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INTERFACE SHEAR STRENGTH OF CONCRETE-TO-CONCRETE BOND WITH AND WITHOUT PROJECTING STEEL REINFORCEMENT

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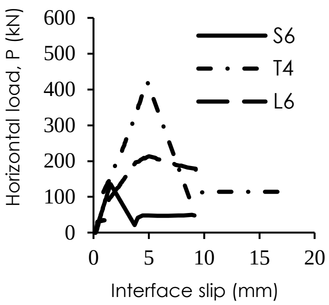
Graphical abstract



Abstract

Composite concrete consists of two elements cast at different times which are the concrete base and concrete topping. To achieve composite action, interface shear strength must be sufficient to resist the sliding motion between the two concrete surfaces in contact. The interface shear strength is mainly depended on concrete cohesion, friction and dowel action. A total of 36 "push-off" tests were performed to study the interface shear strength and to assess the influence of surface texture and steel reinforcement crossing the interface. Three different concrete base surfaces are prepared which include smooth or "left as-cast", roughened by wire-brushing in the transverse direction and steel reinforcement projecting from the concrete base. Eurocode 2 provides design equations for determining the interface shear strength with different surface textures and also the one where projecting steel reinforcement crosses the interface. The experimental results show that the transverse roughened surface produced the highest interface shear strength of 1.89 N/mm^2 (σ_n = 0 N/mm^2), 4.69 N/mm^2 (σ_n = 0.5 N/mm^2), 5.97 N/mm^2 (σ_n = 1.0 N/mm^2) and 6.42 N/mm^2 (σ_n = 1.5 N/mm^2) compared with the other surface textures. This proves that the increase in the degree of roughness contributes to higher concrete cohesion and friction coefficient. However, for the surface with projecting steel reinforcement, the failure is not sudden as experienced by the surface without one. This is due to the contribution of the clamping stress from the dowel action of the steel reinforcements. Meanwhile, for specimens without any projecting steel reinforcements, the interface shear strength depended solely on friction and concrete cohesion of the surface textures. The interface shear strength of surface with and without the projecting steel reinforcement can be predicted using the Mohr-Coulomb failure envelope. This paper also proposed design expressions for concrete-to-concrete bond on surfaces provided with and without projecting steel reinforcement that can be adopted in Eurocode 2.

Keywords: Surface texture, interface shear strength, projecting steel reinforcement, friction, concrete cohesion

Abstrak

Konkrit Komposit terdiri daripada dua unsur dituang pada masa yang berlainan yang merupakan asas konkrit dan penutup konkrit. Untuk mencapai tindakan komposit, kekuatan ricih antara muka mestilah mencukupi untuk menentang gerakan gelongsor di antara dua permukaan konkrit yang berhubung. Kekuatan ricih antara muka bergantung sepenuhnya kepada paduan konkrit, geseran dan tindakan dowel. Sebanyak 36 ujikaji "push-off" telah dijalankan untuk mengkaji kekuatan ricih antara muka dan menilai pengaruh tekstur permukaan dan keluli tetulang yang merintangi antara muka. Tiga permukaan asas konkrit yang berbeza disediakan yang termasuk licin atau "di-situ tuang dibiarkan", kasar oleh dawai berus dalam arah melintang dan keluli tetulang terunjur daripada asas konkrit. Eurocode 2 menyediakan persamaan rekabentuk untuk menentukan kekuatan ricih antara muka dengan tekstur permukaan yang berbeza dan juga di mana keluli tetulang terunjur merintangi antara muka. Keputusan eksperimen menunjukkan bahawa permukaan kasar melintang menghasilkan kekuatan ricih antara muka yang paling tinggi iaitu 1.89 N / mm² (σ_n = 0 N / mm²), 4.69 N / mm² (σ_n = 0.5 N / mm²), 5.97 N / mm² (σ_n = 1.0 N / mm²) dan 6.42 N / mm² (σ_n = 1.5 N / mm²) berbanding dengan tekstur permukaan yang lain. Ini membuktikan bahawa peningkatan dalam tahap kekasaran menyumbang kepada paduan konkrit dan pekali geseran yang lebih tinggi. Walau bagaimanapun, bagi permukaan dengan keluli tetulang terunjur, kegagalan tidak secara serta-merta seperti yang dialami oleh permukaan tanpa keluli. Ini adalah kerana sumbangan tegasan pengapit daripada tindakan dowel keluli. Sementara itu, bagi spesimen tanpa keluli terunjur, kekuatan ricih antara muka bergantung sepenuhnya kepada geseran dan paduan konkrit oleh tekstur permukaan. Kekuatan ricih antara muka pada permukaan dengan dan tanpa tetulang keluli terunjur boleh diramal menggunakan sampul kegagalan Mohr-Coulomb. Kertas kerja ini juga mencadangkan ungkapan rekabentuk untuk ikatan konkrit-ke-konkrit kepada permukaan yang disediakan dengan dan tanpa keluli terunjur yang boleh digunapakai dalam Eurocode 2.

Kata kunci: Tekstur permukaan, kekuatan ricih antara muka, keluli tetulang terunjur, geseran, paduan konkrit

1.0 INTRODUCTION

In precast concrete construction, the structures are usually constructed into two stages. The first stage is usually the installation of precast concrete element (e.g. slab) and the second stage is the application of in-situ concrete topping on the precast slab in order to achieve full composite action. At the same time, applying concrete topping on the precast slab will also increase the ultimate bending capacity and provide diaphragm action on the precast building structure. To achieve this, interface shear strength is transferred through concrete cohesion, friction and dowel action with the provision of shear reinforcement projecting from the precast slab [1-10]. The "shear-friction theory" is commonly used to predict the interfacial behavior of shear strength and normal stress resulting from the frictional force at the interface [1, 3, 4, 6, 8-14]. To characterize the horizontal shear strength at the interface between concrete layers cast at different times, design codes such as ACI 318 [10], Eurocode 2 [9], and CEB-FIB Model Code 2010 [8] recommended certain design values which are based on the surface texture and also steel reinforcement crossing the interface.

In this study, the interface shear stress is characterized using the Mohr-Coulomb model [15-17]. The "push-off" test method is conducted with the purpose of defining the Mohr-Coulomb parameters, such as concrete cohesion and friction coefficient of the concrete-to-concrete interface. The concrete cohesion and friction coefficient of the interface is determined based on two different compressive strength of the concrete layer and four Mohr-Coulomb envelopes from variable normal stress defined from the test results. The Mohr-Coulomb strength parameters are obtained according to Eurocode 2 [9].

The motivation of this study is to quantify the interface shear strength for different surface textures and also with the provision of steel reinforcement crossing the interface. This is important since different Codes of Practice gives different expressions and values. Even the friction coefficient and concrete cohesion is different between the Codes of Practice. To verify this, a total of 36 specimens are experimentally tested using the "push-off" method. The aim of this research is to propose design expressions based in the shear-friction provision in Eurocode 2 [9] for the surfaces with and without steel reinforcement crossing the interface. In order to determine the contribution of variable normal stresses to the interface shear strength, stresses of 0 N/mm², 0.5 N/mm², 1.0 N/mm² and 1.5 N/mm² are applied during the test. Three different types of surface textures are prepared on the top surface of the concrete base, which includes (i) smooth or "left as-cast", (ii) transversely roughened by wire-brushing, and (iii) surface "left as-cast" with the inclusion of shear reinforcement crossing the interface.

2.0 LITERATURE REVIEW

2.1 Codes of Practice

In Eurocode 2 [9], the interface shear strength between two concrete layers cast at different times is a combination of three main components given as:

$$\tau = c.f_{ct} + \mu.\sigma_n + \rho.f_{yd}(\mu.\sin\alpha + \cos\alpha) \leq 0.5\upsilon f_{cd} \qquad (1)$$

where $(c.f_{ct})$ is the concrete cohesion strength resulting from concrete chemical adhesion in the interface layer, in which c is the cohesion coefficient and f_{ct} is the concrete tensile strength of the concrete topping layer, $(\mu.\sigma_n)$ is the frictional force resulting from the friction coefficient at the interface, μ in which σ_n is the normal stress, and $[\rho.f_{yd}(\mu.\sin\alpha + \cos\alpha)]$ is the clamping stress component resulting from the presence of steel reinforcement crossing the interface, in which ρ is the reinforcement ratio, f_{yd} is the design yield stress of the reinforcement and α is the angle between the steel reinforcement and the plane and υ is strength reduction function. Eurocode 2 [9] presented the design expression based on qualitative observation of the surface textures from very smooth to very rough. The recommendation of roughness height for rough surface should be at least 3 mm and for indented or very rough surface at least 5 mm. The friction coefficient ranged from 0.50 – 0.90, while the cohesion coefficient ranged from 0.025 – 0.50 which are postulated for surface profile from very smooth to very rough.

CEB-FIB Model Code 2010 [8] quantifies the surface roughness using the average roughness, R_a which is determined as the mean value of texture height along a certain length, l_m. The surface texture is measured and categorized from very smooth to very rough. Very smooth is where the surface is cast against steel formwork, thus R_a is not measurable. Meanwhile, smooth surface is untreated and cast against wooden formwork where R_a is taken as less than 1.5 mm, and rough surface is roughened by sand blasting where R_a is more than 1.5 mm. For very rough surface, the surface is roughened using high pressure water jet where the indented has an R_a of more than 3 mm. The friction coefficient ranged from 0.50 – 1.40, and the concrete adhesion is categorized into rough and very rough surface with the mean shear resistance ranged from 1.5 – 3.5 N/mm^2. The interface shear strength equation is given as:

$$\tau = \tau_c + \mu(\sigma_n + \kappa.\rho.f_y) \qquad (2)$$

where κ is the interaction "effectiveness" factor and τ_c is the adhesion or interlocking mechanism. The term $\mu(\sigma_n + \kappa.\rho.f_y)$ is contributed from friction and dowel action. The assessment on the strong adhesive bonding is when the adhesive bonding and interlocking are the main contributing mechanisms to the interface shear strength, while the weak adhesive bonding is when friction and dowel action are the main contributing mechanisms to the interface shear strength.

Both Eurocode 2 [9] and CEB-FIB Model Code 2010 [8] compute the friction and cohesion coefficients based on surface roughness characterization. However, the selection of these values may be subjective as creating the surface roughness may differ depending on the pressure applied by the technical operator using the wire brush. Furthermore, the design expression can be separated into surface with and without projecting steel reinforcement. The surface without projecting steel reinforcement is merely depending on the surface roughness to quantify the interface shear strength. Therefore, the friction and cohesion coefficients can be quantified from the interface shear stress and normal stress relationship based on the Mohr-Coulomb failure envelope by correlating them with the roughness parameter. The CEB-FIB Model Code 2010 [8] considers the roughness parameter as average roughness, R_a in the design expression. The design expression of the surface without the projecting steel reinforcement crossing the interface is only taken by the concrete cohesion strength, τ_c where it is only depended on the roughness classification. The friction term in the design expression in Eq. (1) and Equation (2) is available when the steel reinforcement crossing interface is provided.

2.2 Previous Studies

The term "ultimate interface shear strength", denoted by τ_u, means the maximum shear stress of composite concrete that can withstand before the two concrete layers slides relative to one another. In 1966, Birkeland and Birkeland [3] proposed the shear friction theory for precast construction system where the steel reinforcement crossing the interface caused clamping stress at the interface. The saw-tooth ramp is described at the interface as the slope of $tan\,\theta$. The proposed expression is given as:

$$\tau_u = \rho.f_y.tan\,\theta \text{ or } \tau_u = \rho.f_y.u \qquad (3)$$

where ρ is the reinforcement ratio = A_v/A_c of which A_v is the area of reinforcement crossing normal to the interface and A_c is the area of the shear plane, f_y is yield stress of steel reinforcement crossing interface, $tan\,\theta$ is the friction coefficient represented as u and $(\rho.f_y)$ is designated as clamping stress.

Mattock [4] also proposed an equation for the interface shear strength with the contribution from normal stress perpendicular to the shear plane, σ_n and concrete cohesion, c. The proposed equation is given as:

$$\tau = c + (\rho.f_y + \sigma_n)tan\,\alpha \qquad (4)$$

The concrete cohesion, c in Eq. (4) is the minimum strength of the chemical adhesion between the two concretes without any normal and clamping stresses. Using the "push-off" test method, Mattock [4] proposed that c = 2.8 MPa, $tan\,\alpha$ = 0.8, and the values of $(\rho.f_y)$ from the PCI Design Handbook (1992) is limited for $\tau_u \leq 0.3f'_c$. Furthermore, the proposed Eq. (3) is not valid for $(\rho.f_y) \leq$ 1.4 MPa.

An experimental study by Wallensfelsz [18] using the "push-off" technique on 29 composite concrete block specimens identified the peak and post-peak shear stress at the contact surface at failure. A modification to the existing equation in AASHTO LRFD [13] by separating them into Coulomb friction and concrete cohesion is also proposed. The area of concrete where it is considered to be engaged in the interface shear stress is taken as the cohesion. The Coulomb friction equation is originated from the clamping stress of the steel reinforcement crossing the interface and normal stress. The proposed design expression is given as:

$$\tau_u = max|c \cdot A_{cv} \text{ (without steel reinforcement)} \qquad (5)$$

$$\tau_u = max|\mu(A_{vf} + \sigma_n) \text{ (with steel reinforcement)} \qquad (6)$$

where c is the concrete cohesion, A_{cv} is the area of concrete considered to be engaged in the interface shear stress, μ is the friction coefficient, A_{vf} is the area of steel reinforcement crossing the interface within the area of A_{cv} and σ_n is the normal stress. The author concluded that the resistance from steel reinforcement did not occur until the interface concrete formed the crack and the cohesion bond is broken. By using the maximum of these equations would provide accurate predictions especially in increasing the quantity of steel reinforcement at the interface.

Previous research by Jana [16] on 36 "push-off" tests are performed to determine the interface shear strength of precast girders and cast-in-place decks for both normal weight and lightweight concrete. The author proposed modification equation from Wallensfelsz [18] which suggests the maximum of the two components as:

$$\tau_u = max|c \cdot A_{cv} \text{ (without steel reinforcement)} \qquad (7)$$

$$\tau_u = max|\mu\left(A_{vf} \cdot f_y + \sigma_n\right) \text{(with steel reinforcement)} \qquad (8)$$

where f_y is the yield strength of steel reinforcement. The modified equations considered that the increase in the clamping stress is due to the increase amount of the projecting steel reinforcements. The shear resistance is dominated by the dowel action due to the projecting steel reinforcement rather than concrete cohesion and aggregate interlock at the interface.

Santos [1, 14] conducted experimental work on 300 specimens using the slant shear and splitting test method. The failure envelope of the interface is determined from the bond strength in both shear and tension. The Mohr-Coulomb failure criterion is adopted and the pure shear strength of the interface which is without applied normal stress is defined for all specimens. The authors developed design expressions based on the shear friction provision in Eurocode 2 [9] where the proposed expression of the interface shear strength (without steel crossing the interface) is given as:

$$\tau_u = c_d \cdot f_{ctd} \leq 0.25 f_{cd} \text{(without steel reinforcement)} \qquad (9)$$

where c_d is the design value of cohesion coefficient f_{ctd} is the design value of concrete tensile strength and f_{cd} is the design value of concrete compressive strength. Equation (9) is mainly depended on the cohesion strength of the concrete, while for the inclusion of shear reinforcement, the friction coefficient is only considered in the expression which is given as:

$$\tau_u = \mu_d\left(\sigma_n + \rho \cdot f_y\right) \leq 0.25 f_{cd} \qquad (10)$$
(with steel reinforcement)

where μ_d is the design friction coefficient, ρ is the reinforcement ratio = A_v/A_c of which A_v is the area of reinforcement crossing normal to the interface and A_c is the area of the shear plane, and f_y is the yield stress of reinforcement crossing the interface.

The design concrete cohesion, c_d and friction coefficient, μ_d is quantified by roughness parameter of the mean-valley-depth of the primary profile of the surface, R_{vm}. Both expressions are given as:

$$u_d = \frac{1.366\, R_{vm}{}^{0.041}}{\gamma_{fr}} \qquad (11)$$

$$c_d = \frac{1.062\, R_{vm}{}^{0.145}}{\gamma_{coh}} \qquad (12)$$

where γ_{fr} and γ_{coh} is the partial safety factor of friction coefficient and concrete cohesion, respectively. The proposed design expressions are determined for five different surface conditions; smooth or left "as-cast", wire-brushing, sand blasting, shot-blasting and hand-scrubbing or raking.

Mohamad *et al*. [15] developed an experimental study to investigate the shear strength at the interfaces of concrete-to-concrete bond. A total of 60 "push-off" tests were carried out to determine the friction coefficient and to correlate them with the interface shear strength under various normal stresses. The design compressive strength of the concrete base and concrete topping are 40 N/mm^2 and 25 N/mm^2, respectively. The top surface of the concrete base is treated with five different types of surface textures. They include (a) smooth or "left as-cast" with trowelled finish, (b) deep groove formed using a 16 mm steel bar, (c) roughened by wire-brushing in the longitudinal direction, (d) roughened by wire-brushing in the transverse direction, and (e) indented surface cast using a corrugated steel mold. In this study a more conclusive finding has been observed since the normal loads are applied at four different stresses of 0 N/mm^2, 0.5 N/mm^2, 1.0 N/mm^2 and 1.5 N/mm^2. The Mohr-Coulomb failure envelope is used to characterize the relationship between the interface shear strength and the variable normal stresses. The friction coefficient and concrete cohesion are determined for each surface textures. The proposed expression for the interface shear strength is given as:

$$\tau_u = c \cdot f_t + \mu \cdot \sigma_n \leq 0.25 f_{cd} \qquad (13)$$
(without steel reinforcement)

where $(c \cdot f_t)$ is the cohesion strength term denoted as C which is resulted from the concrete chemical adhesion at the interface layer, c is the concrete cohesion and f_t is the concrete tensile strength of the lower strength. The $(\mu \cdot \sigma_n)$ is the frictional force term at the interface resulting from μ (friction coefficient) and σ_n (normal stress).

The surface textures are measured using a portable stylus instrument and the roughness parameter is quantified for each of the surface textures. The mean-peak-height, R_{pm} of the roughness parameter is used in the study to predict the friction coefficient and concrete cohesion. The relationship between R_{pm} and friction coefficient is empirically determined as:

$$u = 0.8766R_{pm^{0.3978}} \quad (14)$$

Meanwhile, the predicted concrete cohesion expression is given as:

$$c = 0.2363e^{0.237R_{pm}} \quad (15)$$

From the findings made by the previous researchers, it can be concluded that the contact surface with and without the projecting steel reinforcement has a significant influence on the interface shear strength between the concrete base and concrete topping. In order to increase the design accuracy, the interface shear strength should be determined from the relationship between the interface shear stress and normal stress. At the same time, friction coefficient and concrete cohesion are defined using the Mohr-Coulomb failure envelope. Previous studies by Santos *et al*. and Mohamad *et al*. [1, 14-15] have proved that the use of roughness parameter to characterize the surface roughness is possible to predict friction coefficient and concrete cohesion especially at the roughened surface. Furthermore, design expressions in Eurocode 2 [9] can be separated into two design equations for the surface with and without the projecting steel reinforcement. Study by Mattock [9] considered concrete cohesion and friction coefficient from the normal and clamping stresses to assess the interface shear strength of surface with projecting steel reinforcement. Meanwhile, Birkeland [3], Wallensfelsz [18], Jana [16] and Santos *et al*. [1, 14] only considered the friction term for surface with projecting steel reinforcement and ignored the effect of concrete cohesion. Moreover, design expression by Birkeland [3] only includes the effect of clamping stress to friction and ignored the normal stress as the interface is initially cracked. For other researchers, they include both the effect of normal stress and the additional clamping stress in the friction term. Therefore, based on the Mohr-coulomb failure envelope, the design expression of interface shear strength for the surface without projecting steel reinforcement should consider both the concrete cohesion and friction from the normal stress. Meanwhile, surface with projecting steel reinforcement should include the effect of clamping stress in the friction expression. This is because the contribution of clamping stress increased the interface shear strength. In addition, the tensile strength of the concrete topping should be considered in determining the concrete cohesion.

3.0 RESEARCH METHODOLOGY

3.1 Material Properties and Surface Preparation

A total of thirty six (36) specimens are prepared which consists of two concrete layers cast at different times and compressive strengths. The specimen dimension is 300 mm wide × 300 mm length with 100 mm deep for the concrete base and 75 mm deep for the concrete topping. Both of the concrete base and concrete topping were provided with a mesh reinforcement of 6 mm diameter plain round mild steel bars. The provision of a mesh of reinforcement was to control creep and shrinkage. The design compressive strength of the concrete base and concrete topping are 40 N/mm^2 and 25 N/mm^2, respectively. Meanwhile, cylinders of 150 mm diameter × 30 mm height are tested at 28 days to determine the splitting tensile strength. The mix design for both concretes together with the test results at 28 days and test day are given in Table 1. The top surface of the concrete base is treated with three different types of surface textures as shown in Figure 1. They include (a) smooth or "left as-cast", (b) "left as-cast" provided with steel reinforcement crossing the interface and (c) roughened by wire-brushing in the transverse direction. For the surface shown in Figure 1(b), the steel reinforcement is embedded perpendicular to the top surface of the concrete base with 9 numbers × 6 mm diameter U-shaped mild steel bars. The projecting steel reinforcement was 6 mm diameter plain round mild steel bars with nominal characteristic yield strength of 250 N/mm^2.
The concrete base is first cast and left for curing using wet burlap until it achieved the design compressive strength of 40 N/mm^2 at 28 days. Then, upon casting the concrete topping, the surface of the concrete base is cleaned using compressed air to remove any debris and concrete laitance. The concrete topping is then casted on top of the concrete base. The specimens are left cured for another 28 days using wet burlap (Figure 2) prior to testing to improve the bond strength at the interface of concrete layers [19]. To confirm the concrete strength, both compressive and splitting tensile strengths are also experimentally tested for the concrete topping at 28 days and on the test day.

Table 1 Mix design proportions and compressive strength for concrete base and concrete topping

Elements	Design compressive strength (N/mm^2)	Water-to-cement ratio (w/c)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
Concrete base	40	0.50	427	842.24	912.43	213.33
Concrete topping	25	0.63	339	884.48	958.19	213.33

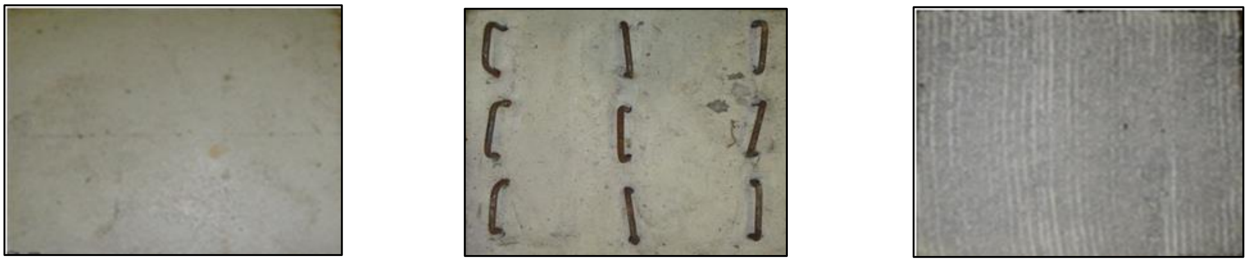
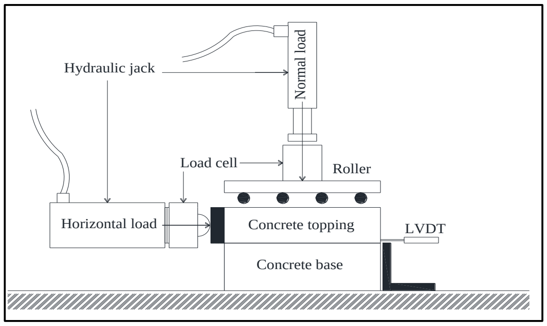

(a) (b) (c)

Figure 1 The surface textures at the top of the concrete bases; (a) smooth or "left as-cast", (b) "left as-cast" with projecting steel reinforcements crossing the interface, and (c) Transversely roughened using wire-brush

Figure 2 Burlaps used for the wet curing

3.2 "Push-off" Test Setup

The interface shear strength of concrete-to-concrete bond is determined experimentally using the "push-off" test method. This method has been widely used by previous researchers [5, 6, 16, 18, 20, 21] to investigate the effects of different surface textures at the interface. A total of 36 tests are performed to analyze the interface shear strength and to make comparison with the expression in Eurocode 2 [9]. The schematic diagram and actual setup in the laboratory is shown in Figure 3. The concrete base is fixed to the testing frame and the load is applied horizontally at the concrete topping using hydraulic jack and 1000 kN load cell. A roller is also placed on top of the specimen to control any uplifting that may occur during the test. Vertical load representing the normal stress is then applied on top of the roller at 0 N/mm^2, 0.5 N/mm^2, 1.0 N/mm^2 and 1.5 N/mm^2. To measure the interface slip, linear variable displacement transducer (LVDT) is positioned horizontally and as close as possible at the interface. The interface shear failure is identified when the cohesion bond at interface is broken. The horizontal load is applied incrementally at every 5 kN until the specimen fails. Failure is well defined when the bond at the interface is broken or when the two concrete layers become separated.



(a)

(b)

Figure 3 "Push-off" test setup; (a) Schematic diagram; and (b) actual setup

4.0 "PUSH-OFF" TEST RESULTS

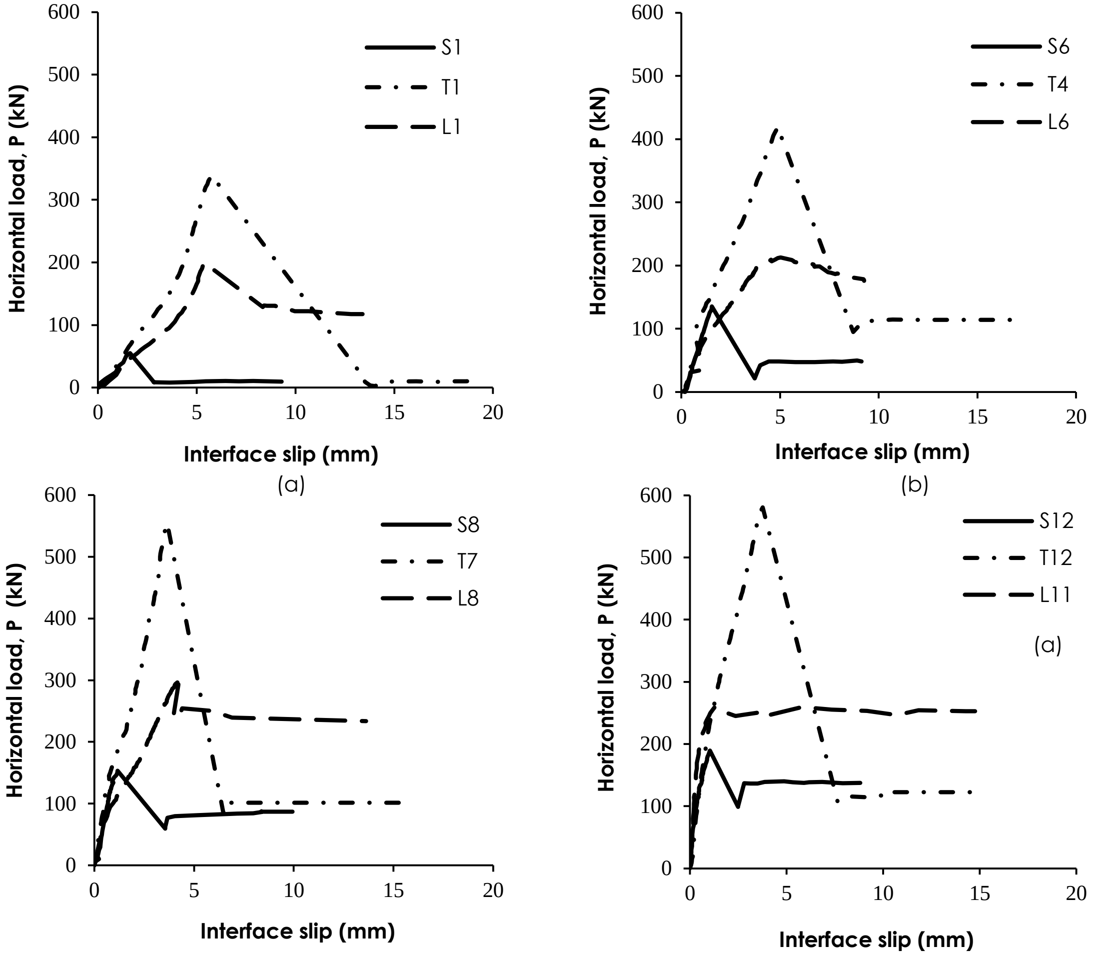
The horizontal load and interface slip relationships of the "push-off" test is shown in Figure 4 for the normal stress of σ_n = 0 N/mm^2, 0.5 N/mm^2, 1.0 N/mm^2 and 1.5 N/mm^2. In the figure, only one result of each surface textures are shown in the graph. In general, all specimens show the same loading pattern. The horizontal load increased linearly with the interface slip until it reached the peak shear load. In this study, the peak shear load is defined as pre-crack interface shear strength which occurred before the interface bond is broken. After the interface bond is broken, the horizontal load drops suddenly depending on the applied normal stress or clamping stress from the steel reinforcement. As loading is further applied, the relationship became plateau until the interface is completely debonded.

During the early loading stages, there is little increase in the interface slip as the horizontal load increases indicate that the specimens are considered in the state of static friction. In this state, the applied incremental horizontal load is trying to break the interface bond until it reaches the pre-crack interface shear strength. In this study, the transverse roughened surface specimens produced the highest peak shear load between 311.77 kN and 577.30 kN for all normal stresses condition before the interface bond is broken. This is then followed by the specimens with steel reinforcement crossing the interface with peak shear load between 125.30 kN and 302.00 kN. The lowest peak shear load is the specimen with smooth surface with peak shear load between 55.10 kN and 189.50 kN.

The static friction coefficient for the different surfaces is determined from the relationship of the horizontal shear load and normal stresses. The cohesion bond strength is determined at σ_n= 0 Nmm^2, while the cohesion coefficient is calculated from the ratio between the horizontal shear load and tensile stress.

The test carried out on 24 specimens of the smooth and transverse roughened surfaces shows the same pattern of which the load increases linearly with small interface slip until it reached the peak shear load. At this point, the interface bond starts to fail where a sudden drop in load and the increasing interface slip is observed. The sudden drop is almost near to 0 kN for specimens at σ_n = 0 N/mm^2. As the horizontal load is further increased, only the interface slip keep increasing (while the horizontal load maintains) until a total debonding is observed. Similar pattern is also observed for the specimens at σ_n = 0.5 N/mm^2, 1.0 N/mm^2 and 1.5 N/mm^2. However, the sudden drop maintained at a certain shear load depending on the applied normal stress. Meanwhile, the other 12 specimens which are provided with steel reinforcement crossing the interface have larger interface slip at every loading increment. This is because the steel reinforcement provides enough resistance to prevent sudden bond failure as experienced by the specimens without steel reinforcements. After reaching the peak shear load, there is no sudden drop in load but maintained at this point with only an increase in the interface slip. This pattern is observed for all specimens but depending on the clamping stress (or normal stress) applied on the specimens.

The peak shear load and interface slip results are summarized in Table 2, Table 3, Table 4 and Table 5 for σ_n= 0 N/mm^2, 0.5 N/mm^2, 1.0 N/mm^2 and 1.5 N/mm^2, respectively. The tables show that as σ_n increases from 0 N/mm^2 to 1.5 N/mm^2, the horizontal load also increases for each surface textures. For the applied σ_n = 0 N/mm^2, the peak shear load for the smooth surface is 55.10 kN, 65.40 kN and 60.40 kN for specimen S1, S2 and S3, respectively, thus, giving an average value of 60.30 kN. In comparison for the applied σ_n = 0.5 N/mm^2, the peak shear load is 124.80 kN, 115.00 kN and 135.50 kN for specimen S4, S5 and S6, respectively (giving an average of 125.10 kN). The peak shear load increases by an average of 64.80 kN compared with the results from σ_n = 0 N/mm^2. For the applied σ_n = 1.0 N/mm^2, the average peak shear load is 150.73 kN showing an increase of 90.43 kN and 25.63 kN compared with the results from σ_n = 0 N/mm^2 and σ_n= 0.5 N/mm^2, respectively. Finally, for σ_n = 1.5 N/mm^2 the average peak shear load is 178.23 kN which is 117.93 kN, 53.13 kN and 27.50 kN higher than the results for σ_n = 0 N/mm^2, 0.5 N/mm^2 and 1.0 N/mm^2, respectively.



(a)

(b)

(c)

(d)

S = Smooth, T = Transverse Roughened, L= Steel Links

Figure 4 Horizontal load-interface slip relationship for (a) σ_n = 0 N/mm² (b), σ_n = 0.5 N/mm² (c), σ_n = 1.0 N/mm², and (d) σ_n = 1.5 N/mm²

Table 2 Summary of test results for σ_n= 0 N/mm²

Surface type	Specimen	Peak shear load (kN)	Average peak shear load (kN)	Interface slip at peak shear load (mm)	Interface shear strength (N/mm²)	Average interface shear strength (N/mm²)
Smooth or "left as-cast"	S1	55.10	60.30	1.62	0.61	0.67
	S2	65.40		1.50	0.73	
	S3	60.40		1.06	0.67	
Transverse roughened	T1	340.00	311.77	5.73	2.06	1.89
	T2	310.10		3.85	1.39	
	T3	285.20		3.97	2.22	
Projecting steel reinforcement	L1	185.00	170.10	3.50	3.78	3.46
	L2	125.30		1.57	3.45	
	L3	200.00		5.38	3.17	

Note:
1. Cube compressive strength at test day, f_{cu}: Concrete base = 47.48 N/mm² and concrete topping = 30.37 N/mm²
2. Concrete splitting tensile strength at 28 days, f_{ct} = 2.99 N/mm²
3. The concrete properties in Note (1) and (2) are taken as an average of three samples

Table 3 Summary of test results for σ_n = 0.5 N/mm²

Surface type	Specimen	Peak shear load (kN)	Average peak shear load (kN)	Interface slip at peak shear load (mm)	Interface shear strength (N/mm²)	Average interface shear strength (N/mm²)
Smooth or "left as-cast"	S4	124.80	125.10	2.02	1.39	1.39
	S5	115.00		2.31	1.28	
	S6	135.50		1.54	1.51	
Transverse roughened	T4	420.40	422.10	4.87	4.67	4.69
	T5	435.60		4.72	4.84	
	T6	410.30		4.52	4.56	
Projecting steel reinforcement	L4	216.30	215.37	3.66	2.40	2.39
	L5	216.80		2.97	2.41	
	L6	213.00		5.02	2.37	

Note:
1. Cube compressive strength at test day, f_{cu}: Concrete base = 46.04 N/mm² and concrete topping = 29.94 N/mm²
2. Concrete splitting tensile strength at 28 days, f_{ct} = 2.99 N/mm²
3. The concrete properties in Note (1) and (2) were taken as an average of three samples

For the transverse roughened surface and the surface with steel reinforcement, the same increasing pattern is observed at peak shear load when σ_n increases from 0 N/mm^2 to 1.5 N/mm^2. The transverse roughened surface increases by 110.33 kN from the average peak shear load of 311.77 kN at σ_n = 0 N/mm^2 and 422.10 kN at σ_n = 0.5 N/mm^2. For σ_n = 1.0 N/mm^2, the average peak shear load is 536.87 kN showing an increase of 114.77 kN compared with the result for σ_n = 0.5 N/mm^2. However, for σ_n =1.5 N/mm^2, there is a small increase of only 40.53 kN (average peak shear load of 577.40 kN) from the results at σ_n = 1.0 N/mm^2.

As for the surface provided with steel reinforcement, the average peak shear load is 170.10 kN at σ_n = 0 N/mm^2. The average peak shear load increases to 215.37 kN at σ_n = 0.5 N/mm^2, showing an increase of 45.27 kN from σ_n = 0 N/mm^2. For σ_n = 1.0 N/mm^2 and 1.5 N/mm^2, the peak shear load is 264.17 kN and 283.80 kN, respectively. This shows an increase of 94.07 kN and 113.70 kN as compared with the results at σ_n= 0 N/mm^2. This increase is the smallest compared to other two surfaces. However, the advantage of adding steel reinforcement at the interface will avoid the sudden separation of the two concrete layers.

The interface slip at the peak shear load showing no particular relationship with the different type of surface textures. For σ_n= 0 N/mm^2 given in Table 2, the interface slip ranged between 1.06 mm to 5.73 mm. For σ_n = 0.5 N/mm^2 given Table 3, the interface slip is in the range of 1.54 mm to 5.02 mm. For σ_n = 1.0 N/mm^2 and 1.5 N/mm^2 given in Table 4 and Table 5, the interface slip is between 1.04 mm and 4.82 mm.

Table 4 Summary of test results for σ_n = 1.0 N/mm^2

Surface type	Specimen	Peak shear load (kN)	Average peak shear load (kN)	Interface slip at peak shear load (mm)	Interface shear strength (N/mm^2)	Average interface shear strength (N/mm^2)
Smooth or "left as-cast"	S7	162.90	150.73	2.40	1.81	1.67
	S8	153.50		1.16	1.71	
	S9	135.80		1.30	1.51	
Transverse roughened	T7	555.30	536.87	3.65	6.17	5.97
	T8	540.20		4.35	6.00	
	T9	515.10		4.82	5.72	
Projecting steel reinforcement	L7	234.60	264.17	2.16	2.61	2.94
	L8	302.00		4.26	3.36	
	L9	255.90		3.62	2.84	

Note:
1. Cube compressive strength at test day, f_{cu}: Concrete base = 45.70 N/mm^2 and concrete topping = 30.15 N/mm^2
2. Concrete splitting tensile strength at 28 days, f_{ct}= 2.99 N/mm^2
3. The concrete properties in Note (1) and (2) were taken as an average of three samples

Table 5 Summary of test results for σ_n = 1.5 N/mm^2

Surface type	Specimen	Peak shear load (kN)	Average peak shear load (kN)	Interface slip at peak shear load (mm)	Interface shear strength (N/mm^2)	Average interface shear strength (N/mm^2)
Smooth or "left as-cast"	S10	178.70	178.23	1.36	1.99	1.98
	S11	166.50		1.67	1.85	
	S12	189.50		1.04	2.11	
Transverse roughened	T10	565.80	577.30	3.93	6.29	6.42
	T11	585.80		4.22	6.51	
	T12	580.60		3.76	6.45	
Projecting steel reinforcement	L10	289.50	283.80	3.86	3.22	3.15
	L11	259.90		1.30	2.89	
	L12	302.00		2.88	3.36	

Note:
1. Cube compressive strength at test day, f_{cu}: Concrete base = 45.56 N/mm^2 and concrete topping = 29.81 N/mm^2
2. Concrete splitting tensile strength at 28 days, f_{ct} = 2.99 N/mm^2
3. The concrete properties in Note (1) and (2) were taken as an average of three samples

5.0 INTERFACE SHEAR STRENGTH

Interface shear strength is calculated from the peak shear load where the concrete cohesion is broken. During this loading stage, the applied horizontal load is gradually increased until the peak shear load is reached. At the same time, small interface slip is also observed between the two concrete layers showing that the composite action is lost as the layers slide relative to each other.

The proposed design approach is based on the different levels of shear stress containing with or without the projecting steel reinforcement. Based on the design expression in Eurocode 2 [9] given in Equation (1), the interface shear strength equation for specimens without projecting steel reinforcement which has been proposed by Mohamad *et al.* [15] as in Equation (13) can be expressed as:

$$\tau_u = c \cdot f_{ct} + \mu \cdot \sigma_n$$

where c is the concrete cohesion, f_{ct} is the concrete tensile strength, μ is the friction coefficient and σ_n is the normal stress. The expression in Equation (13) indicates that the friction coefficient and concrete cohesion increases with the increasing degree of roughness.

The following relationship for the interface shear strength equation for specimens with projecting steel reinforcement can be expressed as:

$$\tau_u = c \cdot f_{ct} + \mu(\sigma_n + \rho \cdot f_{yd}) \tag{16}$$

The projecting steel reinforcement is attached perpendicular to the interface or at 90° from the top surface of the concrete base. The clamping stress of the embedded steel reinforcement is taken as the term $(\rho \cdot f_{yd})$ from Equation (16) where ρ is the ratio of steel area crossing the shear plane to the resisting area and f_{yd} is the design yield strength of the reinforcement. The design expression in Equation (13) and (16) considered that the interface shear strength is a combination of concrete cohesion and friction coefficient from the normal stress acting on the interface, and clamping stress provided by the projecting steel reinforcement at the interface.

6.0 FRICTION COEFFICIENT AND CONCRETE COHESION

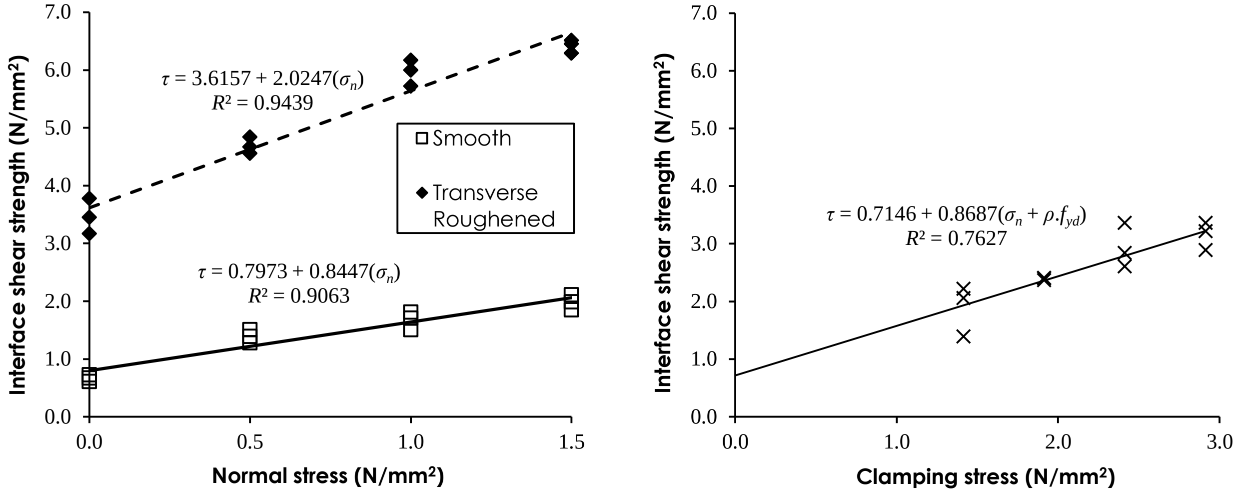
The design expression given in Equation (1) is normally used to determine the interface shear strength between concrete layers cast at different times. However, the values for the friction coefficient, μ and concrete cohesion, c are usually depending on the surface texture. In Eurocode 2 [9], the surface textures are assessed qualitatively in order to obtain the corresponding values of μ and c. The recommended values given in the codes are summarized in Table 6. The relationship between the interface shear strength and normal stress (or clamping stress) is shown in Figure 5(a) for the smooth and transverse roughened, while Figure 5(b) for the surface with steel reinforcement. From the relationships, the friction coefficient and concrete cohesion is then obtained using the Mohr-Coulomb envelope failure criterion as $\tau = C + \mu\sigma_n$ and also the relationship in Equation (1). The equation from the Figure 5(a) is represented as in Equation (13) and the Figure 5(b) is represented as in Equation (16). The findings from the analysis are given in Table 6.

In Equation (1), the term $[\rho . f_{yd}(\mu . \sin\alpha + \cos\alpha)]$ is related to the stress from the projecting steel reinforcement at the interface where the reinforcement ratio, ρ is taken as A_s/A_i of which A_s is the area of reinforcement crossing normal to the interface, A_i is the area of the shear plane and f_{yd} is yield stress of reinforcement crossing interface. The term $(\rho . f_{yd})$ is known as clamping stress and the relationship is shown in Figure 5(b).

Based on the analysis given in Table 6, the transverse roughened surface gives the highest friction coefficient, μ = 2.02 and also the concrete cohesion, c = 1.21. The lowest is the smooth surface where μ = 0.84 and c = 0.27. All the values from the experimental work are higher than the values given in Eurocode 2 especially the transverse roughened. This is because the roughened surface depends on the pressure applied by the operator using wire-brush on the top surface of the concrete base.

Both the smooth or "left as-cast" and projecting steel reinforcement have almost similar values for the friction coefficient and concrete cohesion. However, the friction coefficients are higher than one given in the code. The leveling of troweled finished on the smooth surface may cause differences between the experimental and the values given in the code. On the other hand, the concrete cohesion of both surfaces is almost the same with the values given in the code as shown in Table 6. Therefore, by adding projecting steel reinforcements on the smooth surface only exhibits higher clamping stress at the interface due to the dowel action from the flexural resistance of the steel reinforcements.

The friction coefficient and concrete cohesion of surface with transverse roughened are higher compared to that of the surface provided with projecting steel reinforcement. This is because the transverse roughened has more surface irregularities that can provide more concrete cohesion due to the mechanical interlocking at the interface. The friction also increases with the increasing of the degree of roughness and when normal stress is applied on the contact surface, the interface becomes harder to break compared to that of the smooth. As a result, the interface shear strength of the transverse roughened surface is higher than the surface with projecting steel reinforcement and smooth or "left as-cast" surface. On the other hand, the surface with projecting steel reinforcement gives less interface shear strength than the surface with transverse roughened. This is because of the lesser bonding of the surface area of the steel reinforcement surrounding the interface. However, the surface with projecting steel reinforcement has an additional resistance from the clamping stress that will increase the friction compared to that of the smooth or "left as-cast".



(a) (b)

Figure 5 Mohr-Coulomb envelope failure; (a) Smooth or "left as-cast" surface and transverse roughened surface, and (b) Smooth surface provided with projecting steel reinforcement

Table 6 Comparison between the experimental results and the values given in Eurocode 2 [9]

Surface type	Normal stress, σ_n (N/mm²)	Clamping stress $(\rho.f_{yd})$ (N/mm²)	Splitting tensile strength, f_{ct} (N/mm²)	Friction coefficient, μ		Concrete cohesion, c	
				Experimental in Figure 5, μ_{exp} (from best fit line)	Cl. 6.2.5(2) Eurocode 2	Experimental in Figure 5, c_{exp} $(c = C/f_{ct})$ (from best fit line)	Cl. 6.2.5(2) Eurocode 2
Smooth or "left as-cast"	0	-	2.99	0.84	0.60	0.27	0.20
	0.5						
	1						
	1.5						
Transverse roughened	0			2.02	0.70	1.21	0.40
	0.5						
	1						
	1.5						
Projecting steel reinforcement	0	1.41		0.87	0.60	0.24	0.20
	0.5						
	1						
	1.5						

7.0 DISCUSSION

In order to ensure full composite action of the two concrete layers, the design must be able to resist sufficient interface shear strength. The interface of the two concrete layers is normally resisted by friction, concrete cohesion or aggregate interlock and clamping stress due to dowel action from the projecting steel reinforcement. The interface without any steel reinforcements is usually depending on the degree of roughness. In Eurocode 2 [9], the degree for roughness is taken as the height of roughness and the value is limited to rough surface and the value of the very rough or indented surface is subjected to indentation complying with description figure in the code. Among the codes, only the CEB-FIB Model Code (2010) [8] considers the use of roughness parameter (the average roughness of R_a) to quantify the surface textures. Previous work by Mohamad *et al.* [15] found that the increase in R_{pm} will increase the friction coefficient and concrete cohesion values. Meanwhile, for the surface with projecting steel reinforcement, the increase in friction coefficient comes from the additional clamping stress in the term $[\rho.f_{yd}(\mu.\sin\alpha + \cos\alpha)]$ in Equation (1) and concrete cohesion from the surface textures. Santos [1, 14] suggested using the mean valley depth of R_{vm} to characterize the surface textures of pure interface shear strength without normal stress applied.

The current findings suggest that the highest friction coefficient and concrete cohesion in the interface shear strength equation is the one with transverse roughened compared to that of the smooth and projecting steel reinforcements. Furthermore, the surface without the projecting steel reinforcement failed suddenly at the interface where total failure of the bond is observed. However, for the surface with projecting steel reinforcement, when part of the cohesion bond is broken and the tensioning of the reinforcement prevented the sudden failure to occur.

The relationships in Figure 4 shows that without the projecting steel reinforcements, small interface slip is observed until it reached the peak shear load. Cracking did not form along the interface until the bond broken suddenly. However, for the specimen with projecting steel reinforcements, an initial crack is formed where the concrete cohesion begins to fail. As the crack continues to develop, the steel reinforcement provided additional tensioning at the interface and prevented the crack from widened. Furthermore, the steel reinforcement provides additional clamping stress to prevent sudden failure of the bond. The relationship in Figure 4 also shows that the interface slip is slightly bigger than the one without steel reinforcement. The shear load also decreases slightly after it reached the peak shear load before maintaining at a higher shear load as loading is further increased.

Further comparison on the interface shear strength is analyzed using the proposed concrete cohesion, c and friction coefficient, μ in Table 6. The interface shear strength is then calculated using Equation (13) & (16) and compared with experimental results. The comparison is given in Table 7 and also shown in Figure 6. The interface shear strength from the experimental is taken as the average for each surface textures. By using the slope of the best fit line of the Mohr-Coulomb failure envelope of the friction coefficient and concrete cohesion, the calculated interface shear strength show good agreement with the experimental results. Although the friction coefficient and concrete cohesion of the transverse roughened surface are higher than the values in Eurocode 2 [9] given in Table 6, the interface shear strength of calculated and experimental values show good agreement as shown in Table 7. This is because in Eurocode 2 [9] the values are based on qualitative assessment in which the characterization of rough surface is very subjective between rough and very rough. Furthermore, very rough surface in the code has lower coefficients than the quantification coefficients from the Mohr-Coulomb failure envelope from the experimental work. Therefore, friction coefficient and concrete cohesion of the transverse roughened surface from the slope of the best fit line in Figure 5 shows higher values compared with Eurocode 2. This inconsistency is due to unknown surface roughness profile that needs to be measured using the roughness parameter. Previous studies by Santos *et al.* [1, 14] and Mohamad *et al.* [15] have proved the possibility to predict friction coefficient and concrete cohesion based on the quantification of roughness parameter. In general, the comparison is acceptable between the experimental and the calculated values in which the differences are between 2% and 20%. Scatter of data comparison as shown in Figure 6 is also observed especially as σ_n is increased at every 0.5 N/mm^2 from 0 N/mm^2 to 1.5 N/mm^2. However, this data scatter still shows that the results lie along the 1:1 line.

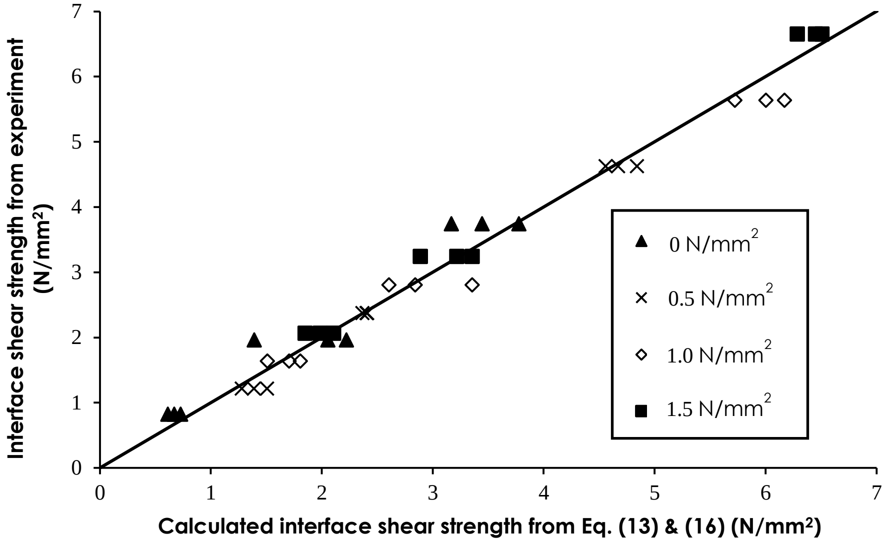


Figure 6 Comparison between the experimental and calculated interface shear strength

Table 7 Experimental and calculated interface shear strength using the proposed concrete cohesion, *c* and friction coefficient, μ

Surface texture	**Applied normal stress, σ_n (N/mm²)**	**Clamping stress, $\rho . f_{yd}$ (N/mm²)**	**Splitting tensile strength, f_{ct} (N/mm²)**	**Friction coefficient, μ from best fit line**	**Concrete cohesion, c from best fit line**	**Average interface shear strength from the experimental, τ_{exp}(N/mm²)** $\frac{Peak\ Load, (V)}{Surface\ Area, (bd)}$	**Calculated interface shear strength from Eq. (13) & (16), τ_{calc} (N/mm²)**	$\frac{\tau_{exp}}{\tau_{calc}}$
Smooth or "left as-cast"	0		3.10	0.84	0.27	0.67	0.84	0.80
	0.5		3.04			1.39	1.24	1.12
	1.0		2.91			1.67	1.63	1.02
	1.5		2.92			1.98	2.05	0.97
Transverse roughened	0		3.10	2.02	1.21	3.46	3.75	0.92
	0.5		3.04			4.69	4.69	1.00
	1.0		2.91			5.97	5.54	1.08
	1.5		2.92			6.42	6.56	0.98
Projecting steel reinforcement	0	1.4	3.10	0.87	0.24	1.89	1.96	0.96
	0.5		3.04			2.39	2.38	1.00
	1.0		2.91			2.94	2.79	1.05
	1.5		2.92			3.15	3.22	0.98

8.0 CONCLUSION

Experimental work using the "push-off" method is carried out to study the interface shear strength of concrete-to-concrete bond with and without projecting steel reinforcements. The aim of the study is to propose a design expression on the interface shear strength based on the shear-friction provision in Eurocode 2 [9] for different surface textures. The findings from the study can be concluded as follows:

(a) Bi-linear curve is observed for the horizontal load-interface slip relationship of all surface textures. Meanwhile, specimen with steel reinforcement shows a non-linear relationship.

(b) The amount of steel reinforcements crossing the interface and the surface texture are the two main parameters of importance on the interface shear strength. The interface shear strength increases accordingly to the increase in the clamping stress from the steel dowel action and the degree of roughness.

(c) Friction coefficient and concrete cohesion from the experimental work are determined from the Mohr-Coulomb envelope of shear-friction relationship formed between the pre-crack interface shear strength and normal stress.

(d) The interface shear strength of specimen without the projecting steel reinforcement depended solely on friction and concrete cohesion of the surface textures. Meanwhile, specimen provided with steel reinforcement contributes higher friction due to the clamping stress from the dowel action.

(e) The shear mechanism for steel reinforcement can be presented as a combination of three components which include concrete cohesion, friction and dowel action.

(f) The proposed friction coefficient, μ and concrete cohesion, c in this study is higher than the values given in Eurocode 2 [9].

(g) The proposed design expression with the steel reinforcement crossing the interface is given in Equation (16).

(h) The modified shear-friction expression in Eurocode 2 [9] for surface with steel reinforcement can be used of which the friction coefficient is the function of clamping stress due to dowel action. The design expression is applied only for steel reinforcement projecting at 90° or perpendicular to the interface.

(i) The clamping stress from the projecting steel reinforcement contributes to flexural resistance due to the dowel action between the concrete and steel interfaces.

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