



An evaluation of the interfacial bond strength of kenaf fibrous concrete and plain concrete composite

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ABSTRACT

The deterioration of concrete structures is a matter of critical concern as it threatens the durability and strength of concrete structures. Kenaf fibrous concrete composite (KFCC) can be used with advantage in new structures such as precast elements, as well as the strengthening, repair and rehabilitation of old structures to improve their durability properties. These structures are composite components, with parts as Plain concrete (PC) and others as KFCC. This study, therefore, investigated the interfacial bonding behaviour between KFCC and PC. Shear, tensile and compressive tests were carried out to measure the bond strength in shear, direct tension and compression respectively for PC to PC, PC to KFCC and KFCC to KFCC interface. Three different types of concrete grade (25, 35, and 45 MPa) were produced for the KFCC and one type of concrete grade (35 MPa) for the substrate PC. The outcome of the test showed that KFCC had an excellent interlock with the surface of the PC substrate, and thus, gives bond strength greater than the strength of PC. New concrete with the highest concrete grade of 45 MPa ensued in high compressive, tensile and shear bond strength.

1. Introduction

Concrete infrastructures in most countries around the world are facing a rapid loss of serviceability, safety and suffering damages from increasing and unpredictable live loads which they are exposed and subjected to in service (Shin and Wan, 2010; Banthia *et al.*, 2014). These civil infrastructures such as roads, sewers, and the built infrastructure of commercial, domestic and public buildings are the basis of any community's health, safety and prosperity. Consequently, they must be kept in good and functional state at all time (Banthia *et al.*, 2014). In response to infrastructure damaged, new construction materials that are sustainable, reliable, effective and economical such as bio composites are used in constructing overlay and patching the damaged or deteriorating part of the structures (Tayeh *et al.*, 2013a; Denarić and Brühwiler, 2006). Bio composites or green materials are the next solutions for sustainability approach in building material and structures nowadays (Drzal *et al.*, 2001). The usage of bio composites in engineering application is meant to achieve the target of creating a green building. Bio composites contain natural fibres which offer lots of advantages such as renewability, recyclability, biodegradability, low specific gravity and provide high specific strength (Izran *et al.*, 2014; Yatim *et al.*, 2011). Using bio composites in the construction industry will also help to reduce the manufacturing of petroleum-based material which helps in reducing cost efficiently. Combination of two different concretes is common in the building structures. Bonding of two concretes plays an essential role in the effectiveness of the structural system. Different strength of concrete, different ages of concretes and type of the concretes affect the bonding strength mechanism at the interface.

There are some parameters also included that influence the interfacial bonding behaviour such as moisture condition, amount of reinforcement

crossing the interface, the compression resistance of weaker concrete, the roughness of the interface mode, the presence of cracking or the stress caused by the normal forces that are acting across the interface (Casal, 1960). Application of biocomposites in enhancing the bonding of concretes will gradually help to increase the efficiency of the building system. The mechanism behaviour of the combination of concretes plays an important role in the structural system. Many applications involved in the bonding of concretes such as repairing, casting joints or precast element connection requires large amounts of cement in them for them to develop an adequate bond with the substrate.

In the context of sustainability, an equally grave concern is that cement production is an environmentally damaging process that generates five percent of global CO₂ emissions (Banthia *et al.*, 2014). Nevertheless, the global production for cement is still increasing, and it was estimated at 4.3 billion tonnes in 2014, translating into a 6.7% increase compared to 4Bt produced in 2013 (The European Cement Association, 2014). Consequentially, the global construction industry is under pressure to dramatically reduce its CO₂ emissions (Banthia *et al.*, 2014). Using Kenaf fibres in the concrete has been proved to overcome the problem since Kenaf can absorb three times CO₂ compare to other plants (Lam and Jamaludin, 2015; Ogunbode *et al.*, 2015). The use of KFCC as replacement of existing conventional concrete to be used for repairing and rehabilitation purpose may give a great impact in engineering application towards sustainability. Recently, many entities have used use bio fibres in the reinforcement of Portland cement concrete (PCC) structures to increase the tensile strength, flexural strength, tensile ductility, flexural toughness, reducing the drying shrinkage, density of concrete and infusing the concrete with self-strain sensing capability of the concrete composite

(Ogunbode *et al.*, 2016; Lam and Jamaludin, 2015; Ramaswamy *et al.*, 1983; Hasan *et al.*, 2012; Ali *et al.*, 2012; Nadgouda, 2014; Vajje and Krishna, 2013; Filho and Joseph, 1999).

Research outcome has shown biofibrous concrete composites (BFCC) to possess the potentials that make it suitable for repair, retrofitting, rehabilitation of reinforced concrete structures (RCS) and as new construction material (Banthia *et al.*, 2014). Such attributes associated with BFCC as described by Parveen *et al.* (Parveen *et al.*, 2012) is its lightweight, improved durability, ductility, sustainability and relatively low cost of production. The improved durability and low density of BFCC related with its flexural and tensile properties make the main idea to use it in rehabilitating and strengthening the regions where the structure is exposed to high mechanical loading and severe environmental stress worthwhile. All other parts of the structures remain in normal structural concrete as these parts are subjected to relatively reasonable exposure. Usually, there always exists a weak connexion between the bond strength of the old and new concrete structures during strengthening and rehabilitation of concrete structures and rehabilitated, or repair of concrete structures is deemed successful when the good bond is achieved between the old and the new concrete (Momayez *et al.*, 2005; Gorst and Clark, 2003; Mu *et al.*, 2002). To successfully practice rehabilitation of deteriorating structures, the understanding of the mechanical properties behaviours at the interface between the old and the new construction materials is expedient (Tayeh *et al.*, 2013a; Tayeh *et al.*, 2013b; Ueda and Dai, 2005). The adhesion between the composite materials is a function of some factors, such as surface roughness and surface polarity of the composite components. In measuring the surface energies and bond strength of the composite material, an understanding of the interfacial adhesion between the fibre and the matrix has to be determined.

The fibre used in this research is a bio-fibre from Kenaf plant. Kenaf plants are blessing to mankind. Its high carbon dioxide (CO₂) assimilation rate and ability to clean the air by consuming large quantities of CO₂ and also absorb nitrogen and phosphorous from the soil, which is the main cause of the greenhouse effect has made Kenaf significant from the standpoint of environmental friendliness. Today Kenaf fibres are envisioned as an alternative medium to replacing conventional materials or synthetic fibres as reinforcement in composites. The low cost, no health risk, low density, high strength and modulus, and availability of Kenaf fibres in some countries have made it befitting for use in composites production (Ogunbode *et al.*, 2015; Patnaik, 2008). Due to the hydrophilic properties of Kenaf fibres, the fibre was subjected to surface treatment by sodium hydroxide reagents (NaOH) to improve the bond characteristics of the interfacial zone between the fibres and the cement matrix and also to reduce its hydrophilic properties (Mahjoub *et al.*, 2014). This reduction in the fibre water sorption characteristics thus improves the fibre durability and reduces its bio degradability. The new concrete in this experiment is the repair concrete, which is the KFCC concrete.

This paper presents results from an experimental test program carried out to fully understand the benefits and potential of KFCC as repair material in concrete structures. This study helped to understand the

morphology and strength of the interface bond strength developed between old concrete and the KFCC repair material. Shear test and tensile test were used in quantifying the bond strength in shear and direct tension, respectively.

2. Experimental programme

2.1 PC and KFCC properties

The mix design is in concomitant with the British DOE procedure. For this research, four different grade of concrete produced. For the NC substrate, a mean compressive strength of 35 N/mm² at 28 days was produced. The KFCC was designed to achieve three different grades at 25, 35, and 45 N/mm². The NC and KFCC contain Type I ordinary Portland cement with a specific gravity of 3.15. River sand with a maximum size of 5 mm, fineness modulus of 2.49, and 10 mm maximum size of crushed granite were used. The fibre used is 50 mm Kenaf fibres which have already undergone surface modification by mercerization treatment method. Figure 1 presents a curl and 50 mm chopped Kenaf fibre used in reinforcing the concrete. 0.75 % volume fraction of the Kenaf fibre was included in the KFCC mix. 1 % superplasticizer was used to improve the workability of the concrete mixture. The mix proportions based on the four different grade of concrete is illustrated in Table 1. The control specimens used consists of 100 x 100 mm cube for the compression strength test in determining the ultimate strength of the concrete grade, 100 x 100 x 300 mm prism for compression bond strength test, direct tensile bond strength test and shear bond strength test.

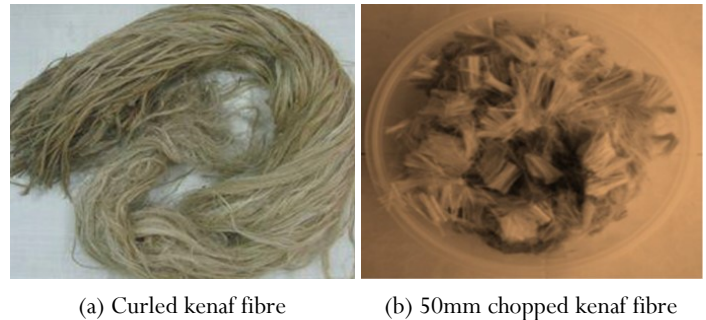


Figure 1 Kenaf fibre

2.2 Specimen preparation

In conducting the test, PC specimen which serves as the substrate and KFCC specimen which serves as the repair or retrofitting material (new concrete) were produced. These two different materials were combined into a single composite specimen and tested. In producing the composite material, two days water cured PC samples were surface prepared to receive and bind to the fresh cast of KFCC samples. A deep groove roughness surface pattern of the substrate was made as shown in Figure 2. After the roughening of the surface, the PC substrate is further cured in water until 28 days from the date of casting.

Table 1 Mix proportion based on the four different grade of concrete

Type of concrete	Concrete Grade	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Course Aggregate (kg/m ³)	Water (kg/m ³)	w/c ratio	Kenaf fibre (kg/m ³)
Normal	35	460	230	761	969	0.5	-
KFCC	25	383	230	903	903	0.6	1200
KFCC	35	460	230	761	969	0.5	1200
KFCC	45	575	230	727	888	0.4	1200

Figure 2 illustrates the pattern of the roughened surfaces of the old PC specimens. These specimens represent the first and the old prism substrate of 28 days for the direct tensile and shear test. The PC substrate specimens were subsequently placed into the prepared wooden moulds. The KFCC mixture was then carried out using a pan mixer and successively cast on 15 minutes moistened and wiped dried old PC grooved roughened surface at 28 days of casting PC in the mould.



Figure 2 Roughness surface pattern of old PC specimens

2.3 Compression test

Compression testing using the modified standard practice for capping concrete based on ASTM C1552 (2015) was carried out. The test provided a plane surface on two bearing surface of samples which purposed to provide a consistent and standardised procedure for compression testing. Capping plate was used having a thickness of not less than 25 mm. The size of each unit is 100 x 100 x 300 mm. Three layers of concrete units were attached to form multi-layered composite concrete sample as shown in Figure 3 and 4. Increasing compressing load was applied to the sample until ultimate failure thus, the maximum compressive load of was obtained at the interfacial bonding. The cracking behaviour was observed. The concrete grade of PC units used was 35 MPa and for KFCC units were 25, 35 and 45 MPa. The result from this test was plotted in the graph of compressive bond strength versus the type of concrete with different grade and presented in Table 2 and Figure 5. The interface failure mode of the compression test sample for KFCC and PC are presented in Figure 6. The PC sample should a catastrophic failure pattern compared to the KFCC sample that had a ductile failure pattern due to the presence of the kenaf fibre in the concrete.

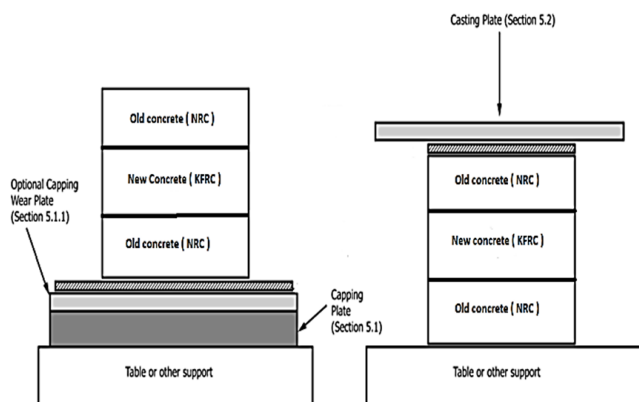


Figure 3 Schematic procedure for compression test (ASTM C1522, 2015)

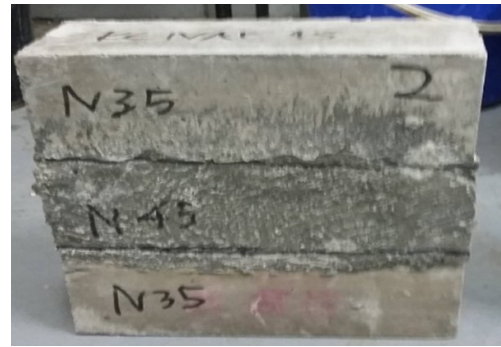


Figure 4 Composite sample composed of KFCC unit bonded to PC substrate unit for compression test

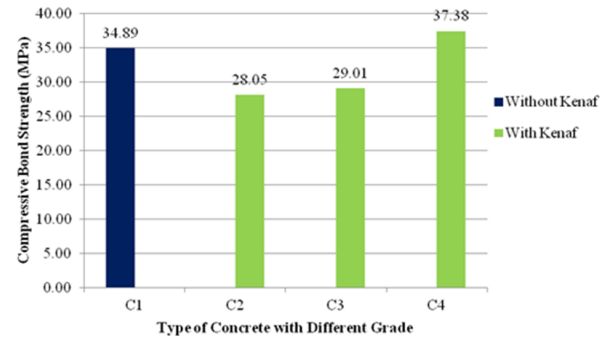


Figure 5 Average compressive bond strength values (T_{av}) for each type of concrete at different grade of concrete



Figure 6 Interface failure mode of compression test sample (a) KFCC (b) PC

Table 2 Compressive strength obtained from each sample

Sample ID	Concrete Grade (MPa)		Max. Force (P) (kN)	Compressive Stress (C) (MPa)	Average C_{av} (MPa)	SD
	PC Old concrete substrate	PC/KFCC New concrete				
C1	35 PC		1020.60	34.02	34.89	1.76
			1107.30	36.91		
			1012.20	33.74		
C2	35 PC	25 KFCC	893.10	29.77	28.05	1.49
			817.80	27.26		
			813.60	27.12		
C3	35 KFCC		859.20	28.64	29.01	0.89
			851.40	28.38		
			900.60	30.02		
C4	45 KFCC		1140.60	38.02	37.38	0.56
			1114.80	37.16		
			1109.10	36.97		

2.4 Direct tensile test

Direct tensile strength test was carried out using the modified standard test method for the tensile strength of concrete surface and the bond strength in accordance to ASTM C1583 (2013) specification. The bond strength and bond behaviour between the PC substrate and three different grades of KFCC material was investigated. In this test, the specimens used have a dimension of 100 x 100 x 300 mm as shown in Figure 7. Figure 7 (a) presents the Schematic procedure for direct tensile test ASTM C1583 (2013) while Figure 7 (b) illustrates sample of KFCC unit bonded to PC substrate unit for direct tensile test. The direct tensile strength test results were presented in Table 3 and Figure 8. The interface modes of failure are also illustrated in Figure 9.



Figure 9 Interface failure mode of tensile test sample (a) KFCC (b) PC

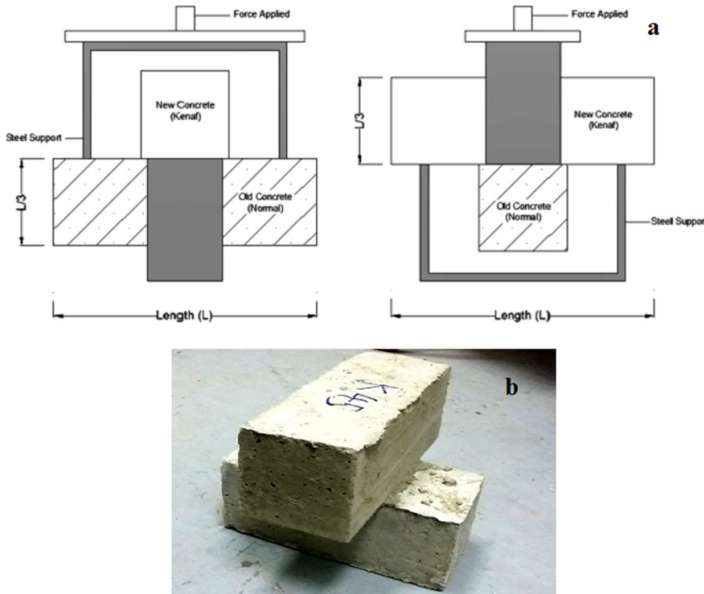


Figure 7 (a) Schematic procedure for direct tensile test (ASTM C1583, 2013)
(b) Composite sample composed of KFCC unit bonded to PC Substrate unit for direct tensile test

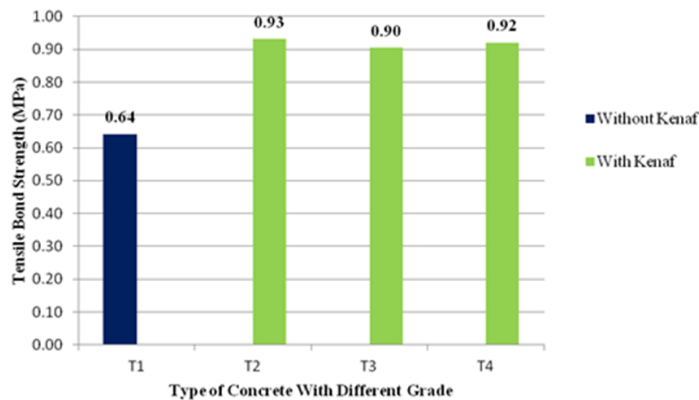


Figure 8 Average direct tensile bond strength values (T_{av}) for each type of concrete at different grade of concrete

2.5 Shear test

The Shear test was done to determine the shear bond strength of the concrete specimen at the interface using a modified simple beam with

Table 3 Tensile bond strength obtained from each sample

Sample ID	Concrete Grade (MPa)		Max. Force (P) (kN)	Shear Stress (S) (MPa)	Average (T_{av}) (MPa)	SD
	PC Old concrete substrate	PC/KFCC New concrete				
T1	35 PC	35	6.51	0.65	0.64	0.07
			5.67	0.57		
			7.07	0.71		
T2	25 KFCC	25	10.15	1.02	0.93	0.10
			8.17	0.82		
			9.64	0.96		
T3	35 KFCC	35	9.46	0.95	0.90	0.08
			9.45	0.95		
			8.21	0.82		
T4	45 KFCC	45	9.97	1.00	0.92	0.10
			8.09	0.81		
			9.56	0.96		

centre point loading in accordance with ASTM C293 (2016) specification. The shear bond strength and shear bond behaviour between the PC substrate and three different grades of KFCC repair material was investigated. In this test, the specimens used have a

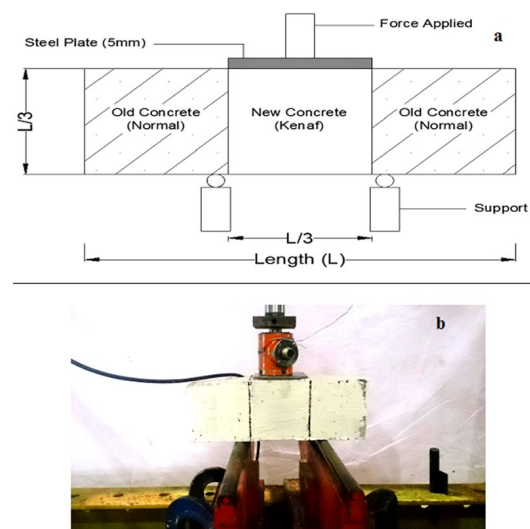


Figure 10 (a) Schematic procedure for shear Test (ASTM C1583/C1583M)
(b) Set up of composite sample composed of KFCC unit bonded to plain concrete substrate unit for shear test

dimension of 100 x 100 x 300 mm. Figure 10 (a) presents the Schematic procedure for shear strength test based on ASTM C1583 (2013). While, Figure 10 (b) illustrates sample set up of KFCC for the shear test. The experimental shear strength test results are presented in Table 4 and Figure 11. The failure mode for the shear specimens is illustrated in Figure 12.

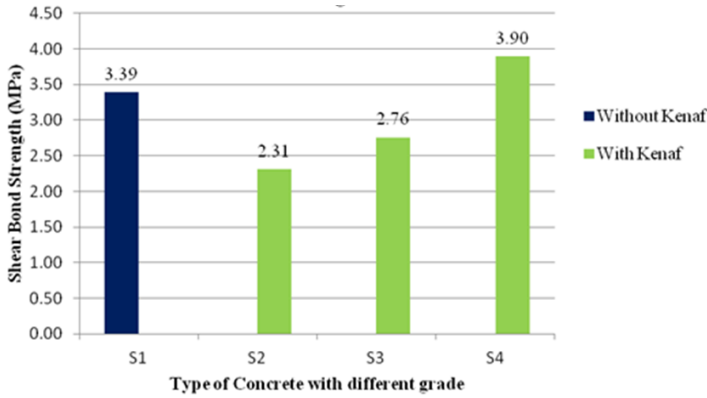


Figure 11 Average Shear Bond strength values (S_{av}) for each type of concrete at different grade of concrete

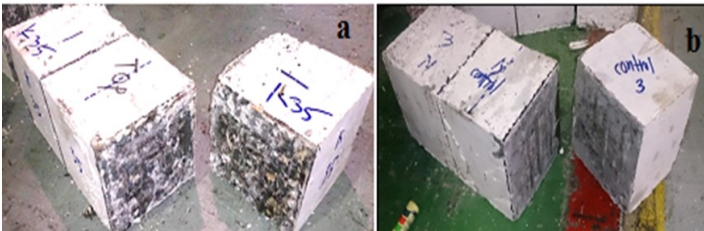


Figure 12 Interface failure mode of shear test sample (a) KFC (b) PC

Table 4 Shear Bond Strength Obtained From Each Sample

Sample ID	Concrete Grade (MPa)		Max. Force (P) (kN)	Shear Stress (S) (MPa)	Average (S_{av}) (MPa)	SD
	PC Old concrete substrate	PC/ KFC New concrete				
S1	PC	35	38.4	3.84	3.39	0.07
		PC	25.9	2.59		
		PC	37.4	3.74		
S2	35 PC	25	27.2	2.72	2.31	0.78
		KFBC	14.1	1.41		
		KFBC	28.1	2.81		
S3	35 PC	35	26.1	2.61	2.76	0.38
		KFBC	31.9	3.19		
		KFBC	24.8	2.48		
S4	45 PC	45	40.1	4.01	3.90	0.40
		KFBC	34.5	3.45		
		KFBC	42.3	4.23		

3. Discussion of results

Based on the result obtained from the cube test, the data showed that the PC has higher compressive strength compared to Kenaf fibrous concrete. Kenaf reduced the compressive strength of concrete since it is weak in resisting compression load. However, the target strength of Kenaf fibrous concrete can be achieved by increasing the concrete grade of PC. Besides, Kenaf fibrous concrete showed small crack compared to PC. This proved that the Kenaf fibrous concrete has more ductile failure mode compare to PC as shown in Figure 4. The compressive bond strength of PC with PC gave higher compressive bond strength

compared with PC attached KFCC of the same grade. Kenaf reduced the compressive bond strength since Kenaf is weak in resisting compression load. However, by increasing the grade of KFCC, the compressive bond strength consequently increased. This outcome is in agreement with a similar study conducted by Shin and Wan (Shin and Wan, 2010) where the old concrete was combined with the different water-cement ratio which is tantamount to the grade of concrete. When using KFCC, the concrete grade was increased higher than PC to improve the compressive bond strength. Not only that, a sample with KFCC shows smaller crack compared to sample with PC only. Hence, KFCC helps concrete to maintain its integrity under load compared to the fibreless concrete.

The shear bond strength of PC with PC was relatively high compared to PC to KFCC with the same grade. However, by increasing the grade of KFCC, the shear bond strength thus increased, agreeing with the findings of Kang et al., (Kang et al., 2015) that states that higher concrete grade gives higher shear strength. However, based on Shin and Wan (Shin and Wan, 2010) study, higher concrete grade of new concrete resulted in lower shear bonding strength. Besides that, from the experiment, for the sample with KFCC, it was found that the surface roughness pattern is not seen as the kenaf fibre filled some of the empty areas of the interlocking surface pattern as shown in Figure 5.5. Present kenaf fibre reduced the friction resistance of both surfaces and reduced shear bond strength between kenaf fibrous concrete and normal concrete. By inspection, it was found that KFCC sample surface roughness pattern as being filled with the fibre to aid the interlocking interface as can be observed in Figure 10a.

Kenaf has been proven to possess good tensile strength properties in concrete. KFCC exhibited tensile strength higher than PC up to 45%. By inspection, it was found that KFCC sample surface roughness pattern as being filled with the fibre to aid the interlocking interface as can be observed in Figure 7a. This showed that the kenaf fibre acts as the bonding element between two concrete surfaces to resist tensile force. By applying KFCC to any old PC for repairing purposes, it will contribute in term of tensile resistance better than normal concrete. Increasing the grade of concrete did not affect the tensile strength increase. However, it improved the compressive bond strength and shear bond strength at the interface. Hence, it could be noticed that KFCC is a good material for repair and retrofitting regarding mechanical properties.

4. Conclusion

Based on the results, observations and analysis of bonding behaviour of KFCC to PC interface; the following can be drawn:

- i. The compressive bond strength of KFCC to PC is lower than that of PC to PC with the same grade. KFCC reduces the compressive bond strength of PC. However, the compressive bond strength of KFCC to PC can be increased by increasing grade of KFCC.
- ii. Shear bond strength of the interfacial bonding of KFCC and PC is lower than that of PC to PC with the same grade. KFCC have a lesser shear bond strength compared to PC. However, the shear bond strength of KFCC to PC can be increased by increasing the grade of KFCC.
- iii. Tensile bond strength of KFCC to PC is higher than that of PC PC with the same grade. KFCC improves the tensile bond strength with PC. However, the different grade of KFCC does not affect the tensile bond strength of KFCC and PC.
- iv. Regarding cracking behaviour, the samples were cracked at the

bonding interface except for compressive test where the samples were cracked at the whole portion of the sample.

- v. KFCC is a good material for repair and rehabilitation of damaged or deteriorating structure. KFCC can improve the tensile strength bonding to other concrete as well as compressive bond strength and shear bond strength by increasing the grade of KFCC. The use of KFCC for repairing and rehabilitation purpose can give a great impact on engineering industry towards sustainability.
- vi. The application of natural fibres such as Kenaf fibre in concrete can exhibit economical and technical benefit for the construction industry. The green concrete developed has an environmental benefit which are of immense importance in the present context of the sustainability of natural resources.

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