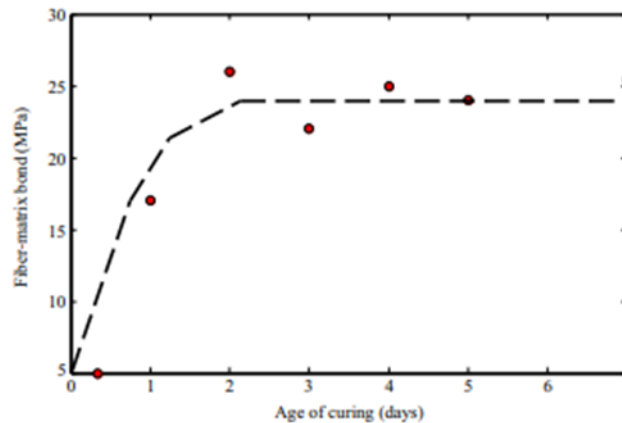


Figure 2: The curing age of the fiber-matrix bond effects [14]

Wille and Naaman [17] also showed that increased matrix strength is important to improve the bond strength of the fiber-matrix but does not assure extraordinarily strong fiber-matrix bonds are developed. Tuyan and Yazici [16] examined the effect of different circumstances on the SIFCON fiber-matrix bond (normal, steam, and autoclave). As the curing conditions improve, the interface between the fiber and matrix improves. Autoclave cure, which transformed fiber mode to tensile failure, was the highest in the matrix fiber bond. After eight hours of steam treatment, the fiber matrix binding was the same as after ordinary water treatment for 28 days. The fiber-matrix interactions of FRC constructed using AR-glass (alkaline resistance) fibers in early years, were explored by both experimental and numerical methods. He determined that the fiber's size, type, and material and the increase of its strength affect the distribution of stress and the fiber [14]. The influence of the fine aggregate on the fiber-matrix bond on straight, hooked, and twisted fibers was looked at Kim [18]. Only twisted fibers showed an increase in the fiber-matrix interfacial connection when the sand-to aggregate ratio (S/a) rose from 0.444 to 0.615. The sand to aggregate ratio does not impact the fiber matrix link, however, in both straight and hooked fibers. It is due to improved mechanical interactions of the matrix microstructure and fiber-matrix in twisted fiber. The rise in fine aggregation to coarse aggregate was achieved with the reduction of coarse aggregate content.

3.4 The Length of Fiber

According to Robins [12], increasing the hook steel fiber length from 12 to 25 mm increased the fiber pullout load across a limited range. According to Shannag [19], increasing the embedment depth of straight steel fibers by 200–300% can increase ultimate pullout load and pullout toughness. The performance of the fiber-matrix interface during fiber pullout changes as the fiber embedment length grows. However, a constant average fiber-matrix bond was reported for different embedment lengths for polypropylene fibers.

Tuyan and Yazici [9] investigated the SIFCON fiber-matrix under different embedment lengths. The ultimate pullout load can be increased by increasing the fiber embedment length in the SIFCON matrix from 10 mm to 30 mm. Increased embedding length of coconut fibers improves ultimate pullout load and toughness, according to Ali [20]. As a result, the micromechanical model (Model-1 in Figure 3) that assumed a continuous interfacial connection along the fiber's length was proven to be erroneous. This was due to the Poisson effects of the fiber.

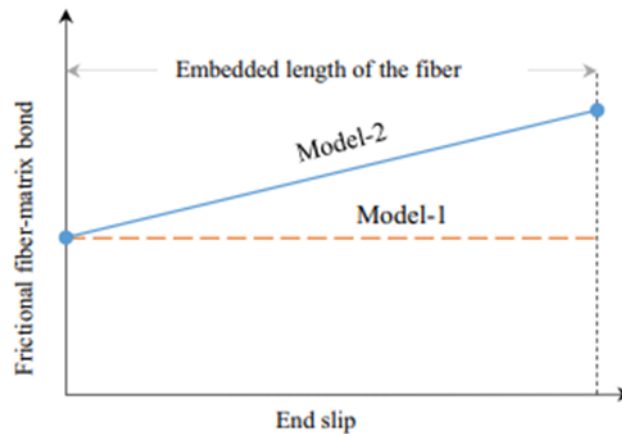


Figure 3: The fiber-matrix bond model [20]

4. Discussions

This chapter will go over the study review analysis on the factors that influence relative fiber-matrix stiffness in fiber-reinforced concrete, such as fiber kinds, fiber alignment, matrix strength and composition, and fiber length.

4.1 Analysis on Types of Fiber

Figure 4 shows the pullout load using flat-crimped fibers, flat-end fibers, hooked-end fibers, round-crimped fibers and double-anchored fibers. The maximal pullout load is 1.2 kN for fibers with 50 mm length and 1.14 mm equivalent diameter, as determined by Chin and Xiao [10] in prior research. Richardson and Heather [11] also show that increasing the size, number, intensity, or degree of fiber deformations increases ultimate pullout load while lowering pullout toughness, and vice versa.

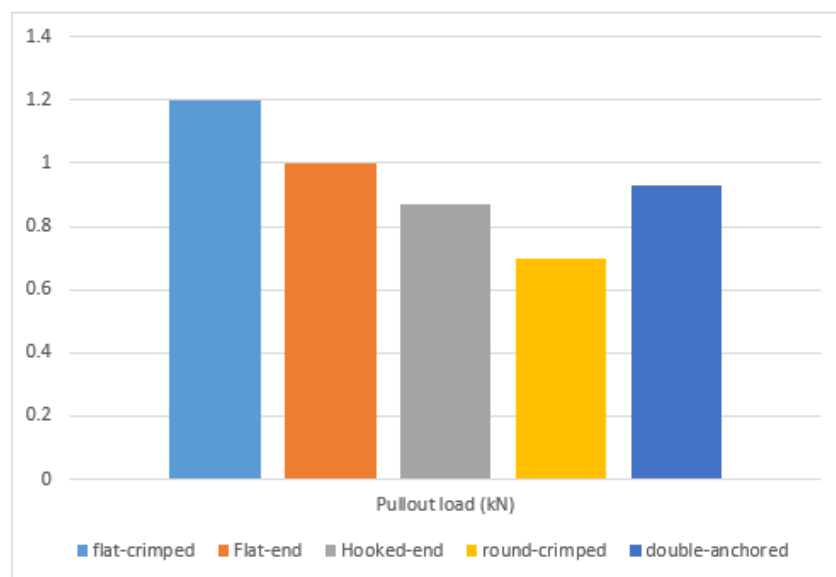


Figure 4: Pullout load based on types of fiber

4.2 Analysis on Alignment of Fibers

Figure 5 shows the pullout load using (A) flat-crimped fibers, (B) round-crimped fibers and (C) hooked-end fibers. Pullout toughness rises with fibre orientation, peaking at 10°-20° fibre orientation angles. With increasing fibre alignment angles, the toughness of all fibres decreases. In a 10° alignment angle, the highest pullout load borne by hooked-end fibres is 210 Nmm.

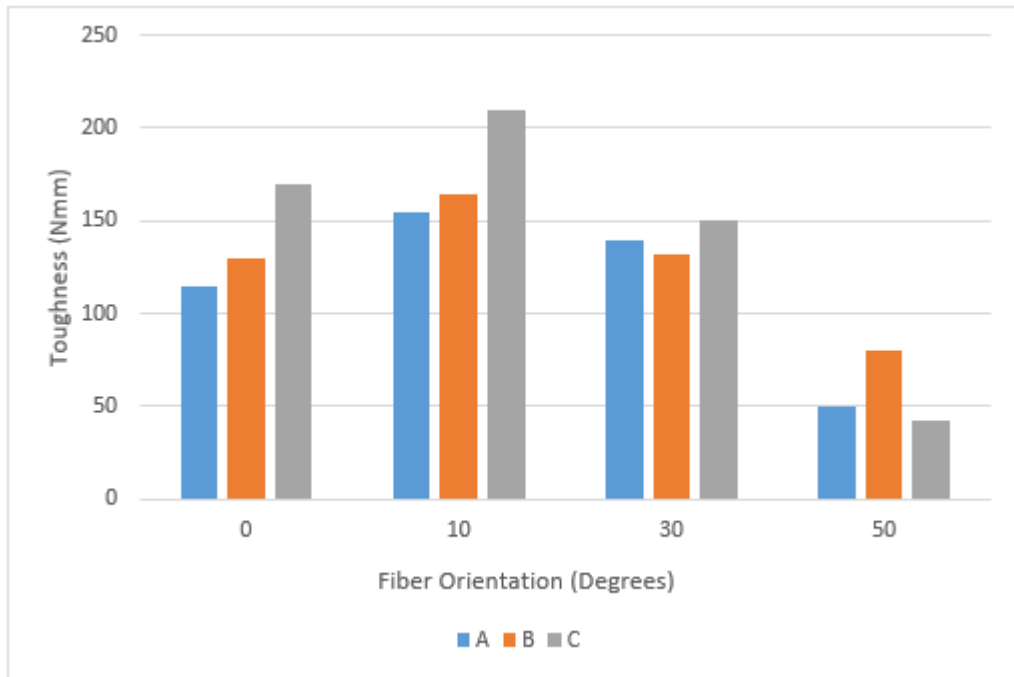


Figure 5: Toughness against orientation of fibers (degrees)

4.3 Analysis on Strength and Composition of the Matrix

Figure 6 shows the pullout load using (A) flat-cripped fibers, (B) hooked-end fibers and (C) round-cripped fibers. The graph illustrates that as the matrix strength grows, so does the peel pullout toughness and final reaction. However, when the fiber orientation angle increases, the rate of growth slows. As a result, the alignment angle affects fiber toughness. It can also be determined that the stress distribution along the fiber is influenced by the development of concrete strength as well as the fiber's size, type, and material.

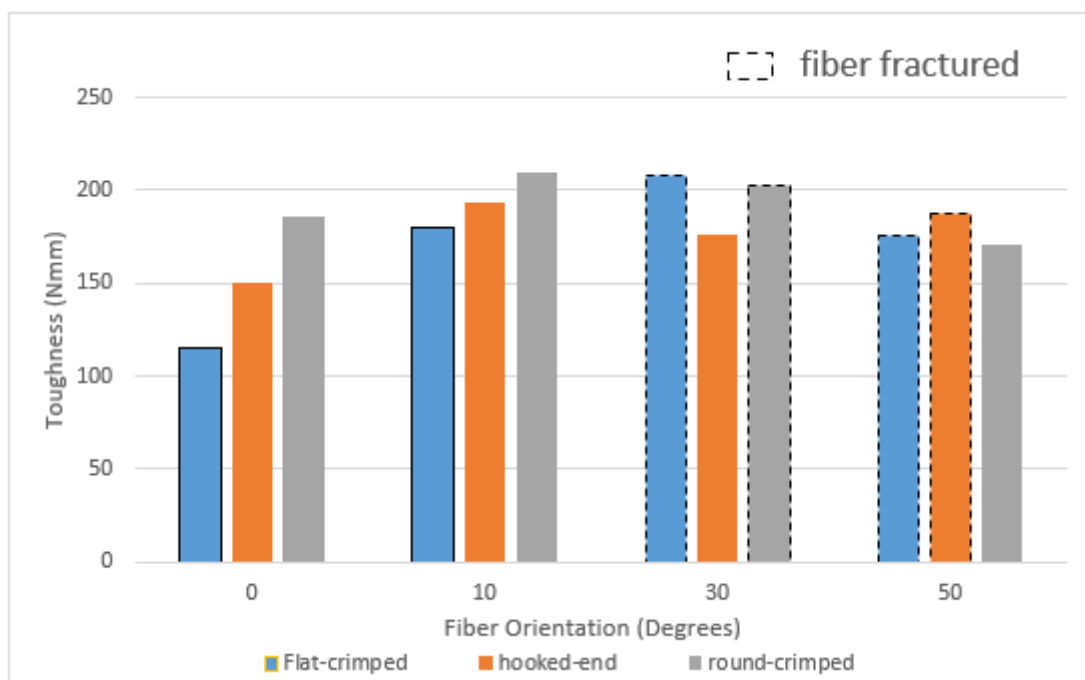


Figure 6: Toughness against orientation of fibers (degrees)

4.4 Analysis on Length of Fiber

Improve the embedment length and orientation of a hooked-end fiber to increase the size and harshness of the pullout reaction (concerning the loading direction). The hooked-end can only be fully bent (resulting in maximum peak pull-out load and toughness) if the total fiber embedment length is greater than the hooked-end length; otherwise, the hooked-end will only be partially straightened, resulting in a significant reduction in pullout performance. This result can be seen in Figure 4.4.

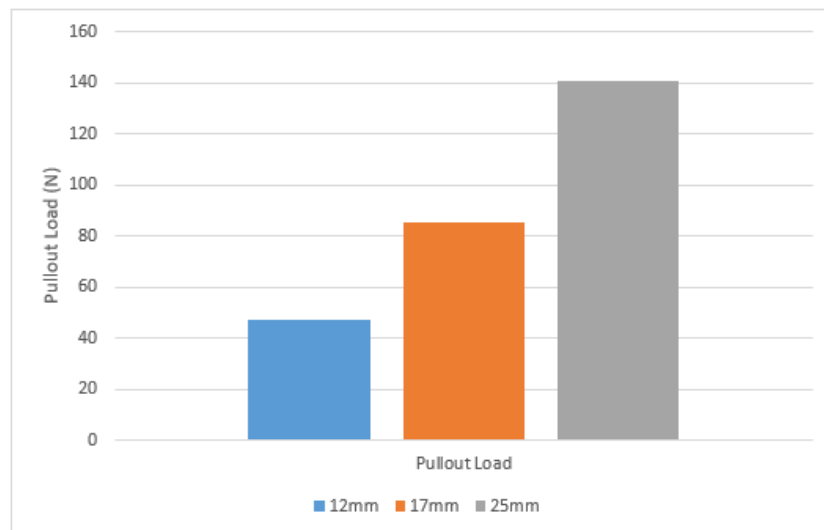


Figure 7: Pullout load against length of fibers (degrees)

5. Conclusions and Recommendations

The parameters that influences the factor of relative fiber-matrix stiffness of fiber-reinforced concrete were emphasized in this research. The feasibility of each parameters in increasing strength of fiber-reinforced concrete is evaluated. The following conclusions may be derived from the findings of this study:

According to studies, the hooked-end type of fiber gives the highest strength towards fiber-reinforced concrete depending on the materials among those five types of fiber which is flat-crimped fibers, flat-end fibers, hooked-end fibers, round-crimped fibers and double-anchored fibers. The parameters are observed from the pullout load and toughness of the fibers by separating them into each parameter. Even though all the parameters are interlinked, the studies of each parameters can differentiate and accomplishing every result for each parameter.

Although a significant number of experimental tests were carried out to investigate the effects of each parameter that could affect the strength of fiber-reinforced concrete (FRC), the optimal test and result for attaining the best results were still not found. In addition, further research is needed to improve the interaction between the factors influencing the properties of fiber-reinforced concrete and the parameters acting on those factors that will affect fiber-reinforced concrete in the process of collecting and analyzing the data obtained from the study. Further study and analysis are required in order to quantify and better understand the processes involved with the usage of internally bonded fibre-reinforced concrete (FRC) systems for strength and shear applications. New design models and detailed guidelines may be created as a result of this. These new design standards should, without a doubt, result in more cost-effective, simpler, and safer uses of fibre reinforced concrete (FRC).

Acknowledgement

The authors would also like to thank the Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia for its support.

References

- [1] Wafa, F. F. (1990). Properties & applications of fiber reinforced concrete. *Engineering Sciences*, 2(1).
- [2] Wu, H., Lin, X., & Zhou, A. (2020). A review of mechanical properties of fibre reinforced concrete at elevated temperatures. *Cement and Concrete Research*, 135, 106117.
- [3] Nishane, U. R., & Thakare, N. U. (2017). Experimental studies on fiber reinforced concrete (FRC). *Int. Journal of Engineering Research Application*, 7, 40-44.
- [4] Arunakanthi, E., & Kumar, J. C. (2016). Experimental studies on fiber reinforced concrete (FRC). *International Journal of Civil Engineering and Technology*, 7(5), 329-336.
- [5] Pešić, N., Živanović, S., Garcia, R., & Papastergiou, P. (2016). Mechanical properties of concrete reinforced with recycled HDPE plastic fibres. *Construction and building materials*, 115, 362-370.
- [6] Irwan, J. M., Asyraf, R. M., Othman, N., Koh, K. H., Annas, M. M. K., & Faisal, S. K. (2013). The mechanical properties of PET fiber reinforced concrete from recycled bottle wastes. In *Advanced Materials Research* (Vol. 795, pp. 347-351). Trans Tech Publications Ltd.
- [7] Naaman, A. E. (2008). High performance fiber reinforced cement composites. Naaman AE. *High-performance construction materials: science and applications*. Singapore: World Scientific Publishing, 91-153.
- [8] Yin, S., Tuladhar, R., Shi, F., Combe, M., Collister, T., & Sivakugan, N. (2015). Use of macro plastic fibres in concrete: A review. *Construction and Building Materials*, 93, 180-188.
- [9] Tuyan, M., & Yazıcı, H. (2012). Pull-out behavior of single steel fiber from SIFCON matrix. *Construction and Building Materials*, 35, 571-577.
- [10] Chin, C. S., & Xiao, R. Y. (2012). Experimental and nonlinear finite element analysis of fiber cementitious matrix bond-slip mechanism. In *High Performance Fiber Reinforced Cement Composites 6* (pp. 145-152). Springer, Dordrecht.
- [11] Richardson, A., & Heather, M. (2013). Improving the performance of concrete using 3D fibres. *Procedia Engineering*, 51, 101-109.
- [12] Robins, P., Austin, S., & Jones, P. (2002). Pull-out behaviour of hooked steel fibres. *Materials and structures*, 35(7), 434-442.
- [13] Lee, Y., Kang, S. T., & Kim, J. K. (2010). Pullout behavior of inclined steel fiber in an ultra-high strength cementitious matrix. *Construction and Building Materials*, 24(10), 2030-2041.

- [14] Abbas, Y. M., & Khan, M. I. (2016). Fiber–matrix interactions in fiber-reinforced concrete: a review. *Arabian Journal for Science and Engineering*, 41(4), 1183-1198.
- [15] Abu-Lebdeh, T., Hamoush, S., Heard, W., & Zornig, B. (2011). Effect of matrix strength on pullout behavior of steel fiber reinforced very-high strength concrete composites. *Construction and Building Materials*, 25(1), 39-46
- [16] Tuyan, M., & Yazıcı, H. (2012). Pull-out behavior of single steel fiber from SIFCON matrix. *Construction and Building Materials*, 35, 571-577.
- [17] Wille, K., Tue, N. V., & Parra-Montesinos, G. J. (2014). Fiber distribution and orientation in UHP-FRC beams and their effect on backward analysis. *Materials and structures*, 47(11), 1825-1838.
- [18] Kim, J. J., Kim, D. J., Kang, S. T., & Lee, J. H. (2012). Influence of sand to coarse aggregate ratio on the interfacial bond strength of steel fibers in concrete for nuclear power plant. *Nuclear Engineering and Design*, 252, 1-10.
- [19] Shannag, M. J., Brincker, R., & Hansen, W. (1997). Pullout behavior of steel fibers from cement-based composites. *Cement and Concrete Research*, 27(6), 925-936.
- [20] Ali, M., & Chouw, N. (2013). Experimental investigations on coconut-fibre rope tensile strength and pullout from coconut fibre reinforced concrete. *Construction and Building Materials*, 41, 681-690.