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Interfacial bond strength between micro synthetic fibre-reinforced patch repair mortar and concrete substrate

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Abstract

The interfacial bond strength between a concrete substrate and repair materials plays an important role in the overall performance of a concrete patch repair system. In this paper, patch repair materials made from micro synthetic fibre-reinforced mortar were cast on the surface of a concrete substrate with smooth interfacial texture (as cast) with the aim of investigating the interfacial bond strength as a function of variations in fibre volume fraction without interference from the influence of roughness by surface treatment. The bond strength was determined by an experimental method using slant shear and tensile splitting test. The result showed that the inclusion of micro synthetic fibre increases the bond strength and the magnitude of the increment depends on the fibre volume fraction. The optimum increase of bond strength is found in the mortar with a fibre volume fraction of 0.06%, giving an increase of 40.21% and 48.71% for slant shear and tensile splitting bond strength specimens at the age of 7 days, respectively. Furthermore, tests on micro synthetic fibre-reinforced repair mortar with fibre volume fractions of 0.06% at the ages of 1, 3, 7, and 28 days were conducted to see the development of the bond strength. The slant shear test gives a higher bond strength than the corresponding tensile splitting tests. The smooth interfacial texture between the repair materials and concrete substrate provides adequate adhesion but insufficient friction. This study also established the correlation between slant shear, tensile splitting, and mechanical properties of micro synthetic fibre-reinforced patch repair mortar.

Keywords: Bond strength, Concrete patch repair, Concrete substrate, Micro synthetic fibre repair mortar, Slant shear, Splitting

1. Introduction

Concrete is widely used in the construction industry (to construct buildings, roads, bridges, dams, and so on) due to the following reasons: it is available in various geographical locations, can be produced at a low cost, is versatile, and is considered to be a durable material. Although concrete has been designed to have good durability, the deterioration of concrete during its service life remains unavoidable. Deterioration of concrete can occur due to physical, chemical, and mechanical effects, resulting in reduced structural strength and serviceability [1]. The deterioration is characterized by a variety of symptoms such as cracking, spalling, delamination, etc. [2]. To remedy the deterioration, a repair system may be chosen to restore the strength and serviceability of the structural concrete [3]. This option may be considered a better solution to the creation of new structures to replace the deteriorated one; the latter will take a longer time to be realised and requires a huge cost [4].

Repair of concrete deterioration is essential, to ensure the concrete structure will achieve the planned service period and also to improve the safety factor and serviceability of related components as it is expected to improve the function and performance of structure, restore the strength including load-bearing capacity, stiffness, and toughness of the structure, recover the size and appearance of concrete, and improve its durability [5].

Before repairs are carried out, identification of the cause of the concrete deterioration needs to be carried out. Possible sequences of events leading to damage must be identified to obtain suitable and compatible repair methods [6]. Patch repair is a concrete repair method that is easy to apply, has high compatibility, and is effective, in terms of cost [4]. Durability and compatibility between repair materials and concrete substrates are important factors that determine the overall performance of patch repair systems on concrete [7]. Most of the problems associated with concrete repair systems are the lack of compatibility between repair materials and concrete substrates caused by physical, chemical, and mechanical processes in repair materials, resulting in failures in concrete repairs [8, 9]. One of the parameters that can be used as a benchmark for concrete patch repair performance is the interfacial bond strength between the repair material and the concrete substrate [10-15].

The interfacial area is weak due to the pores formed [10-12, 16]. Based on previous research, it has been shown that the property of the interfacial bond strength is the main factor that determines the success of concrete repair systems, where this property depends on two processes: chemical bond strength (adhesion) and friction between the concrete substrate and the repair material [10, 17]. The interfacial bond strength is further influenced by various factors, including curing, surface treatment and, most significantly, the type

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and composition of the repair material itself [4, 13-15]. Therefore, the selection of repair materials needs to be considered, to achieve a good interfacial bond strength [18].

Various types of repair materials have been widely developed to repair damage to concrete, such as cement-based materials, epoxy resins, polyester resins, latex polymers, and polyvinyl acetate. Cement-based repair material and resin polymer or epoxy is the most widely used type of repair material [19, 20]. The mechanical properties of the repair material should resemble the structure being repaired as closely as possible. In this case, cement-based repair material is more recommended than resin-based repair material. Cement-based repair materials can make an inconspicuous difference to concrete substrates, even without the use of coatings. Cement-based materials with the properties of rapid hardening and high early mechanical strength are suitable for the concrete repair materials [20], and also it can provide resistance to fire while epoxy resins have low glass transition temperatures resulting in poor fire performance [21]. Based on previous research conducted by Pacheco-Torgal et al. [22], it is also shown that cement-based repair mortar gives better adhesion than epoxy-based repair mortar on moist surfaces. The adhesion between the repair material and the concrete substrate (which is a component of the interfacial bond strength) is the fundamental property of the patch repair that allows the return of the initial strength of the structure.

Cement-based mortar is widely used as a repair material because of its various advantages. The advantages of cement mortar are that it is lightweight, rigid, and malleable, and has a stable volume, fast application, and good finishing surface. However, cement mortar also has the disadvantages of low ductility and tensile strength. A general solution to overcome this weakness is to increase the bonding strength, plasticity, and ductility with the use of admixture such as fibre. Fibre can increase tensile and bending strength, which helps produce products with high slenderness, bending strength, and expected bonding strength [23]. Reinforcing mortars with randomly distributed short fibres can also increase the tensile strength and toughness of the cement matrix by controlling the initiation, propagation, and merging of cracks [24].

Patch repair may have to be applied on a small and thin size, so the maximum dimensions of the aggregates and fibres used are limited. Therefore, the use of micro-sized fibres is worth considering because of their compatibility with different types of patch repair sizes. Some previous studies have shown that the addition of various types of microfibres, such as metallic microfibre, mineral microfibre, synthetic microfibre, and natural microfibres can increase the ductility and toughness of cement paste significantly, with a 10% fibre fraction volume limit. With the proper use of fibre volume fractions, concrete failure modulus can change from originally brittle to quasi-ductile. When used in mortar, the use of microfibres will provide improvements to mechanical properties [24].

Based on previous research, the effects of fibre in cement-based repair material have been considered. Polymer-based synthetic fibres are versatile and their performance in a matrix is quite different from the others. The most commonly used fibres in cementitious composite is polypropylene, polyethylene, polyamide, and polyvinyl alcohol fibre [25]. Yoo and Banthia [26] investigated the effect of polymer-based synthetic fibre and steel fibre on the mechanical properties of the interfacial bond strength between repair material and concrete substrate by conducting slant shear tests with different slants. They found that steel fibre enhanced the interfacial bond properties because of the dowel effect, while synthetic fibre improved interfacial bond properties owing to micro-crack deviation, blunting, and reduction of shrinkage cracking and damage during operation. Kim and Bordelon [27] investigated three kinds of macrofibre (a textured synthetic, a stretched synthetic, and a hooked-end steel fibre) and they found that the tensile fracture strength within the fibre-reinforced mortar and interfacial tensile bond strength between the fibre-reinforced mortar and concrete substrate were all higher than the mortar without fibre reinforcement. Overall, the interfacial tensile bond strength did improve because the fracture path that occurred through the mortar layer was bridged by the fibre near the interface surface; the magnitude of the improvement depends on the fibre volume fraction. Ghoneim et al. [28] studied the effects of polymer-based synthetic fibre on the cement-based matrix and they found that the synthetic fibre varieties had cross-sectional shapes with different surface finishes which further improved bond properties and prevented brittle fracture by improving the ductility of the matrix. It increases the crack control, the ultimate load, and overall ductility by resisting sufficient tensile stresses without fibre pull-out. The higher bond strength is produced by the bridging mechanism that synthetic fibre reinforcement brings to the matrix. Based on Doğan and Demir [25], it is found that synthetic fibre (i.e. polyamide fibre) has a wide range of uses including concrete coating, repair mortar, shotcrete, and precast concrete elements with its easy mixing applicability, corrosion resistance, durability, and high tensile strength compared to polypropylene and polyethylene fibre. It is very beneficial as this fibre reinforcement exhibits a significant increase in tensile splitting and flexural strength.

Previous research by Zanotti et al. [12, 29] studied the effect of synthetic fibre (i.e. polyvinyl alcohol fibre) and showed that the fibre reinforcement improves the overall performance of repair in cement-based matrix applications and, particularly, the bond compatibility of repair material and concrete substrate (the interfacial bond strength), overall strength, and crack resistance. The beneficial effect of the synthetic fibre on the interfacial bond strength between the repair material and concrete substrate can be explained by the following mechanisms: (i) fibre reducing hygrothermal damage, such as repair cracking and delamination induced by restrained shrinkage; (ii) fibre mitigation of operational damage by enhancing damage tolerance and promoting interfacial soundness while the bond is being developed; (iii) fibre enhancing interfacial failure resistance, after the shear failure and the mortar residues adhering to the concrete substrate contribute to fibre bridging. In line with this, previous research conducted by Xiao et al. [30] about synthetic fibre in engineered cementitious composites, showed that the bond strength of cement composite specimens with a fibre volume fraction of 1.0%, 1.5%, and 2.0% increased by 1.5, 2.5, and 3.1 times larger than specimens without fibre. This is due to the bridging effect that controls splitting cracks in cement composites, so the frictional shear force on the interface increases and the magnitude of the increment depends on the fibre volume fraction.

It has been shown that the most important effect of fibre on the improvement of concrete repair interfacial bond strength can be traced from the bridging mechanism offered by the fibre [12, 26, 27, 29]. However, research on interfacial bond strength in repair material with micro-sized synthetic fibre is very limited, especially synthetic fibre with polyamide material. Therefore, this study will be useful to fill the gap of information in this current knowledge. The interfacial bond strength itself consists of bond by adhesion, friction, and mechanical interlocks. For a smooth interface, the mechanical interlocks are missing. This research aims to identify the authentic influence of micro synthetic fibre inclusion in the patch repair materials to the adhesion and friction of the interface between repair materials and a concrete substrate without the interference from the influence of roughness by surface treatment. The adhesion is identified by an experimental method via tensile splitting tests, while the combined adhesion and friction is determined via slant shear tests. The success of this investigation will open new opportunities to develop micro synthetic fibre-reinforced repair mortar meeting the minimum interfacial bond strength requirements, as sufficient bond strength will guarantee the two matrices can act as a composite with monolithic behaviour in concrete patch repair system.

2. Materials and methods

2.1 Materials and properties

In this experimental program, normal concrete, with a compressive strength of 30 MPa, was selected as the concrete substrate. The normal concrete was designed according to SNI-7656-2012 [31]. The concrete mixture consists of Portland cement, water, natural river sand, and coarse aggregate of crushed stone with a maximum dimension of 12.7 mm, without any additive in the mix. The mixture had a w/c ratio of 0.48. The final composition of the concrete is presented in Table 1. The mechanical characteristics of the concrete were determined on cylinder specimens with a diameter of 150 mm and a height of 300 mm, in accordance with ASTM C39 [32] for the compressive strength test and ASTM C469 [33] for the elastic moduli test. The obtained properties are given in Table 2.

Table 1 Mix design of 1 m^3 normal concrete

Material	Mass (kg/m^3)
Cement	450.00
Fine aggregate (sand)	659.39
Coarse aggregate	1,020.65
Water	215.20

Table 2 Mechanical properties of normal concrete substrate (28-day)

Type of test	Test result (MPa)
Compressive strength test	30.09
Elastic moduli test	25,391.08

The repair materials investigated in this research were cement-based mortar reinforced with polymer-based monofilament micro synthetic fibres at various fibre volume fractions. The fibre was 12 mm in length and had an ultimate tensile strength of 900 MPa. Micro synthetic fibre and its properties are shown in Table 3 and Figure 1. Accelerators were added to the mix to speed up the mortar setting time. The w/c ratio used was 0.35 and the accelerator substituted the water at 10% by weight of cement. The mix proportion of micro synthetic fibre-reinforced mortar is shown in Table 4. The compressive strength of the micro synthetic fibre-reinforced patch repair mortars was determined on 50 mm x 50 mm x 50 mm cube specimens following ASTM C109 [34]. Meanwhile, the elastic moduli were determined on cylinder specimens with a diameter of 150 mm and height of 300 mm, according to ASTM C469 [33]. The obtained compressive strengths and elastic moduli of micro synthetic fibre-reinforced mortar are shown in Table 5 and Table 6. In Table 5 and Table 6, the modular ratio of repair mortar to concrete substrate is also given.

Table 3 Properties of micro synthetic fibre [35]

Category	Properties
Fibre class	EN 14889-2 Class 1
Raw material	100% Polyamide 6.6
Fibre type	Monofilament
Specific gravity	1,14 gr/cm^3
Length	12 mm
Filament diameter	27 mm
Tensile strength	900 MPa
Elongation at break	17,55 %
Melting point	260 °C
Alkali resistance	Excellent
Resistance to corrosion	Excellent
Number of fibres/kg	111.000.000

Figure 1 Micro synthetic fibre [35]

Table 4 Mix design of 1 m^3 micro synthetic fibre reinforced repair mortar

Fibre volume fraction (V_f)	**Cement (kg/m^3)**	**Fine aggregate (sand) (kg/m^3)**	**Water (lt/m^3)**	**Accelerator (lt/m^3)**	**Micro synthetic fibre (kg/m^3)**
0.00%	800.00	1.600.00	200.00	80.00	0.00
0.04%	800.00	1.600.00	200.00	80.00	0.40
0.06%	800.00	1.600.00	200.00	80.00	0.60
0.08%	800.00	1.600.00	200.00	80.00	0.80
0.10%	800.00	1.600.00	200.00	80.00	1.00
0.12%	800.00	1.600.00	200.00	80.00	1.20

Table 5 The 7-day mechanical properties of repair mortar with various fibre volume fraction

Fibre volume fraction V_f (%)	**Compressive strength f_c' (MPa)**	**Elastic moduli E (MPa)**	**Modular ratio**
0.00	20.99	17,091.00	0.67
0.04	27.10	25,504.14	1.00
0.06	28.44	26,212.31	1.03
0.08	26.02	24,260.04	0.96
0.10	25.14	23,114.62	0.91
0.12	23.70	21,212.56	0.84

Table 6 Mechanical properties of repair mortar with 0.06% fibre volume fraction

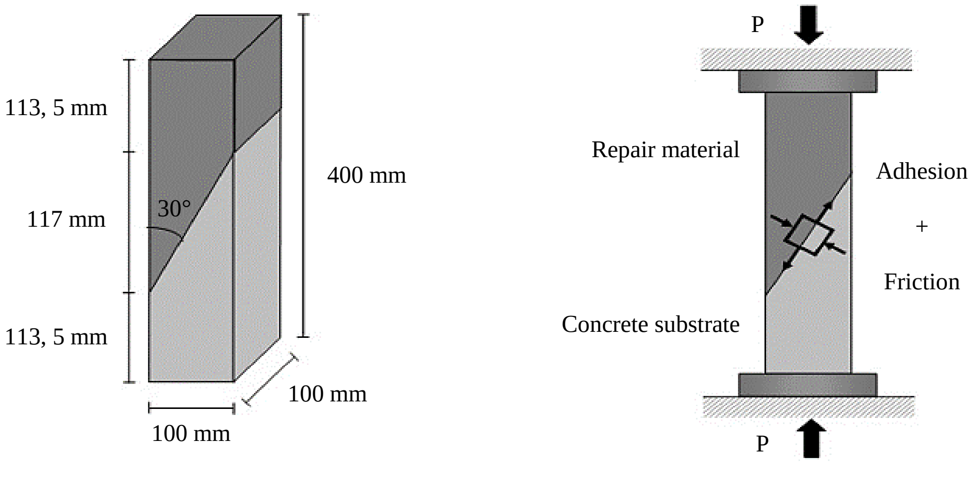
Age (days)	**Compressive strength f_c' (MPa)**	**Elastic moduli E (MPa)**	**Modular ratio**
1	15.33	18,713.30	0.74
3	24.91	22,924.21	0.90
7	28.67	26,397.83	1.04
28	32.79	28,022.26	1.10

2.2 Slant shear test

The slant shear test specimens were based on BS-EN 12615/1999 [36] and comprised two parts: prismatic concrete substrates and prismatic repair materials, with an inclination angle of 30° to the vertical axis. The two parts were used to make up prismatic specimens with dimensions 100 mm x 100 mm x 400 mm (see Figure 2 (a)). The production of slant shear test specimens consisted of two steps, following the steps adopted by previous study [37]. First, the normal concrete substrates were cast with a bond-line of 30° to the vertical axis. Second, the concrete substrates were then cured using a wet burlap sack and kept in a room at a temperature of 24°C ± 2°C. After 28 days, repair materials were cast on the remaining half of the prism to form the composite prisms. Before applying the repair materials, concrete substrate surfaces were treated by coating with a bonding agent with a smooth interface connection texture. A bonding agent was used for an interfacial coating and its proportion was 1:1.25 by weight of cement (see Table 7). The slant shear test was then carried out at specified ages by applying the compressive stress on the prismatic specimen using a Universal Testing Machine (UTM), as shown in Figure 2 (b).

Table 7 Proportion of bonding agent for coating interfacial surface

Material	**Amount of 1 m^2 interfacial area**
Bonding agent	1.00 (lt/m^2)
Cement	1.25 (kg/m^2)



(a) (b)

Figure 2 Slant shear specimen (a) and test set up (b)

2.3 Tensile splitting test

The tensile splitting test specimens were based on ASTM C496 [38] and consisted of two parts: half-cylinder concrete substrates and half-cylinder repair materials with a smooth interface texture. The two parts made up cylindrical specimens with a diameter of 150 mm and height of 300 mm. The splitting test specimens were basically created in a similar way to the slant shear specimens. The concrete substrates were cast in a half of the cylinder mould, the mould was demoulded after 24 hours, and then the specimens were stored for curing. After 28 days, the concrete substrates were put back into a half cylinder mould, and repair materials were cast on the remaining half of the cylinder to form the composite cylinders, following the steps adopted by previous study [39, 40]. Before the repair materials were applied, concrete substrate surfaces were treated by coating with a bonding agent. The splitting test was performed by applying compressive stress along the bond line, as shown in Figure 3.

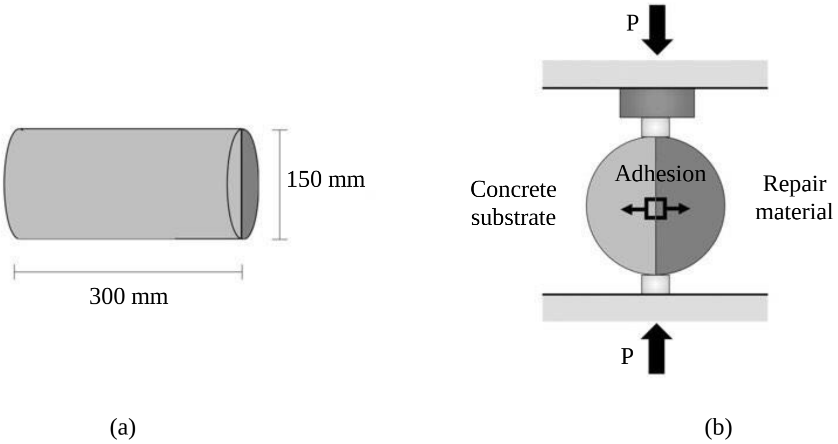


Figure 3 Tensile splitting specimen (a) and test set up (b)

3. Results and discussion

3.1 Slant shear test

The results of slant shear testing on repair mortar reinforced with various fibre volume fractions and the failure modes are presented in Tables 8 and 9. The failure modes are also shown in Figure 4 and the slant shear bond strength test results are graphically portrayed in Figures 5 and 6.

3.1.1 Slant shear failure mode

Generally, the observed failure modes can be categorised as follows: pure interfacial failure (a), with no cracking or fracturing in either the repair material or normal concrete substrate; interfacial failure, combined with minor cracking in the repair material (b); and interfacial failure combined with fracturing in the repair material (c). The three types of failure modes are shown in Figure 4 (a), (b), and (c), respectively. Other possible failure modes, such as crushing of repair mortar or concrete substrate or both (double failure) was not identified in this investigation.

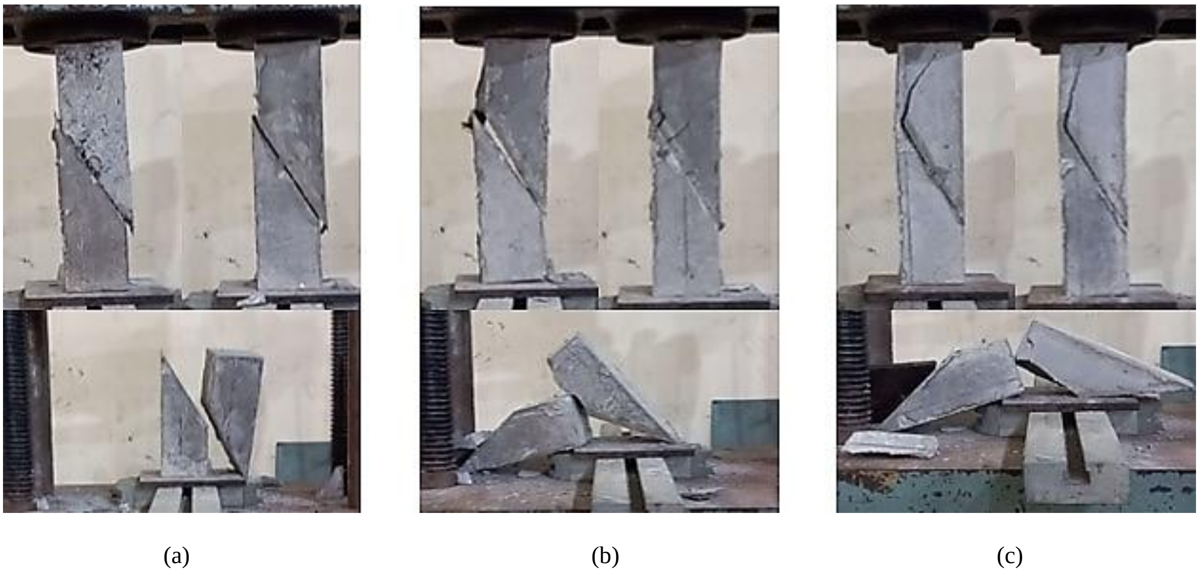


Figure 4 Slant shear failure (a) mode A, (b) mode B, and (c) mode C

In this research, smooth interfacial texture (as cast) was designated to determine the interfacial slant shear bond strength as a function of variations in fibre volume fraction. Interfacial bond strength is promoted by adhesion and friction mechanisms. A smooth interfacial texture lacks the friction contribution that would be expected on a rough surface. Hence, the smooth interfacial texture results in interfacial failures, which may combine with cracking or fracturing in some repair materials. These findings are in line with those of Tayeh et al. [41, 42] and Nugroho et al. [43].

An interfacial failure is evidently recognised by a separation along the bond line between the repair material and the concrete substrate. The stress that causes this type of failure mode represents the actual bond strength between two composite matrices. On the other hand, the stress that causes the other failure modes, such as concrete failure, repair material failure, or double failure, represents the minimum bond strength value [4]. Although all the specimens experienced interfacial failure, micro synthetic fibre reinforcement slightly influences the failure mode. In repair mortars without fibre reinforcement, the failures that occurred were interfacial failure combined with fracturing in the mortar repair. Meanwhile, in repair mortars with micro synthetic fibre reinforcement, failure behaviour is identified by purely interfacial failure with the exception of repair mortar with 0.04% and 0.12% fibre volume fraction. The later shows interfacial failure with minor cracking in repair mortar.

3.1.2 Influence of fibre volume fraction on slant shear strength

Generally, repair mortar with micro synthetic fibre reinforcement provides a better slant shear bond strength. An increase in the slant shear bond strength by 5.29-40.21% are obtained in this investigation. The increase in the interfacial bond strength that occurs in repair mortar with micro synthetic fibre reinforcement could be a result of the micro synthetic fibre that are mutually intertwined at the interface, which entrapped air voids on the interface and bridge the two composite matrices. However, the addition of fibre volume fractions that exceed the optimum volume fraction tends to cause the interfacial bond strength value to decrease due to decrease in the homogeneity of the mixture (see Table 8 and Figure 5).

Table 8 The 7-day slant shear bond strength of repair mortar with various fibre volume fraction

ID	Fibre volume fraction V_f (%)	Ultimate load P (N)	Bond strength f_b (MPa)	Average bond strength f_{bav} (Mpa)	COV (%)	Failure mode
SS-F0.00-7A	0.00	62,762.56	2.72	2.68	2.75	C
SS-F0.00-7B	0.00	62,762.56	2.72			C
SS-F0.00-7C	0.00	59,820.57	2.59			C
SS-F0.04-7A	0.04	83,356.53	3.61	3.50	2.78	B
SS-F0.04-7B	0.04	80,414.53	3.48			B
SS-F0.04-7C	0.04	78,943.53	3.42			B
SS-F0.06-7A	0.06	84,827.52	3.67	3.75	3.12	A
SS-F0.06-7B	0.06	85,317.86	3.69			A
SS-F0.06-7C	0.06	89,730.85	3.89			A
SS-F0.08-7A	0.08	78,943.53	3.42	3.34	2.23	A
SS-F0.08-7B	0.08	75,511.21	3.27			A
SS-F0.08-7C	0.08	76,982.20	3.33			A
SS-F0.10-7A	0.10	75,020.87	3.25	3.18	4.06	A
SS-F0.10-7B	0.10	75,511.21	3.27			A
SS-F0.10-7C	0.10	70,117.55	3.04			A
SS-F0.12-7A	0.12	64,723.89	2.80	2.82	1.57	B
SS-F0.12-7B	0.12	66,194.89	2.87			A
SS-F0.12-7C	0.12	64,233.56	2.78			B

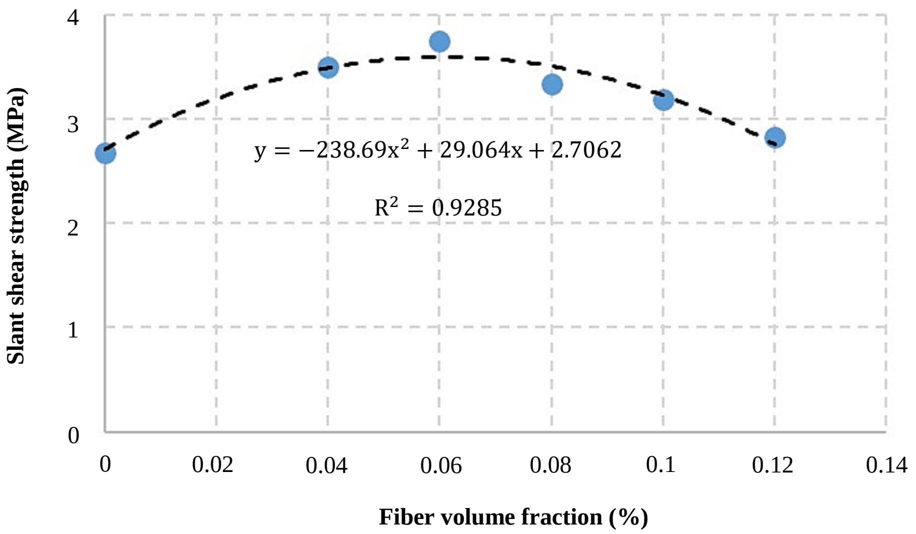


Figure 5 Influence of fibre volume fraction on 7-day slant shear strength of repair mortar

3.1.3 Development of slant shear strength

The bond strength development of repair mortar with fibre volume fraction of 0.06% determined by slant shear test is presented in Table 9 and Figure 6. The 1, 3, and 7-day slant shear bond strength represents about 27.93%, 47.11%, and 74.33% of the 28-day slant shear bond strength. The increase in slant shear bond strength occurs significantly at the age of 1-7 day, which might be related to the contribution of the bond due to the hydration progress accelerated by the use of accelerators.

Table 9 Slant shear bond strength of repair mortar with 0.06% fibre volume fraction

ID	Age of patch repair (days)	Ultimate load P (N)	Bond strength f_b (MPa)	Average bond strength f_{bav} (MPa)	COV (%)	Failure mode
SS-F0.06-1A	1	30,890.95	1.34	1.40	6.60	B
SS-F0.06-1B	1	34,813.61	1.51			B
SS-F0.06-1C	1	31,381.28	1.36			B
SS-F0.06-3A	3	51,484.91	2.23	2.36	5.11	A
SS-F0.06-3B	3	55,407.57	2.40			A
SS-F0.06-3C	3	56,878.57	2.46			A
SS-F0.06-7A	7	86,298.52	3.74	3.73	2.57	A
SS-F0.06-7B	7	83,846.86	3.63			A
SS-F0.06-7C	7	88,259.85	3.82			A
SS-F0.06-28A	28	118,660.47	5.14	5.02	3.12	A
SS-F0.06-28B	28	117,189.47	5.07			A
SS-F0.06-28C	28	111,795.81	4.84			A

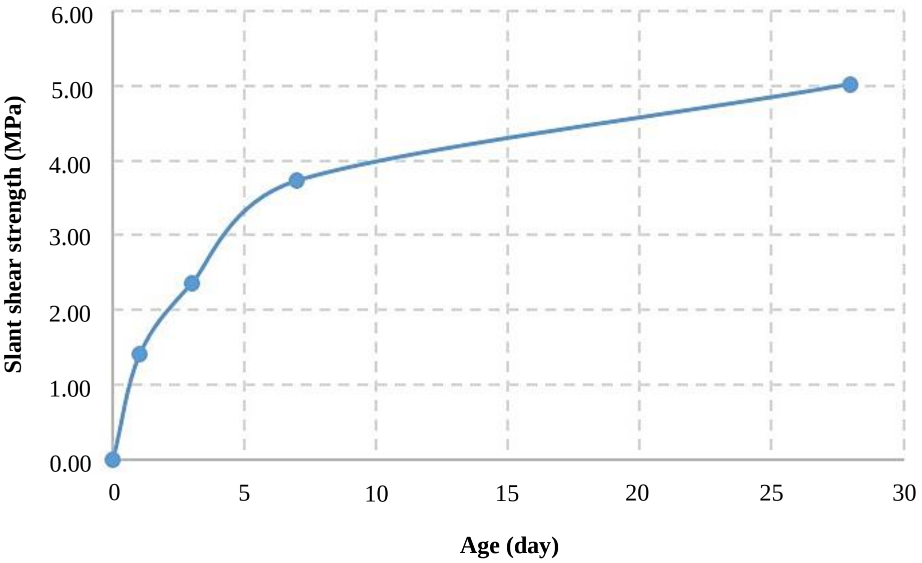


Figure 6 Slant shear bond strength development of repair mortar with fibre volume fraction 0.06%

3.1.4 Slant shear strength vs compressive strength

Examining the 7-day slant shear strength of patch repair shown in Table 8 indicates that the highest slant shear bond strength of 3.12 MPa is given by repair mortar with a fibre volume fraction of 0.06%. It seems this bond strength correlates well the mechanical properties of this repair mortar (see Table 5) where repair mortar with fibre volume fraction of 0.06% also produces the highest compressive strength and elastic modulus. Similarly, the development of slant shear strength is found to be a corresponding to the strength gain of the compressive strength in Table 6. Such correlation of slant shear bond strength and compressive strength is presented in Figure 7. According to Figure 7, it is confirmed that a linear correlation between the slant shear bond strength and the compressive strength can be established by a factor of 0.1928x -1.7027. Based on this factor, it is found that the slant shear bond strength is about 9%-15% of the compressive strength. The higher the compressive strength, the higher the slant shear bond strength value. This is in line with previous study conducted by Kristiawan and Prakoso [4] and Kristiawan et al. [44], where mechanical properties (i.e. compressive strength and elastic moduli) of the two materials composing specimens for measuring slant shear will affect the result with a linear correlation. Increasing compressive strength of repair materials could increase the normal stress in the interface for the same shear stress. Since the presence of normal stress increases the friction on the interface, the observed bond strength will increase [4].

3.1.5 Acceptance limit of slant shear bond strength

According to the ACI Concrete Repair Guide [45], repair materials shall meet the minimum specification of slant shear bond strength as shown in Table 10. The table is useful for determining the selection of suitable materials to be applied to concrete repair.

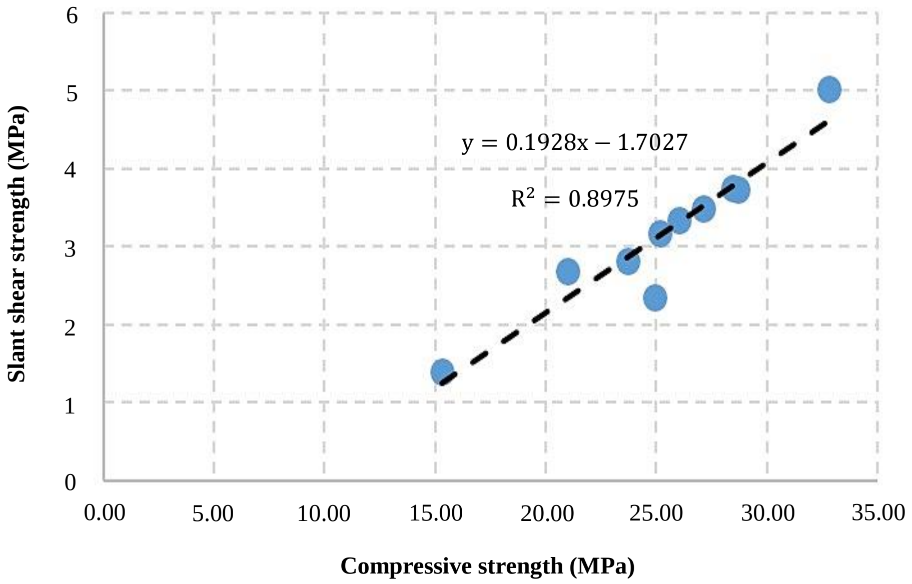


Figure 7 Slant shear bond strength and compressive strength correlation

Table 10 Minimum acceptable slant shear bond strength range [45]

Age of patch repair (days)	Slant shear bond strength f_b (MPa)
1	2, 76-6, 90
7	6, 90-12, 41
28	12, 41-20, 68

Based on this guideline, all the specimens do not meet the minimum slant shear bond strength range as specified in Table 10, which further emphasizes the necessities for surface preparation related to surface roughness of concrete substrate in concrete repair system. This is in line with the results of previous research [41-43, 46, 47], which in addition to the repair material properties, the surface roughness has a strong influence on the slant shear bond strength. Surface roughness will increase bond strength through friction mechanism, with the use of a surface preparation system in the repair process, the bond strength of the repair products can be greatly improved [13].

3.2 Tensile splitting test

The results of tensile splitting testing on repair mortar reinforced with various fibre volume fractions and the failure modes are presented in Tables 11 and 12. The failure modes are also shown in Figure 8 and the tensile splitting bond strength test results are graphically portrayed in Figures 9 and 10.

3.2.1 Tensile splitting failure mode

Generally, the failure modes can be categorised as follows: pure interfacial failure, no cracking and fracturing in both repair material or normal concrete substrate (A); interfacial failure combined with cracking in repair material (B); and interfacial failure combined with minor cracking in both repair material and concrete substrate (C). Each of these failure modes is indicated in Figure 8 (a), (b), and (c), respectively. Similar to that of slant shear bond strength, all of the splitting test results are interfacial failures. Some of the specimens i.e. repair mortars without fibre reinforcement experienced interfacial failure combined with cracking in repair material (see Table 11).

(a) (b) (c)

Figure 8 Tensile splitting test failure (a) mode A, (b) mode B, and (c) mode C

3.2.2 Influence of fibre volume fraction on tensile splitting bond strength

Overall, repair mortars with micro synthetic fibre reinforcement provides a better tensile splitting bond strength than repair mortars without fibre reinforcement. An increase of tensile splitting bond strength by 7.75-48.71% are obtained in this research when micro synthetic fibre is added in the mixture. The highest magnitude of 7-day splitting bond strength is 1.73 MPa, which occurred in repair mortar with a fibre volume fraction of 0.06% (Table 11). An increase of fibre volume fraction above 0.06% tends to decrease the tensile splitting bond strength (Figure 9) because the homogeneity of the mixture associated with the tensile force between particles decreases. The failure behaviour that occurs in the tensile splitting test also further confirms that micro synthetic fibre provides better resistance to cracking with the bridging effect that controls splitting cracks in cement composites [30].

Table 11 The 7-day tensile splitting bond strength repair mortar with various fibre volume fraction

ID	Fibre volume fraction V_f (%)	Ultimate load P (N)	Bond strength f_t (MPa)	Average bond strength f_{tav} (MPa)	COV (%)	Failure mode
B-F0.00-7A	0.00	80,904.86	1.14	1.16	2.26	B
B-F0.00-7B	0.00	84,337.19	1.19			B
B-F0.00-7C	0.00	81,395.20	1.15			B
B-F0.04-7A	0.04	117,189.47	1.66	1.62	4.21	A
B-F0.04-7B	0.04	117,189.47	1.66			A
B-F0.04-7C	0.04	108,853.82	1.54			A
B-F0.06-7A	0.06	117,679.80	1.66	1.73	4.04	A
B-F0.06-7B	0.06	121,602.46	1.72			A
B-F0.06-7C	0.06	127,486.45	1.80			A
B-F0.08-7A	0.08	107,873.15	1.53	1.57	2.44	A
B-F0.08-7B	0.08	113,266.81	1.60			A
B-F0.08-7C	0.08	110,815.15	1.57			A
B-F0.10-7A	0.10	92,182.51	1.30	1.33	2.39	A
B-F0.10-7B	0.10	96,595.50	1.37			A
B-F0.10-7C	0.10	93,653.51	1.32			A
B-F0.12-7A	0.12	86,788.85	1.23	1.25	2.24	A
B-F0.12-7B	0.12	88,259.85	1.25			A
B-F0.12-7C	0.12	90,711.51	1.28			A

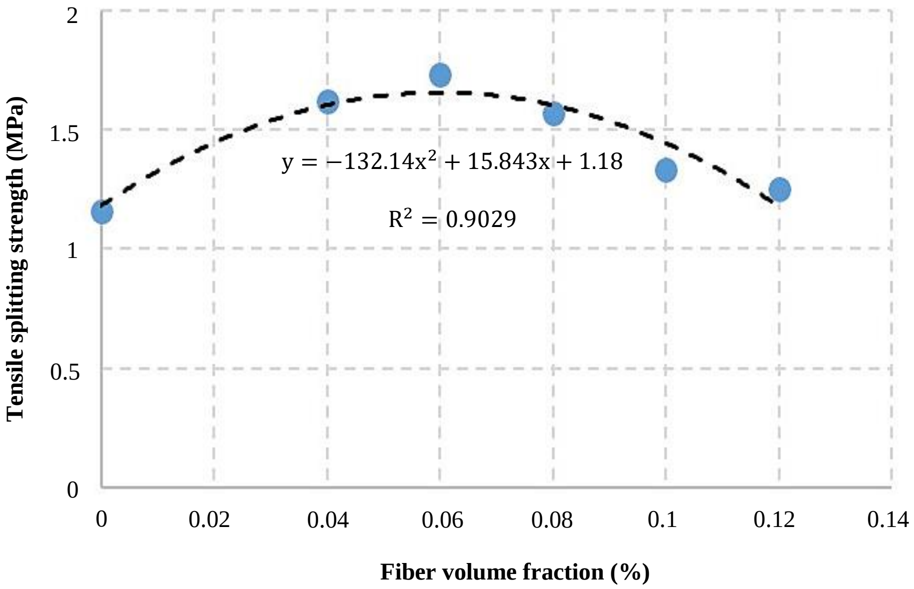


Figure 9 Influence of fibre volume fraction on the 7-day tensile splitting bond strength

3.2.3 Development of tensile splitting bond strength

Table 12 and Figure 10 show the development of tensile splitting bond strength of a micro synthetic fibre-reinforced patch repair mortar. The 1, 3, and 7-day tensile splitting bond strength represents about 50.53%, 76.91%, and 88.46% on the 28th day. It is also interesting to note that different failure modes exist, depending on the age of the repair material. Interfacial failure modes, combined with cracking in the repair mortar, can be observed on 1-day specimens. This could be due to the fact that the repair mortars have not developed sufficient strength at an early age, and so it cannot sustain compression load along the bond line during the splitting test. Meanwhile, after 28 days, the specimens exhibit an interfacial failure mode combined with minor cracking in both the repair mortar and concrete substrate. This type of failure can be attained when the repair material has developed sufficient compressive strength, comparable to the concrete substrate, and, at the same time, has attained an adequate bond to the concrete substrate [44].

Table 12 Tensile splitting bond strength development of repair mortars with fibre volume fraction of 0.06%

ID	Age of patch repair (days)	Ultimate load P (N)	Bond strength f_t (MPa)	Average bond strength f_{tav} (MPa)	COV (%)	Failure mode
B-F0.06-1A	1	68,156.22	0.96	0.99	3.70	B
B-F0.06-1B	1	73,059.54	1.03			B
B-F0.06-1C	1	69,136.88	0.98			B
B-F0.06-3A	3	102,479.49	1.45	1.51	4.14	A
B-F0.06-3B	3	106,402.15	1.51			A
B-F0.06-3C	3	111,305.48	1.57			A
B-F0.06-7A	7	130,918.78	1.85	1.74	6.59	A
B-F0.06-7B	7	114,737.81	1.62			A
B-F0.06-7C	7	122,583.13	1.73			A
B-F0.06-28A	28	138,273.77	1.96	1.96	4.08	C
B-F0.06-28B	28	144,648.09	2.05			C
B-F0.06-28C	28	133,370.44	1.89			C

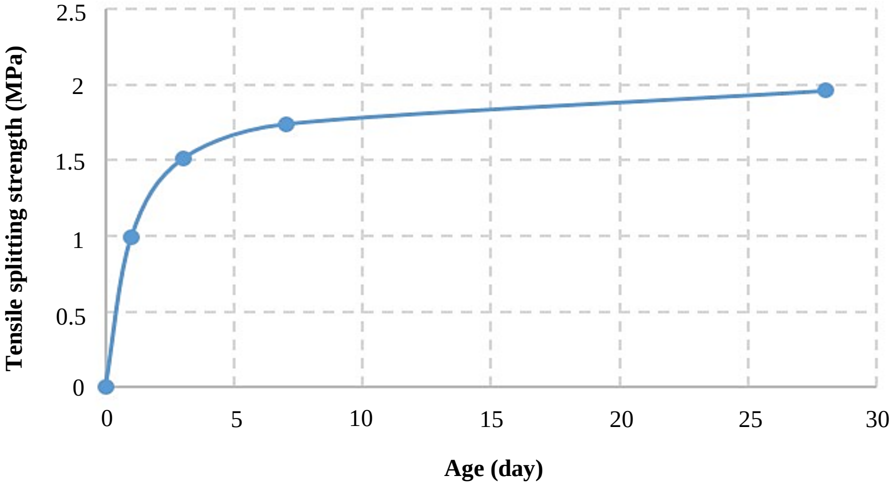


Figure 10 Tensile splitting bond strength development of repair mortars with fibre volume fraction of 0.06%

3.2.4 Tensile splitting bond strength vs compressive strength

Similar to the slant shear bond strength, it seems that the tensile splitting bond strength also correlates well with the mechanical properties of this repair mortar (see Table 5), where repair mortar with a fibre volume fraction of 0.06% also produces the highest compressive strength and elastic modulus. The progress of tensile splitting bond strength with age also corresponds to the development of compressive strength. The correlation of tensile splitting bond strength and compressive strength is presented in Figure 11.

Figure 11 confirmed that the tensile splitting bond strength and compressive strength have a linear correlation by a factor of 0.0605x -0.0464. Based on this factor, it is found that the tensile splitting bond strength is only about 5.2%-6.5% of the compressive strength.

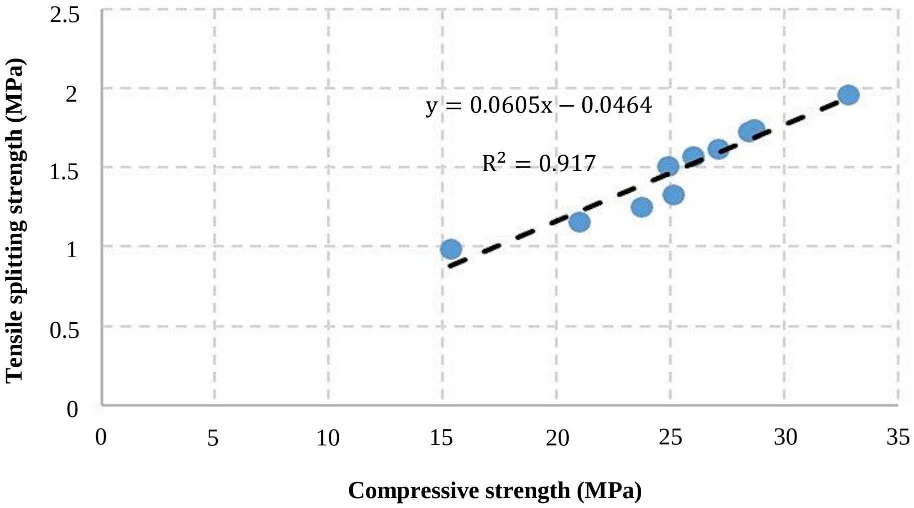


Figure 11 Tensile splitting bond strength and compressive strength correlation

3.2.5 Acceptance limit of tensile splitting bond strength

Sprinkel and Ozyildirim [48] proposed a categorisation of bond quality based on the tensile splitting bond strength, as shown in Table 13. The repair mortars investigated in this research fall into the range of fair to very good, for specimens aged 1 and 3 days. Meanwhile, the 7 and 28-day micro synthetic fibre-reinforced patch repair mortars have very good bond quality. No specimens fall within the poor-quality category.

Splitting test results mainly indicate the adhesion of the repair material to concrete substrate. The adhesion is not as significantly affected by the surface texture as that of friction. Therefore, most of the tensile splitting bond strength of the investigated repair materials fall within the very good category, even though they are determined on a smooth interface. This is in line with previous study conducted by Tayeh et al. [49, 50], assessment and microstructural analysis of adhesion in composites consist of two matrices shows that the results of the splitting tensile tests indicated the high bond strength between the repair material and concrete substrates, regardless the type of surface roughness. Bond strength increases as a function of the repair material ability to develop the bond to concrete substrates and entrapped air voids near the transition zone so that the bond is improved due to the adhesion mechanism.

Table 13 Quantitative bond quality, in terms of tensile splitting bond strength [48]

Bond quality	Tensile splitting bond strength f_t (MPa)
Excellent	≥ 2.1
Very good	1.7-2.1
Good	1.4-1.7
Fair	0.7-1.4
Poor	0.0-0.7

3.3 Slant shear and tensile splitting test correlation

The relationship between slant shear strength and tensile splitting strength is presented in Figure 12. The relationship is obtained from the linear regression of data from Tayeh et al. [41, 42], Tayeh et al. [32], and Sabah et al. [35]. As expected, slant shear bond strength is greater than the corresponding tensile splitting bond strength. This is because both adhesion and friction contribute to the measured bond strength in the slant shear test while, for the tensile splitting test, the bond strength is only provided by the adhesion mechanism. It is also interesting to note that the results of the current experiment are laid below the linear relationship of the slant shear versus the tensile splitting bond strength. This lower position could indicate that, at a similar splitting strength, the slant shear bond strength of the investigated repair materials is less than the slant shear strength of other repair materials. The inferior slant shear strength of the investigated repair materials is attributed to the smooth surface texture of the interface, which does not provide sufficient friction. Meanwhile, the repair materials reported by other researchers [31, 32, 35] have undergone surface treatments using various methods to roughen the interfacial texture, thereby increasing the friction coefficient.

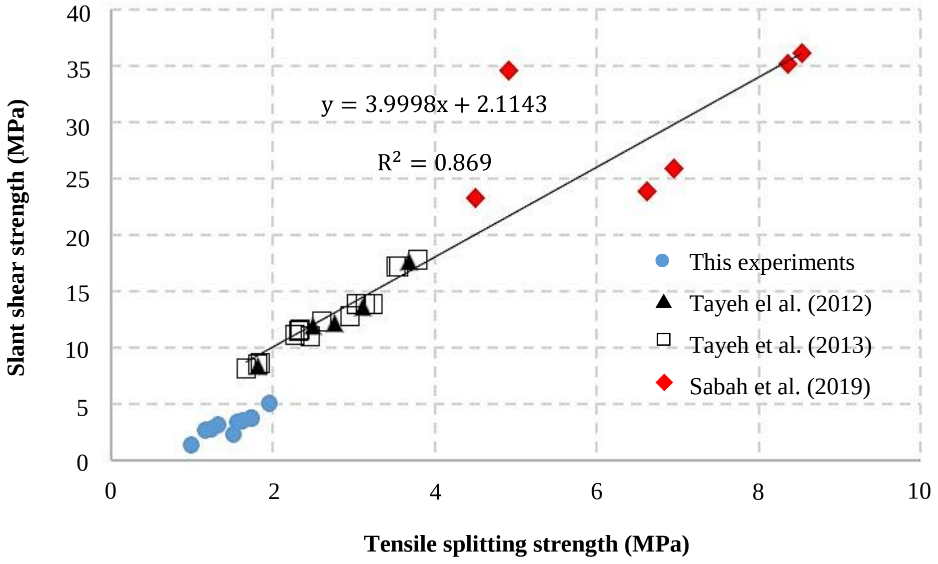


Figure 12 Slant shear and tensile splitting bond strength correlation

4. Conclusions

This paper investigated the interfacial bond strength and behaviour between the normal concrete substrate and micro synthetic fibre-reinforced patch repair mortar. The following conclusions are offered:

Micro synthetic fibre has an effect in increasing the interfacial bond strength. Based on the slant shear and tensile splitting test, the optimum fibre volume fraction of micro synthetic fibre leading to the highest interfacial bond strength is 0.06%. It is also confirmed that a linear relationship can be established between both slant shear bond strength versus compressive strength and tensile splitting bond strength versus compressive strength.

The failure modes of the specimens with a smooth interfacial texture (as-cast), in both slant shear tests and the tensile splitting tests, are that of interfacial failure, i.e. indicated by the separation of the repair materials component and the concrete substrate component. Additionally, some specimens show interfacial failure in combination with fracturing or cracking. The inclusion of micro synthetic fibres also changes the failure mode, depending on the age of the patch repair.

A linear relationship between slant shear bond strength and tensile bond strength can be established. Slant shear bond strength tends to produce a higher bond strength value than the tensile splitting test because the slant shear test allows both the adhesion and friction to contribute to the measured bond strength, whereas the tensile splitting test only evaluates the adhesion.

Smooth interfacial texture produces sufficient adhesion, but it provides little contribution to the friction.

For further research, push-off testing can be done on micro synthetic fibre reinforced repair mortar to obtain the adhesion and friction coefficient parameters, so that the bond envelope criteria can be established.

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