Simulation and Model Prediction of Interfacial Concrete-to-Concrete Shear-Friction Behavior

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Abstract: Concrete-to-concrete composites are extensively used in a wide range of construction applications, including the construction of buildings, bridges, pavements, dams, and tunnels. Characterizing the structural performance of various approaches has been the subject of extensive study over the past several decades. The purpose of this study's evaluation is to give a thorough review of the present state of the art as well as pertinent information on the performance of concrete-to-concrete composites. Design and environmental issues are specifically analyzed and discussed. These include the interface state and mismatch between the overlay and substrate. Some experimental program also assessed the ability to forecast shear-friction under a variety of load combinations. According to the findings, a suitable choice of overlay and bonding agent composition, interface condition, casting and curing conditions, as well as assessment procedures, not only results in improved structural performance and durability, but also in optimized material consumption and casting costs, resulting in a more sustainable approach. This article will help engineers and practitioners optimize their own composites by elucidating the characteristics that improve the performance of these composites. This is a consideration for the application development of layered concretes.

1 INTRODUCTION

Concrete-concrete composites with several layers have various current uses, some of which include buildings, bridges, pavements, dams, and tunnels. These are only a few of the many modern applications for concrete-concrete composites. These composites are utilized mostly for the purposes of either reinforcing or repairing the structures that are already in existence, as well as for the construction of new structural parts, including precast to cast-in-place elements (Du et al., 2022; Xia et al., 2021). Hardened concrete pieces can be set against either fresh or hardened concrete, depending on the application. The installation of prefabricated concrete segments for tunnel linings is an example of the placement of hardened concrete against hardened components. On the other hand, the use of fresh concrete against hardened concrete sections is an example of the use of fresh concrete for bridge deck overlay (Yang & Lee, 2019). Over the past century, concrete overlays have been used as a long-lasting, economical, and environmentally friendly method of rehabilitation/strengthening (X. Wang et al., 2022).

The America's Infrastructure 2021 Report Card indicates that 46,154 (7.5%) of the nation's 617,000 bridges are structurally deficient and require immediate and long-term rehabilitation (ASCE, 2021). Over fifty percent of Europe's bridges are more than half a century old, and many of them are being considered to support loads that are greater than what they were originally intended for (M. G. Alexander et al., 2008; Bhattacharyay, 2012). A concrete overlay that has been carefully planned out and constructed can give strength and stiffness while also shielding the underlying layer and reinforcement from chemical damage. This has the potential to increase the lifespan of the concrete structure by at least thirty

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years, which is beneficial for both the economy and the environment (Gagg, 2014; S. Wang & Li, 2007; C. Wu & Li, 2017).

Not only for that, climate change as the increment of pollutants to the atmosphere effect the environment lately (M. Alexander & Beushausen, 2019; M. G. Alexander et al., 2015; Suryanto et al., 2015), where the corrosive environment become more common (M. Alexander & Beushausen, 2019; Lindvall, 2003). It has been documented that the amount of concrete infrastructure that is severely corroded year after year continues to drastically expand (Indra Komara et al., 2019; Wright et al., 2019). In that case, strengthening concrete structure led to the global attention (Al-Majidi et al., 2018; Dehn et al., 2015). Meanwhile, enhancing concrete construction quality, durability, and service life can reduce carbon emissions per cubic meter. This is due to the improved concrete's capacity to withstand wear and tear (W. Zhang et al., 2018). One alternative that attracted many users is layering concrete method or concrete to concrete. This not only substitute only apart of the concrete, but also minimize the working parameters (Al-majidi et al., 2019; Zhou et al., 2020). Reinforcing and rehabilitating structures often uses concrete-to-concrete contacts (Taklas, Leblouba, Barakat, & Al-sadoon, 2022; Taklas, Leblouba, Barakat, Fageeri, et al., 2022; Xia et al., 2021), as well as in the construction of prefabricated concrete structures (Andrew et al., 2019; Van Tittelboom & De Belie, 2013). Additionally, the differential contracting and stiffening of concrete components close to the contact (H. L. Wu et al., 2019), as well as the degree of hydration, are distinct from one another. When the concrete is loaded and then contracted, it is easy for weak links to form at the interface between the two types of concrete (Arezoumandi et al., 2015).

Interfaces made of concrete are required in order to transfer loads from the concrete of the substrate to the concrete of the superstructure (Quraishi et al., 2017). Therefore, the shear performance of the interface is of the utmost importance for ensuring monolithic behavior and the safe service of concrete composite components (Baghi & Barros, 2016; Liu et al., 2019; Pimanmas & Maekawa, 2001; P. Z. Zhao et al., 2017). There are three features associated with the mechanism of load transfer of shear forces at concrete-to-concrete surfaces (Walraven et al., 1987; Xia et al., 2021). These properties are (a) cohesion, (b) friction, and (c) dowel action. The remainder of this section will focus on identifying and contrasting three key moments in the measurement of the ultimate shear strength of concrete-to-concrete interfaces that have occurred over the course of the past sixty years (Peng et al., 2019; Xia et al., 2021; D. Zhang et al., 2012).

Concrete overlaying has established itself as the method of choice for pavement rehabilitation, and it has continued to see tremendous growth in the United States: it accounted for 12% of the total concrete paving in the country in 2017, up from 2% in the year 2000 (ASCE, 2021). This ever-increasing popularity is directly correlated to recent leaps forward in testing techniques, requirements, and other technical areas, as well as to advancements in those areas. This illustrates the significance of concrete-concrete composites as an option for prolonging the service life of aged infrastructure and ensuring the durability of newly constructed structures (ASCE, 2021).

The application of a concrete overlay as a method for the rehabilitation of structures is an intriguing possibility; nevertheless, extensive research on the material's early-age performance as well as its long-term durability is required. This poor performance can be attributed to the improper selection of construction materials, an improper construction procedure, or a combination of both (He et al., 2021; Teo & Loosemore, 2010). In order to achieve monolithic behavior, the interfacial bond strength of multi-layered concrete composites needs to be strong enough to transfer loads between individual concrete layers (Dehn et al., 2015; Gagg, 2014). Even though applying a concrete overlay is a potentially useful method for the rehabilitation of structures, more research on the material's early-age performance as well as its long-term endurance is necessary (Shu et al., 2021; S. Wang & Li, 2007).

The aim of this study is to review the contribution and the important factor of the shear-friction concrete to concrete. Some recommendation will also be discussed such as cohesion, friction, bonded parameter and dowel action.

2 SYSTEMATIC LITERATURE REVIEW

The concept of analysis in this paper is implied using systematic literature review, to measure the findings based on the area of concrete-to-concrete method (Baghi & Barros, 2016; Taklas, Leblouba, Barakat, Fageeri, et al., 2022). The step approach was adopted as illustrated in Figure 1. The parameter is closely paired with the previous analysis that was identified by other researchers. Recommendation then listed to corroborate findings (Daneshvar et al., 2022).

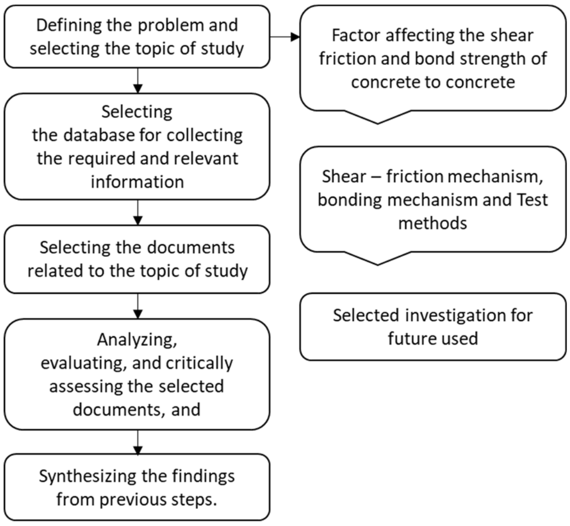


Figure 1: Method illustration based on SLR (Daneshvar et al., 2022).

Birkeland and Birkeland were the ones who first proposed the "shear-friction theory" in 1966. This theory is often referred to as the "linear formula to estimate the ultimate shear stress of concrete interfaces." (Walraven et al., 1987; Xia et al., 2021). This theory accounts for the fact that various surface preparations might result in vastly varied levels of friction. This is demonstrated by the research that follows, which also takes into consideration a term that represents the contribution of cohesion. Cohesion is being read in this context as adhesive bonding and mechanical interlocking. While chemical and physical bonding are responsible for the development of adhesive connections, mechanical interlocking can be achieved by providing the appropriate roughening and allowing the resulting uneven surface contour to take shape (Peng et al., 2019; Walraven et al., 1987; Xia et al., 2021; Yang & Lee, 2019). After that, another group of researchers investigated the dowel action of interfaces, which refers to the resistance of reinforcing bars to bending where they pass the interface (Du et al., 2022).

When two different kinds of materials are used in various layers of concrete, two different kinds of conditions will take place; one of these conditions, cohesion, will interact with the strength capacity of both kinds of materials. Those cohesion primarily considered by materials properties interface conditions; roughness, mechanical and physical behaviours and also the bonding agent if it is used as the based of the connection to concrete to concrete (Walraven et al., 1987). Not only for that, but materials distribution also distributes on the bonding of the cohesion parameter i.e., aggregate size and type, supplementary cementitious materials and additive (Jensen et al., 2016; Setina et al., 2013).

According to the findings of Alrefaei et al., the ultimate shear strength at concrete-to-concrete interfaces experienced a sizeable rise as a direct consequence of an increase in the compressive strength of the concrete (Alrefaei et al., 2018). When studying how recycled coarse aggregate replacement ratios affected shear strength. According to the results of the study, there was a negative impact on the shear strength of the material when the recycled coarse aggregate replacement ratio was more than 30%. This was the case in all of the scenarios that were analyzed (Rao et al., 2007). In addition, the findings of another investigation led the researchers to the conclusion that the employment of a bonding agent has an effect, in addition to having an impact on mechanical interlocking. This conclusion was reached as a result of the findings of the first study. In order to accomplish the impact of enhanced shear strength that is required, the development of a bonding bridge at the interfaces should be considered the primary purpose of a bonding agent (Lepech et al., 2008; C. Wu & Li, 2017).

The friction parameter will be subject to further evaluation in the future. The forces that were exerted due to the clamping state under reinforcement and the compression forces that were put perpendicular to the contact are the normal causes of friction. This condition corresponds to the sufficiency roughened surface. In order to conduct direct shear tests, the researchers constructed specimens with normal pressures ranging from 0 to 9.8 MPa (Arezoumandi et al., 2015; C. Wu & Li, 2017). As normal pressure increased, the interface's ultimate shear strength increased, and its growth rate decreased. Direct shear testing on concrete specimens under different normal loads were also conducted (Nuaklong et al., 2019; Wong et al., 2010). These tests determined material shearing behavior. Normal stress did not affect concrete specimen shear stiffness. It delayed the final shear strength, indicating friction mobilization at the peak.

Dowel action for strengthening bending resistance is also explored. Reinforcement and bar position effect dowel parameter (Kamal et al., 2008). The results showed that reinforcing increased interface ultimate strength and residual strength. Besides reinforcement quantity, (Arezoumandi et al., 2015; Redwood, 2011) revealed that residual strength depends on the shear reinforcement angle relative to the applied force. The research also examined how bar diameters, pre-tension, and concrete cover affected dowel action and offered a model to predict it (Arezoumandi et al., 2015). (Arezoumandi et al., 2015). Shear-transfer behavior with different reinforcing ratios and material properties and ACI estimations of ultimate strengths (American concrete Institute, 2014) and the AASHTO (AASHTO Subcommittee on Materials, 2016) shear-friction models. Cohesion, friction, and dowel action have not yet been determined. Thus, more research is needed to determine how shear transmission, cohesiveness, friction, and dowels affect concrete-to-concrete interface stress and slide.

2.1 Shear – Friction

When determining the shear strength between two pieces of concrete, one of the methods that is utilized the most frequently is the shear-friction hypothesis. In 1966, Birkeland and Birkeland were the ones who initially presented the design concept behind this notion (Walraven et al., 1987; Xia et al., 2021). Since then, the vast majority of the most important standard codes, such as the ACI 318–1, have adopted it.

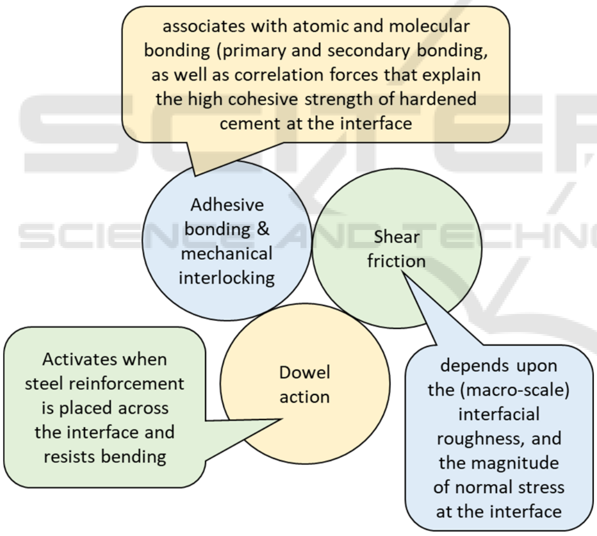


Figure 2: Shear – friction theory: three main components contribute to load transfer mechanism (Lin & Erkut, 2013).

The development of this theory, which led to considerable alterations of the design codes, is the topic of the in-depth analyses have provided in their outstanding reviews (Xia et al., 2021; Yang & Lee, 2019). These include the use of adhesive bonding and mechanical interlocking, as well as dowel action and shear friction. (See Figure 3). Atomic and molecular bonding (primary and secondary bonding) and correlation forces induce adhesion at the point of contact, giving cured cement its high cohesive strength. Along with adhesion, mechanical interlocking is a micro-level activity that relates to the behavior in which the major processes are sliding friction at extremely small shear slip values and irreversible deformation of the matrix. This behavior is distinguished by the fact that the shear slip values are significantly lower than expected. Adhesion is also a micro-level activity (Li et al., 1995; Lin & Erkut, 2013).

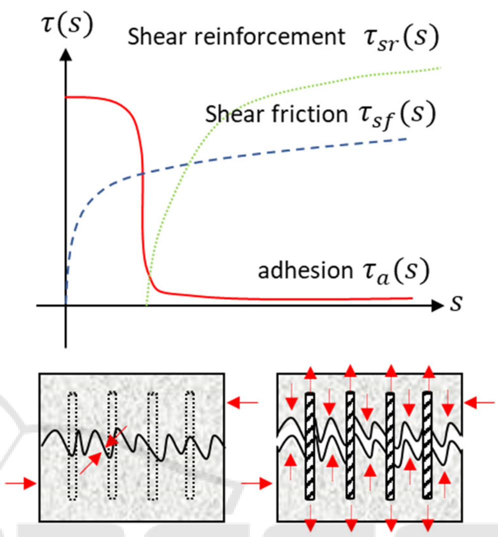


Figure 3: Load transfer mechanism of concrete to concrete – contribution of adhesion vs. shear friction vs. shear reinforcement (Lin & Erkut, 2013).

This behavior also includes adhesion as one of its components. The adhesion and interlocking processes are influenced by a number of factors, such as the composition of the concrete, the type of adhesive bonding agent used, the interfacial roughness at the micro-scale, the characteristics of the interfacial transition zone, micro-mechanical factors, and micro-cracks (Husein et al., 2022; Japan Society of Civil Engineers, 2007; Lim & Li, 1997; ZHANG et al., 2014; P. Z. Zhao et al., 2017).

According to fib 2010, adhesive bonding and mechanical interlocking shear transfer is efficient at very small shear slip values (usually below 0.05 mm) and is expected to decrease with increasing shear slip at the contact. This is because the shear transfer is proportional to the amount of shear stress that is applied to the interface. This is due to the fact that adhesive bonding and mechanical interlocking are both effective ways of transferring shear pressures at very low amounts of shear slip.

This is because the shear transfer is effective even at extremely low shear slip values, which is the primary reason for this observation. After compressive normal forces deteriorate adhesion, shear friction, which opposes the relative movement of concrete layers parallel to their interface, becomes the main load transmission mechanism at intermediate slip values. Shear friction opposes concrete layer displacement parallel to their interface. This is because shear friction is a force that works against the relative movement of concrete layers; hence it causes this effect. Concrete layers do not move in parallel because shear friction prohibits it. The macroscale roughness of the contact and the normal tension at the interface are the primary factors that determine shear friction. Dowel action begins to take place when the steel reinforcement resists bending. Dowel action is triggered by the addition of steel reinforcement across the junction (Du et al., 2022; Walraven et al., 1987).

The relative shear slip that occurs between concrete layers along the interface causes the upper and lower ends of crossing steel reinforcing bars to be moved laterally in an outward direction. The bending stresses are caused by the axial tensile forces of the reinforcement and the joint opening (Li et al., 1995; Lin & Erkut, 2013). This bending resistance is described as having a dowel action. The resistive stress size is affected by the type of crossing reinforcement, the percentage of that reinforcement, and flexural resistance (Bastian et al., 2020; I. Komara et al., 2018, 2020; Indra Komara et al., 2019; Oktaviani et al., n.d.).

2.2 Design Expression

Birkeland and Birkeland 1966 proposed shear-friction theory (Walraven et al., 1987; Xia et al., 2021) in order to figure out the ultimate longitudinal shear stress at concrete-to-concrete connections. The design of this theory can be represented by an equation. (1). The normal friction coefficients are affected by surface preparation in the following ways: 1) Monolithic concrete has a value of 1.7; 2) Construction joints that have been artificially roughened have a value of 1.4; and 3) Regular construction joints and concrete-to-steel interfaces have a value between 0.8 and 1.0. The coefficient for monolithic concrete is 1.7, the coefficient for artificially roughened building joints is 1.4, and the coefficient for ordinary construction ranges from 0.8 to 1.0.

$$v_u = \mu \rho f_y \tag{1}$$

$$v_u = 1.38 + 0.8(\rho f_y + \sigma_n) \tag{2}$$

$$v_u = k\sqrt{f_c(\rho f_y + \sigma_n)} \tag{3}$$

$$v_u = C_1(\rho f_y)^{c_2} \tag{4}$$

$$C_1 = 0.822 {f_c}^{0.406} \tag{5}$$

$$C_2 = 0.159 {f_c}^{0.303} \tag{6}$$

$$v_u = C_1(0.007\rho f_y)^{c_2} \tag{7}$$

$$v_u = c{f_c}^{1/3} \leq \beta \nu f_c \tag{8}$$

$$v_u = \mu(\rho k f_y + \sigma_n) \leq \beta \nu f_c \tag{9}$$

$$v_u = \alpha\rho\sqrt{f_y f_c \leq \beta \nu f_c} \tag{10}$$

A number of investigations have shown that this design expression could be enhanced by integrating other aspects such as interface cohesion (which is comparable to adhesion and aggregate interlock), the lowest concrete strength, and deformation-induced dowel action caused by shear, bending, and tension. The most important contributions will be covered in the paragraphs that follow. Equation (2) is what people usually mean when they talk about the "modified shear-friction theory." The first equation depicts the cohesiveness of the contact, which is assumed to remain unchanging and is equal to 1.38 MPa. The second term depicts the clamping stresses that are being applied. The coefficient of friction is considered to be constant if it stays at 0.8 during an experiment. In Equation 3, the concrete's strength has been explicitly integrated. It was assumed that k was equal to 0.5 for initially uncracked interfaces at the beginning of the study (Peng et al., 2019).

The research also used the "sphere model" to describe the interaction between aggregates, binding paste, and interface zone. A complete experimental study using push-off specimens with fractured interfaces calibrated the nonlinear design expression (Equation (5) to (7)). The initial research was carried out in order to discuss and investigate the effect that the dowel action mechanism has on the total shear strength of the contact. Later, a design expression was proposed (Equation (8) – (10) that explicitly includes the contribution of the following three load transfer mechanisms: 1) cohesion, due to the contribution of adhesion and aggregate interlocking; 2) friction, due to the longitudinal relative slip between concrete layers and therefore influenced by the surface roughness and the normal stress at the shear interface; and 3) dowel action, due to the contribution of the flexural resistance of the shear residuum. Table 1

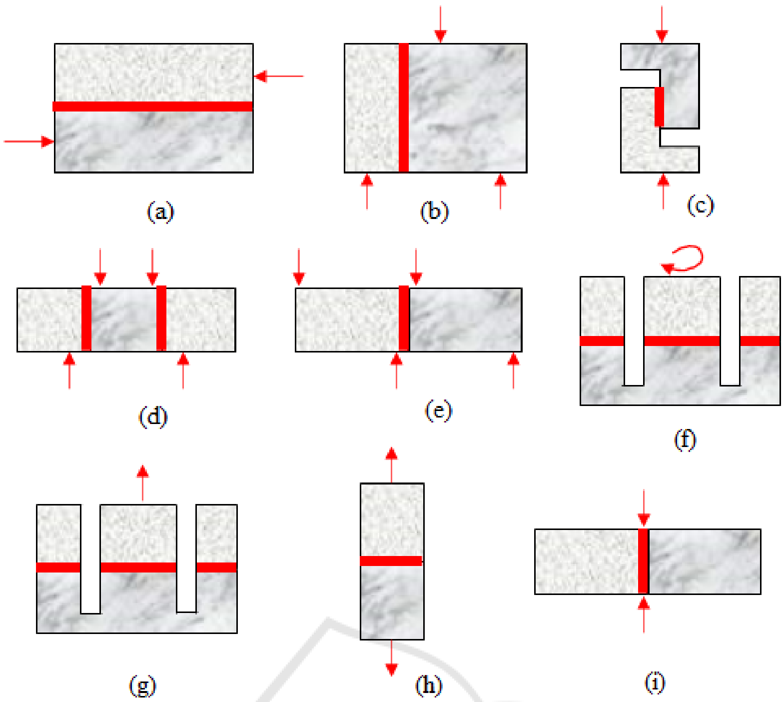


Figure 4: Shear test (a) – (f) and tensile test (g) – (i); (a) Mono surface shear, (b) Bi – surface shear, (c) push off (double L-shaped), (d) Direct double shear under JSCE, (e) FIP standard shear, (f) Twist - off.

presents the parameters of the design expression suggested by Randl also proposed that the Sand Patch Test be used to evaluate surface roughness in accordance with ASTM E965(2001)12.

$$v_u = \rho f_y(\mu sin\alpha + cos\alpha) \qquad (11)$$

Table 1: Surface preparation identfiying cohesion.

Surface preparation	High – pressure water – blasting	Sand – blasting	Smooth
Surface roughness, *R, mm*	≥ 3.0	≥ 0.5	-
Coefficien of cohesion *c*	0.4	0.0	0.0
Coefficient of friction μ			
f'c ≥ 20 MPa	0.8	0.7	0.5
f'c ≥ 35 MPa	1.0	0.7	0.5
k	0.5	0.5	0.0
α	0.9	1.1	1.5
β	0.4	0.3	0.2

According to ACI 318 (American Concrete Institute (ACI 318-99), 1999), a crack that already exists or could potentially occur, an interface between different materials, or an interface between two concretes cast at distinct dates could all be potential causes of a fracture that runs across a particular plane. At the concrete-to-concrete interface, friction is a factor that affects the ultimate longitudinal shear stress (Equation 11). There is a lack of specific exploration of cohesion and dowel action.

When analyzing surface conditions, the following four factors are taken into account: 1) Concrete that is placed against hardened concrete with the surface being clean but not intentionally roughened (= 0.6); 2) Concrete that is placed against hardened concrete with the surface being clean and intentionally roughened to a full amplitude of 6.35 mm (0.25 in.) (= 1.0); 3) Concrete that is placed monolithically (= 1.4); and 4) Concrete that is anchored to as-rolled structural steel by headed studs or reinforcing bars. (= A modification factor that is associated with the concrete's density is denoted by the parameter known as. For this parameter, it is anticipated that normalweight concrete will have a value of 1.00, while all lightweight concrete will have a value of 0.75. When employing aggregates of both the normalweight and lightweight varieties, the modification factor needs to be computed while taking into consideration the volumetric proportions of each aggregate type, and it can't be higher than 0.85.

3 CASE STUDY – SUPPORTED EXPERIMENTAL PROGRAM

In order to characterize concrete bonding under a wide variety of different types and combinations of loadings, a variety of testing methodologies have been devised. The stress that is applied to the interface and the concrete layers in each of these test methods is the primary distinction between them. This is because each of these test methods use a unique specimen and loading setup. Because of this, the value of the bond strength, which is normally measured as the highest force required to physically pull the two surfaces apart divided by the (macroscopic) surface of contact, is greatly reliant on the sort of testing method that was used. Because the interfacial bond strength can change by a factor of 8 depending on the type of test procedure (Peng et al., 2019).

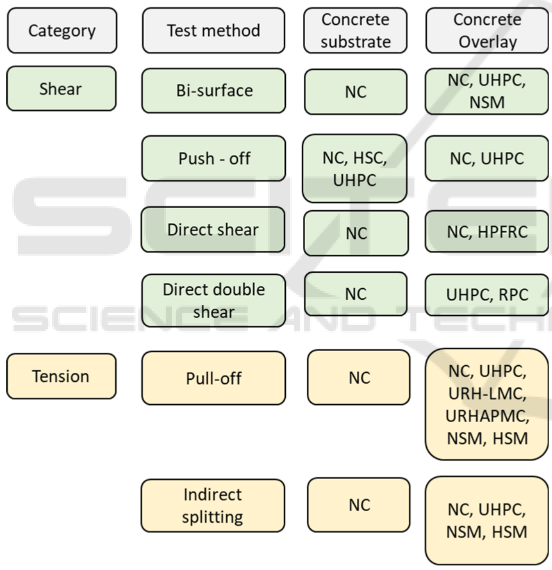
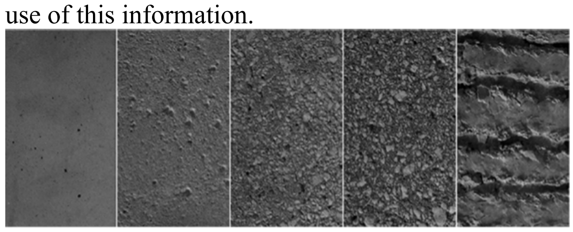


Figure 5: Test methods – shear vs. tension; NC: normal concrete, HSC: high steel concrete, HPC: high performance concrete, UHPC: ultra-high-performance concrete, NSM: normal strength mortar, UHPFRC: ultra-high-performance fibre reinforced concrete, URH-APMC: ultra-rapid hardening acrylic polymer modified concrete.

The past research also came to the conclusion that the test method should be designed to be as similar to the real or desired conditions as is practically practicable. In addition, the modes of failure that are detected using these test methods are dependent on the loading conditions as well as the materials that are utilized (Xia et al., 2021). In general, the failure modes in concrete-to-concrete composites can be categorized as either cohesive or adhesive failures, as shown in Fig. 5, depending on the location of the main observed crack paths (Walraven et al., 1987). This is the case because cohesive failures are more likely to occur when the two types of concrete are mixed together.

In the case of cohesive failure, the cracks appear within the bulk of the concrete itself, either in the overlay or the substrate (Taklas, Leblouba, Barakat, Fageeri, et al., 2022). When a bonding agent is employed, the adhesive failure mode can follow one of three distinct probable failure paths depending on where the crack appears (Du et al., 2022; Peng et al., 2019; Xia et al., 2021). Failure to cohere is typically thought to be indicative of strong bonding since it demonstrates that the strength of the interfacial bond is greater than that of the bulk concrete (Walraven et al., 1987; X. Wang et al., 2022; P. Zhao et al., 2017). In this context, increasing the bond strength is believed to have the effect of moving the place of failure from the interface to the bulk concrete. Increasing the interfacial roughness, making the overlay binding matrix stronger, or introducing an interfacial bonding agent are the standard methods for accomplishing this (Walraven et al., 1987; Xia et al., 2021; Yang & Lee, 2019). The pre-existing substrate/overlay flaws, such as micro cracks and specific stress state (induced by the sample preparation, for example), should not be ignored and may lead to the early crushing or rupture of the bulk concrete. These defects should not be ignored. In this particular scenario, the theory that higher bond strength can be achieved is shown to be unreliable (Daneshvar et al., 2022; Yang & Lee, 2019).

In some cases, the adhesive failure must be artificially induced (for example, by creating a pre-notch), so that an accurate measurement of the bond strength may be obtained. It is helpful to do systematic investigations of certain design parameters and quantify their impact on the structural integrity and bond performance of concrete-concrete composites. This can be accomplished through the use of this information.



(a) (b) (c) (d) (e)

Figure 6: Surface preparation consists of the following steps: (a) casting; (b) wire brushing; (c) sand blasting; (d) shot blasting; and (e) hand scrubbing.

The types of loads that are applied to the interface serve to categorize the testing procedures into one of three primary groups: the tensile, shear, and mixed-mode groups (see Fig. 6). Shear is one of the most common types of loadings that is applied to the interface under real conditions. It can be caused by differential time-dependent deformation between concrete layers (shrinkage), the passage of traffic loads on multi-layer concrete pavement and bridge decks, the transfer of shear through the joints, etc. Shear is one of the most common types of loadings that is applied to the interface under real conditions. In addition, preparation of the substrate surface also one of the considerations to identify the shear friction mechanism. The various surface preparation can be seen in Figure 6.

According to the examples that are presented in Figure 6, it is possible to deduce that surface preparation also takes into account the shear friction that is linked to the concrete components that interact with the substrate.

4 SUMMARY AND CONCLUSIONS

Concrete-to-concrete composites have seen widespread use over the past three decades, and their applications have grown increasingly diverse. The enormous body of literature that was produced during this time period provides evidence of the significance of the repair approaches, but it may also give results that are ambiguous or even contradictory. The goals of this study are to (1) present a complete description on the test procedures used for the evaluation of the performances of concrete-to-concrete composites and (2) conduct a systematic examination of the elements that affect these characteristics. Both of these goals will be accomplished by the end of this article. By doing so, the authors seek to make it simpler for interested parties to access an examination of the pertinent literature. The most important findings can be summed up as follows:

- Bi-surface shear tests, pull-off test, direct shear test, direct double shear test, and indirect splitting are mechanical tests used to analyze the concrete-to-concrete composite's shear friction behavior. Combination tests, such as four-point bending and three-point bending, can produce more accurate results in similar situations.
- The predominant failure mode in concrete-to-concrete composites was either cohesive or adhesive, depending on the position of the largest fissures.
- In addition to moisture condition, type and qualities of the adhesive agent, roughness, reinforcement, and shrinkage, additional criteria that affect the shear friction behavior are roughness, reinforcement, and shrinkage.
- Certain forms of concrete have a high shear friction capacity, including HPC and ECC overlays in particular.

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