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Review

Interfacial bond in concrete-to-concrete composites: A review

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ABSTRACT

Concrete-to-concrete composites have been widely used in a broad range of applications such as buildings, bridges, pavements, dams and tunnels. Numerous studies have been carried out to characterize the structural performance of these composites. This paper presents a state-of-the-art review and key information on the performance of concrete-to-concrete composites. Specifically, design and environmental factors (interface condition, bonding agents, concrete properties, mismatch in overlay and substrate, fibers and admixtures, temperature, humidity) are reviewed and discussed. The test methods developed to determine bond strength under various load combinations are also described. The findings show that a proper selection of overlay and bonding agent composition, interface condition, casting and curing conditions as well as assessment techniques not only result in greater structural performance and durability but also in an optimized material usage and casting cost, leading to a more sustainable approach. Considering the growing application of layered concretes in the recent decade, this review aims at clarifying the parameters that maximize the performance of these composites and at supporting engineers and practitioners in optimizing their composites.

1. Introduction

Nowadays, multi-layered concrete-concrete composites are increasingly used in a wide range of applications such as buildings, bridges, pavements, dams, and tunnels. These composites are mainly used to strengthen and/or repair the existing structures as well as to construct new structural members such as precasts to cast-in-place elements. Depending on the application, a hardened or a fresh concrete can be placed against hardened concrete parts. The use of precast concrete segments for tunnel linings is an example of placing a hardened concrete against hardened parts while bridge deck overlay is an example of using fresh concrete against hardened concrete parts. Concrete overlays have been employed for more than 100 years to serve as a durable, cost effective, and sustainable rehabilitation/strengthening technique [1]. According to the America's Infrastructure 2021 Report Card, 46,154 (7.5 %) of the 617,000 reported bridges in the national bridge inventory are structurally deficient and in need of urgent effective and durable rehabilitation solutions [2]. In Europe, over 50 % of the bridges are above 50 years old, and currently carrying higher loads than what they were originally designed for [3]. A well-designed and constructed concrete overlay can provide additional strength and stiffness, and protect the underlying layer and reinforcement from deleterious agents. This, in turn, can extend the service life of the concrete structure by 30 years or more and provide economic and environmental benefits [4]. Concrete overlaying has proven the technique of choice for pavement rehabilitation, and has sustained a rapid development in the USA: it represented 12 % of total concrete paving in 2017, compared to 2 % in 2000 [1]. This increasing popularity goes hand in hand with recent technical developments, advanced testing methods, and updates in specifications. This highlights the importance of concrete-concrete composites as a sustainable solution towards extending the service life of deteriorating infrastructure and ensuring the durability of new constructions.

While placing a concrete overlay is a promising avenue to rehabilitate structures, both early-age performance and long-term durability need to be investigated carefully. According to an estimation by Mather and Warner [5], up to half of all concrete repairs fail. This poor performance is attributed to improper material selection, inappropriate construction method, or a combination of both [6–8]. The multi-layered concrete composites should present an interfacial bond strength sufficient to transfer the load between concrete parts, resulting in a monolithic behavior. A weak bond strength can lead to improper stress transfer and premature debonding. The interface between concrete parts

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is usually treated as a weak point and is the most critical area within the whole composite due to the material discontinuity, high pore accumulation, and micro-cracks concentration [9]. Failure at concrete-to-concrete interface can jeopardize the entire repairing process and hence lead to a reduction of the service life of the repaired structure [10]. Typical failures in concrete-concrete composites consist in delamination from the substrate and/or cracking of the overlay, often attributed to non-uniform shrinkage under restrained conditions [9,11,12]. The cracks usually initiate at the edges of the concrete overlay and propagate towards the center, causing local debonding of the overlay from the concrete substrate, and eventually loss of load-transfer capacity [13].

Despite numerous investigations and a range of novel overlaying materials, robust concrete rehabilitation remains a challenge to the repair industry and researchers. This will be more critical with the remarkable repair costs. It was estimated that to repair and maintain around 1.1 million bridges across Europe, a budget of at least €6.6 billion should be dedicated every year while replacing them costs more than €400 billion. This issue is both European and global. According to the 2021 Infrastructure Report Card, repairing structurally deficient or functionally obsolete bridges, demands a budget of at least €22.7 billion, annually [2]. The poorly designed or executed maintenance solutions, including overlay placement, may result in even higher costs. This emphasizes the requirement for appropriate design guidelines for concrete strengthening and repairing projects, including overlay material selection and application techniques. The use of precast concrete members with cast-in-place parts represents an important and developing market due to higher speed of construction, improved work zone safety, as well as reduced variable quality control, labor cost, and environmental impacts compared to fully on-site concrete casting [14]. Here again, the proper bonding between the precast and the cast-in part is of great importance to ensure the load transfer and monolithic structural performance of the resulting composite. The facing challenges are similar, except in this case the precast concrete is younger and the bonding may suffer less from differential shrinkage between layers.

Research efforts on concrete-to-concrete interfaces have so far mainly focused on the improvement and assessment of the bonding between different layers of concretes. Numerous studies have been carried out to identify the relevant design and environmental parameters and to quantify their effects on the bonding properties. This paper presents a state-of-the-art review of experimental and numerical investigations on the concrete-to-concrete bond strength, emphasizing the primary influencing factors dictating its behavior. This review is mainly focused on fresh concrete overlays placed on concrete substrates, due to their prevalence in applications.

2. Methodology

A systematic literature review (SLR) [15], as one of the most commonly used techniques to summarize research findings in the area of building engineering and construction materials [16,17], was followed. Following the SLR method, a five-step approach was adopted, including: (1) defining the problem and selecting the topic of study, (2) selecting the database for collecting the required and relevant information, (3) selecting the documents related to the topic of study, (4) analyzing, evaluating, and critically assessing the selected documents, and (5) synthesizing the findings from previous steps.

In this project, the topics of investigation were (1) the factors affecting the bond strength of concrete-concrete composites and (2) the specific test methods to measure such strength. Three well-known bibliographic resources (Web of Science, Google Scholar, and Scopus) were selected to collect the relevant information. To find the appropriate documents, the following search string used was: (i.e., [*concrete-concrete*] OR [*concrete-to-concrete*] OR [*concrete bond strength*] OR [*old-new concrete*] OR [*concrete interface*] OR [*concrete interfacial bond strength*] OR [*bond concrete repair*] OR [*concrete repair mortar*] OR [*concrete substrate*] OR [*concrete surface roughness*] OR [*concrete bond test*] OR [*concrete pull-off bond*] OR [interface] ANDNOT [steel-concrete] ANDNOT [rebar concrete] ANDNOT [rock concrete] ANDNOT [interfacial transition zone] ANDNOT [fiber externally bonded concrete] ANDNOT [fiber externally strengthened concrete] ANDNOT [carbon fiber] ANDNOT [frp concrete] ANDNOT [cfrp concrete] ANDNOT [gfrp concrete] ANDNOT [anchorage] ANDNOT [reinforced plastics]). This search string resulted in 692 documents including original research articles, review papers and conference proceedings, all in English language between January 1990 and June 2021. The search fields to find the relevant documents included title, keywords, and abstract. The irrelevant documents were removed after reading the abstracts. Furthermore, the references cited in the selected documents were reviewed to identify documents missing in the previous steps. Fig. 1(a) shows the number of publications over time since 1990, correlating well with the topics of interests mentioned before. Fig. 1(b) shows the countries with the largest number of published documents on the topic of interest. The United States publishes the largest number of documents, followed by China. The VOSviewer software was used to analyze the network of co-authorships between countries, identifying nine main groups, as shown

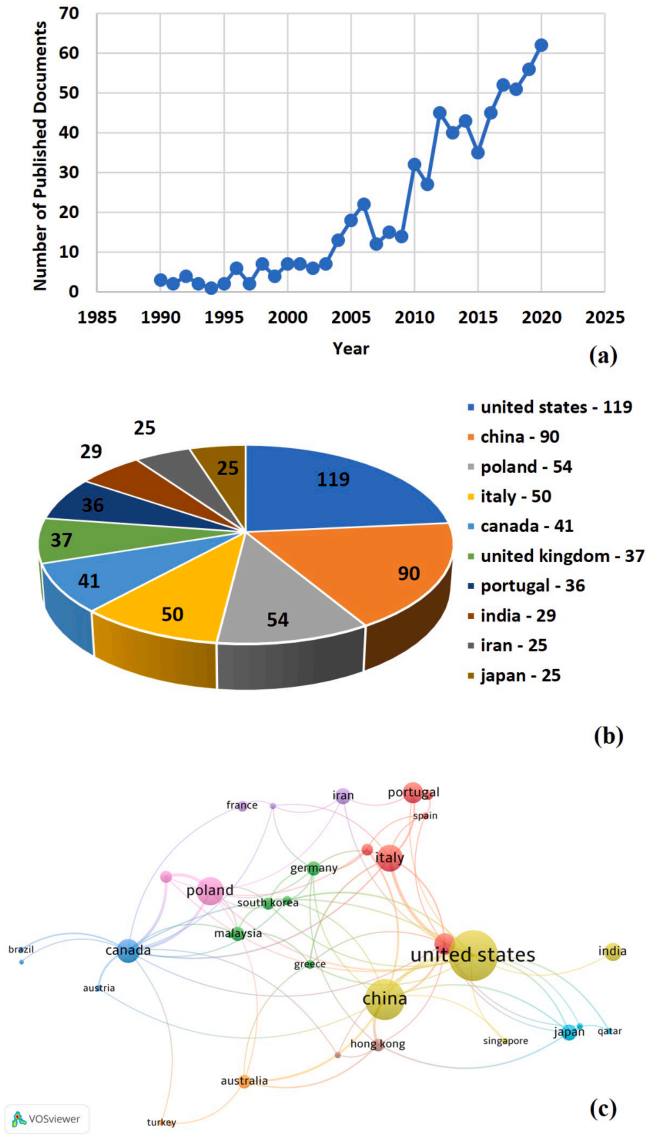


Fig. 1. Overview of published documents on the topic of interest: (a) the annual trend, (b) countries with the largest number of publications, and (c) network map showing the co-authorship between countries.

in Fig. 1(c).

The most used keywords and the number of times they have appeared in the relevant publications are shown in Fig. 2(a). As expected, the terms “concretes”, “concrete”, “concrete substrate”, “reinforced concrete”, “repair”, “bond strength (materials)”, and “substrates” are the most prevalent. Fig. 2(b) shows the co-occurrence of the keywords. Overall, nine clusters could be identified and are shown by different colors. For example, the cluster shown by the red color is mainly about the testing approaches while the cluster shown by the green color is mainly about the repair material and bond strength.

Fig. 3 shows the overview of the journals where the documents on the bond strength of concrete-concrete composites have been published. In Fig. 3(a), the sources with the largest number of documents are shown while in Fig. 3(b), the network map shows the co-citation between different sources. Four main clusters of sources can be identified in Fig. 3 (b), mainly dominated by the topics on structural concrete, materials science, materials engineering, and transportation concrete.

3. Bonding mechanisms

The shear-friction theory is one the most widely used approaches to evaluate the shear strength between concrete parts. The design philosophy of this theory, originally proposed by Birkeland and Birkeland in 1966 [18], has been adopted by most major standard codes, including the *ACI* 318–14, Eurocode 2, fib Model Code 2010, and CSA A23.3–04. The evolution of this theory, resulting in significant modifications of the

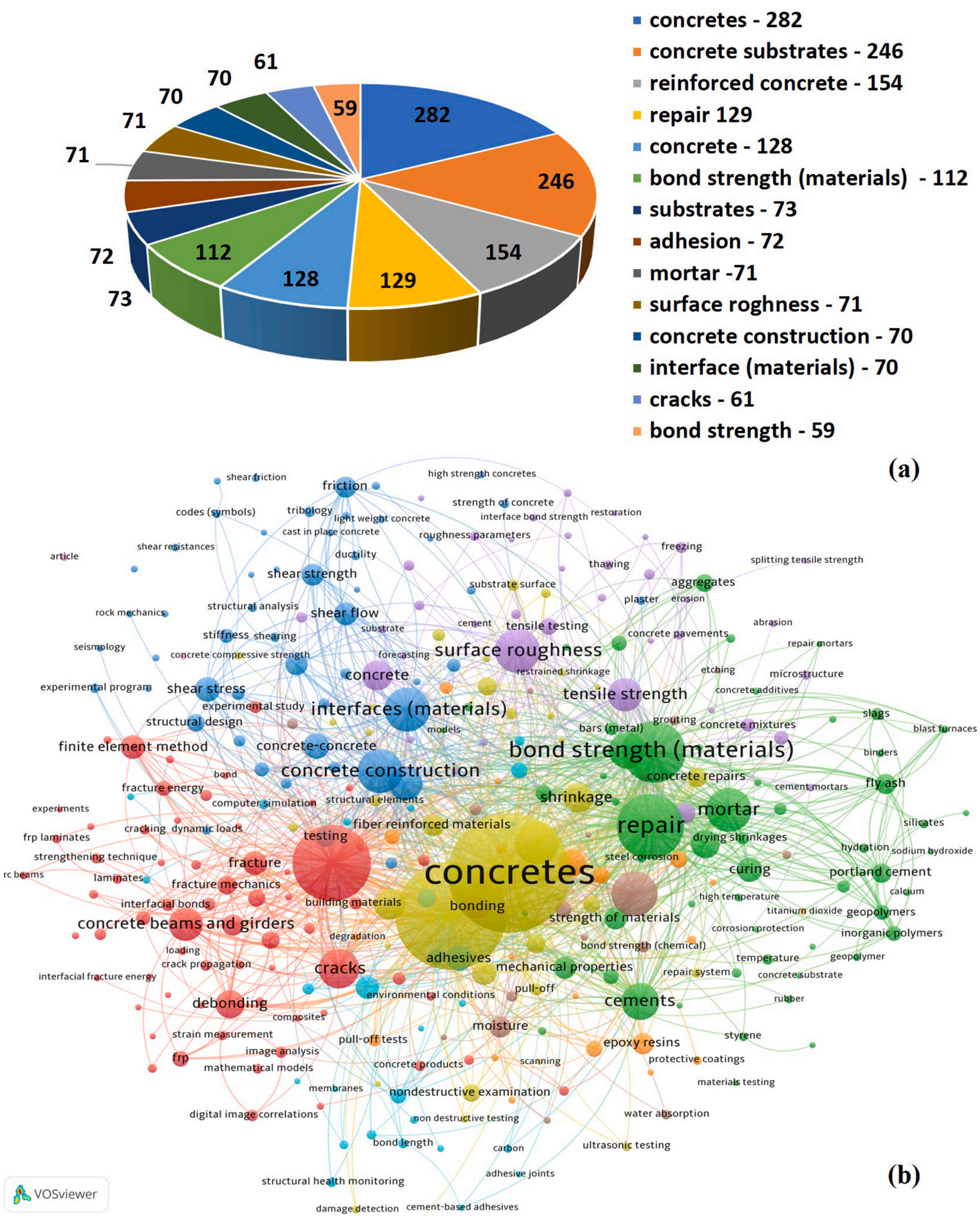


Fig. 2. Overview of the keywords in published documents on the topic of interest: (a) most appeared keywords, (b) network map showing the co-occurrence of the keywords.

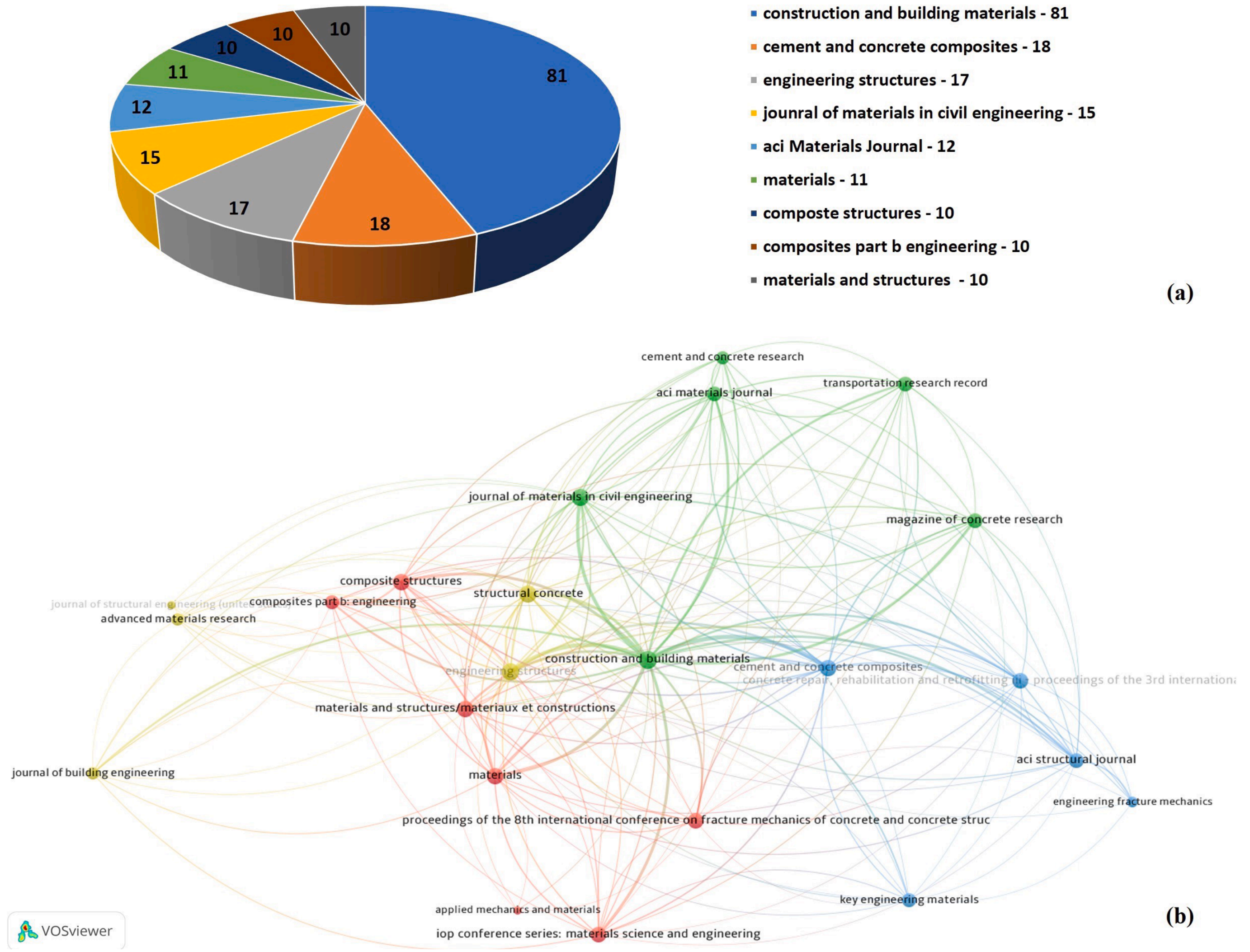


Fig. 3. Overview of the sources where the documents on the topic of interest have been published: (a) sources with the largest number of documents, (b) network map showing the co-citation of the sources.

design codes, has been the subject of the excellent reviews by Santos and Julio [19] and Randl [20]. Furthermore, Harris et al. [21] comprehensively investigated the nature of shear-friction behavior through an in-depth review complemented by an experimental study. According to the shear-friction theory, the load transfer mechanism between the concrete members is governed by the contribution of three main components [20,22], namely (i) adhesive bonding and mechanical interlocking, (ii) shear friction, and (iii) dowel action (Fig. 4) [23]. Adhesion is mainly associated with atomic and molecular bonding (primary and secondary bonding, as well as correlation forces that explain the high cohesive strength of hardened cement [24]) at the interface. Along with adhesion, mechanical interlocking refers to micro-level behavior in which sliding friction at very small shear slip values and irreversible deformation of the matrix are the essential mechanisms [25]. The adhesion and interlocking are affected by several factors such as concrete composition, type of adhesive bonding agent, interfacial roughness at micro-scale, characteristics of the interfacial transition zone (ITZ), micro-mechanical related factors, and micro-cracks [1,2,4,10–12]. The shear transfer associated with adhesive bonding and mechanical interlocking is effective at very small shear slip values (typically below 0.05 mm according to fib 2010 [22]) and expected to degrade with increasing shear slip along the interface as shown in Fig. 4 [19,26]. In the presence of compressive normal forces applied to the interface, shear friction, a force resisting the relative displacement of concrete layers parallel to their interface, becomes the main load transfer mechanism at intermediate slip values after degradation of adhesion. Shear friction mainly depends upon the (macro-scale) interfacial roughness, and the magnitude of normal stress at the interface. Dowel action is the third resisting component and is activated when steel reinforcement is placed across the interface and resists bending [22]. The steel reinforcement is designed to become the dominant load transfer mechanisms at higher slip value. In this case, the relative shear slip between concrete layers along the interface results in lateral displacement of the upper and lower ends of crossing steel reinforcement bars, inducing bending stresses that are superimposed by the axial tensile forces created in the reinforcement owing to the joint opening [20,22]. This resistance to the bending is called dowel action. The magnitude of resisting stresses relies on the type, percentage, and flexural resistance of the crossing reinforcement.

4. Test methods

Various test methods have been developed to characterize concrete-concrete bondings under different types and combinations of loadings. The key difference among these methods is the stress exerted on the interface and concrete layers as each of these test methods owns specific specimen and loading configurations. The bond strength value, typically measured as the maximum force necessary to physically pull the two surfaces apart divided by the (macroscopic) surface of contact, is, as a

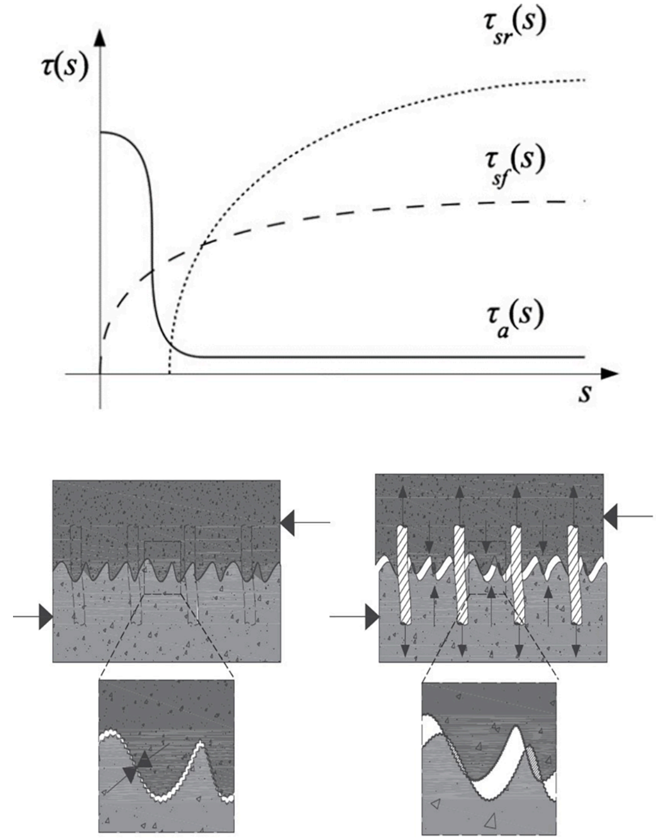
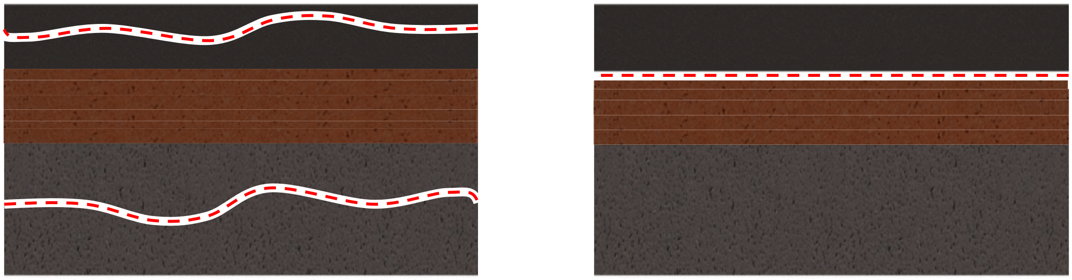


Fig. 4. Contributing factors in load transfer mechanism of concrete-concrete composites. $\tau_a(s)$ is the contribution of the adhesion, $\tau_{sf}(s)$ is the contribution of the shear-friction and $\tau_{sr}(s)$ is the contribution of the shear reinforcement for the shear stresses. Figure adapted with permission from [19,26,27].

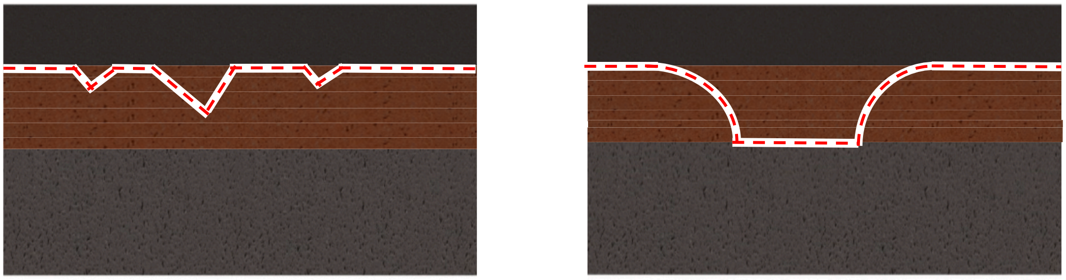
result, highly dependent on the type of the test method. Momayez et al. [28] showed that the interfacial bond strength can vary by a factor of 8 depending on the type of test method, concluding that the test method should match the real/desired conditions as closely as possible. Moreover, the failure modes observed in these test methods depend upon the loading conditions and materials used. In general, as shown in Fig. 5, the failure modes in concrete-to-concrete composites can be categorized as either cohesive or adhesive failures, depending on the location of the main observed crack paths [29]. In cohesive failure, the failure happens within the bulk concrete, either in the substrate or in the overlay. The adhesive failure mode contains three different potential failure paths when a bonding agent is used, depending on where the crack occurs [29]. Cohesive failure is usually considered representative of a robust bonding, demonstrating the greater strength of the interfacial bond compared to that of the bulk concrete. In this regard, shifting the location of failure from the interface to the bulk concrete is considered a consequence of increasing the bond strength. This is typically done by increasing the interfacial roughness, improving the strength of the overlay binding matrix, or applying an interfacial bonding agent [30–33]. Nevertheless, the pre-existing substrate/overlay defects such as micro cracks and specific stress state (introduced by the sample preparation, for example) should not be overlooked and may result in early crushing/rupture of the bulk concrete. In this case, the hypothesis of superior bond strength is unreliable [34]. In some instances, the adhesive failure is forced (by a pre-notch for example) so that an actual value of bond strength can be obtained. This is useful to perform systematic studies of specific design parameters and measure their impact on the structural integrity and bond performance of the concrete-concrete composites [35].

Depending on the type of applied load to the interface, the test methods are classified into three major categories, namely tensile, shear, and mixed-mode groups (see Fig. 6). Shear is one of the most common types of loadings applied to the interface under real conditions, resulting from differential time-dependent deformation between concrete layers (shrinkage), passing of traffic loads on the multi-layer concrete pavement and bridge decks, transferring of shear through the joints, etc. Table 1 provides a summary of published research results, listing the test



(a) Cohesive failure

(b) Interfacial failure



(c) Serrated interfacial failure

(d) Alternating crack

Fig. 5. Schematics of different failure modes based on crack path locations. The red dashed lines represent the main crack path approximate location: adapted with permission from [29,36]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

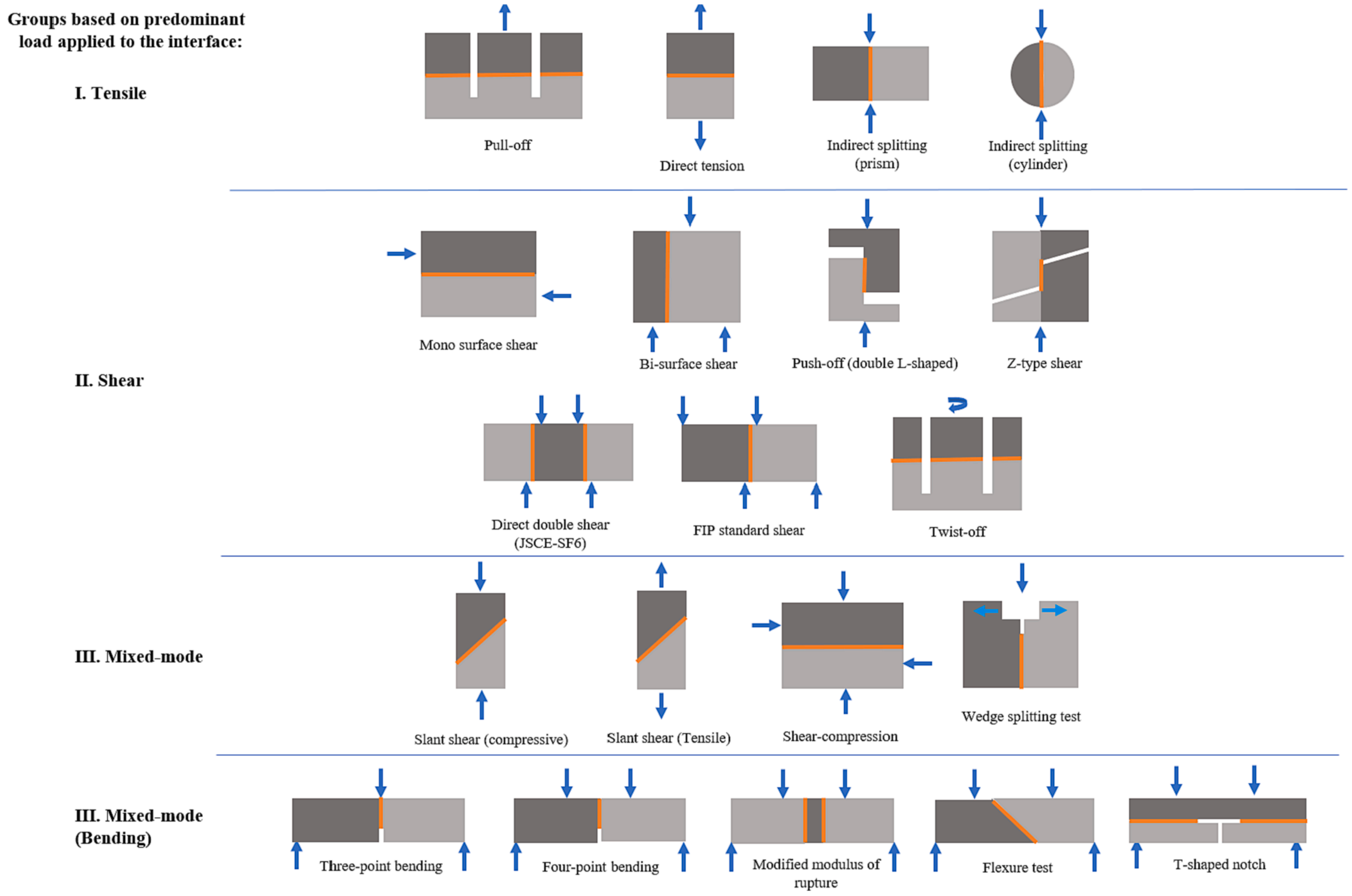


Fig. 6. Schematics of different test methods used to assess concrete-concrete bond strength.

methods, the materials used and the studied parameters. In the following subsections, the most widely used bond test methods are discussed.

Throughout this review, the concrete-concrete composites are called in format of X-Y in which X and Y represent the type of concrete used in the overlay and substrate, respectively.

4.1. *Pull-off test*

In this method, a core is drilled perpendicularly to the interface, down to 1 cm below the interface, and a pulling force is applied through a steel dolly glued to the core. Due to its simplicity, the test can also be carried out in-situ, and is therefore recommended by many standard codes. Results have shown that the overlay thickness influences the tensile bond strength, with a thicker overlay leading to a higher tensile bond strength [12]. Through a numerical analysis, Austin et al. [70] showed that a 15 to 20 mm drilling depth into the substrate results in a more uniform stress distribution along the interface and hence gives a more accurate estimation of bond strength. On the other hand, this test is vulnerable to set up misalignment, improper gluing of the disc and improper core geometry. Moreover, the core drilling may induce microcracks, lowering the bond strength [38]. A comparison between different test methods, namely slant shear, bi-surface shear, pull-off, and tensile splitting tests revealed that the bond strength measured with the pull-off test was the lowest one and can be treated as a conservative estimation [28]. This can be attributed to the issues mentioned above, as well as the load being applied exclusively perpendicularly to the interface, obliterating the role of friction.

In the case of UHPC-NC composites, the common pull-off test method may not be able to provide a clear insight into the bond condition as the failure often propagates to the weakest substrate layer (cohesive failure). To overcome this issue, Valipour and Khayat [35] developed two solutions. In their modified pull-off test, they reduced the bonded area of the core by placing a thin metal washer along the core perimeter prior to overlay casting (see Fig. 7(a)). This aimed at concentrating the induced tensile stress along the interface, leading to interface debonding failure. However, this modified test method may not always be sufficient if the differential stiffness and strength between concrete layers is too high [35]. To further address issues associated with the occurrence of cohesive failure, they proposed a new test configuration in which the overlay has a reversed flat conical shape bonded to the concrete substrate with cylindrical shape as shown in Fig. 7(b). The gradual reduction in the overlay cross section was designed to further concentrate the tensile stress at the interface, and hence increasing the possibility of interface debonding. Using this conical design, Valipour and Khayat [35] measured the tensile bond strength of the UHPC-NC samples and observed adhesive failures in all tested samples with a relatively low coefficient of variation. This test method should therefore be preferred to characterize the tensile bond strength of composites with high differential stiffness and strength.

4.2. *Splitting tensile test*

The splitting tensile test, also known as Brazilian test, is an indirect way of assessing the tensile bond strength of concrete-concrete composites. In this test, a standard prism specimen with circular or square cross section is placed on its side and subjected to a compressive force, aligned with the interface, causing splitting horizontal tensile stresses. In comparison with some of the most common tensile test methods such as pull-off or direct tension, the splitting tensile test is known to report an

Table 1
Summary of test methods.

Category	Test method	References	Concrete substrate	Concrete overlay	Studied parameters
"Tension"	Pull-off	[12,28,35,37,38]	NC	NC, UHPC, URH-LMC, URH-APMC, NSM, HSM	Material strength, overlay composition, age, fiber reinforcement, bonding agent, sample geometry, test setup
	Indirect splitting	[12,28,39–41]	NC	NC, UHPC, NSM, HSM	Material strength, differential shrinkage and stiffness, permeability, overlay modification, bonding agent, surface roughness, fiber reinforcement, failure criterion
"Shear"	Bi-Surface	[28,42–44]	NC	NC, UHPC, NSM	Material strength, crossing reinforcement, differential shrinkage and stiffness, permeability, overlay modification, bonding agent, surface roughness, surface moisture, fiber reinforcement
	Push-off	[45–48]	NC, HSC, UHPC	NC, UHPC	Material strength, castellated key, dowel bar, overlay modification, surface roughness, fiber reinforcement
	Direct shear	[49–51]	NC	NC, HPFRC	Material strength, crossing reinforcement, overlay modification, surface roughness, curing temperature, fiber reinforcement
	Direct double shear	[52,53]	NC	UHPC, RPC	Material strength, age, overlay modification, W/B ratio, surface roughness, fiber reinforcement, curing condition, surface moisture, interface stress state
"Mixed mode"	Slant shear	[12,41,54–58]	NC, HPC, UHPC	NC, HPC, UHPC, URH-LMC, URH-APMC, NSM and HSM	Material strength, overlay composition, crossing reinforcement, differential shrinkage and stiffness, permeability, overlay modification, bonding agent, surface roughness, surface moisture, fiber reinforcement, crossing reinforcement, sample geometry, test setup, failure criterion
	Wedge splitting	[36,59–62]	NC, HPC	NC, PCCM	Material strength, crossing reinforcement, overlay modification, surface roughness, bonding agent, casting and curing temperatures, freeze–thaw cycles, fiber reinforcement
	Three-point bending	[63–66]	NC, OM	NC, UHPC, SC, FRM, Geopolymer mortar	Material strength, overlay and substrate modification, surface roughness, surface moisture, fiber reinforcement
	Four-point bending	[67–69]	NC	UHPC, SHCC	Material strength, overlay modification, thickness, freeze–thaw cycles, nature of bond, fiber reinforcement

NC: normal concrete; HPC: high-performance concrete, UHPC: ultra high-performance concrete; URH-LMC: ultra-rapid hardening latex-modified concrete; URH-APMC: ultra-rapid hardening acrylic polymer-modified concrete; NSM: normal strength mortar; HSM: high strength mortar; HPFRC: ultra high-performance fiber-reinforced concrete; OM: ordinary mortar; FRM: fiber reinforced mortar; SC: sand concrete; PCCM: polymer-cement modified mortar; SHCC: strain hardening cement composite.

overestimated bond strength value [12]. Zhang et al. [32], for example, measured the tensile bond strength of UHPC-NC composites with both direct and splitting tensile tests, and showed that the latter test gave on average 60 % higher bond strength values than the direct tensile test. They attributed this result to the fact that the applied compressive force develops small regions of compression on the top and bottom parts of the specimen, which counteract indirect tensile stress at vicinity of interface edges and hence cause non-uniform tensile stress distribution. Santos and Julio [39] assessed the effect of interfacial roughness and differential shrinkage on the tensile bond strength of NC-NC composites through splitting tensile test. They reported the inability of this test method to capture the impact of variations in interfacial roughness and differential shrinkage on the tensile bond strength, while the effects could be observed in slant shear tests discussed later. On the positive side, sample misalignment, that may produce large scatter in the results of direct tensile and pull-off tests, is less problematic in the tensile splitting tests [71,72].

Despites providing quantitative results on bond strength, these tension tests, including pull-off and splitting tensile tests, ignore the contribution of friction forces and therefore misrepresent most real field cases, where the interface is subjected to mixed shear-tension.

4.3. Direct shear test

In the last decades, various test setups have been developed to capture the shear bond strength of concrete-concrete composites [46,73,74]. In these test methods, one concrete part is typically braced, and the pushing load is applied to the other part parallel to the interface, inducing shear stresses at the interface. A roller support is usually placed on top of the composite to stabilize the position of the sample. Two different types of tests have been used to assess the shear bond strength, namely conventional and modified push-off tests (Fig. 8) [49]. The modified version enables the application of an additional normal load to the interface preventing high stress concentrations at the corners, and addressing one of the main drawbacks of the conventional push-off test. The modified test has usually been employed for cases where the concrete is laid as precast slabs/beams or cast in-situ over the beams. Push-off tests have been carried out on samples both with and without steel stirrup crossing the interface, leading to very different results. In this regard, Wu et al. [73] evaluated the shear bond strength in UHPC-UHPC composites through a Z-shape push-off test.

Due to the contribution of friction forces, the direct shear tests result in higher bond strength values than direct pure tensile tests. Guo et al. [75] studied the bond behavior of rapid repair material concrete and measured the shear bond strength to be 2 to 3 times greater than the tensile strength obtained from tensile splitting tests. However, compared to mixed-mode tests such as the slant shear test, the shear bond strength gained by direct shear tests is lower even compared to the extrapolated cohesion value obtained from failure envelope (see section 4.7) [12].

It is worth mentioning that the direct shear test can be delicate to perform. One of the issues is the occurrence of an interface bending moment due to force eccentricity, resulting in a change in the magnitude and direction of principal shear stresses [12]. To address this issue, a bi-surface shear test was first introduced by Momayez et al. [44]. In this test, the specimen is a cube where the overlay thickness is half of the concrete substrate. As shown in Fig. 6, the applied compressive load makes two shear planes within the specimen, one along the interface and the other one within the concrete. Compared to other shear test methods, this test provides advantages such as high producibility, easy fabrication (standard cubic mold 150 mm), symmetrical loading, and closer simulation of the field stress state [44]. It was also shown that this test is sensitive to the surface roughness, moisture condition, and the use of bonding agent at the interface, and insensitive to differential stiffness between concrete parts [42]. On the other hand, Momayez et al. [44] showed that the bond strength measured with this method is dependent on the specimens size, i.e. the smaller the specimen, the greater the bond strength.

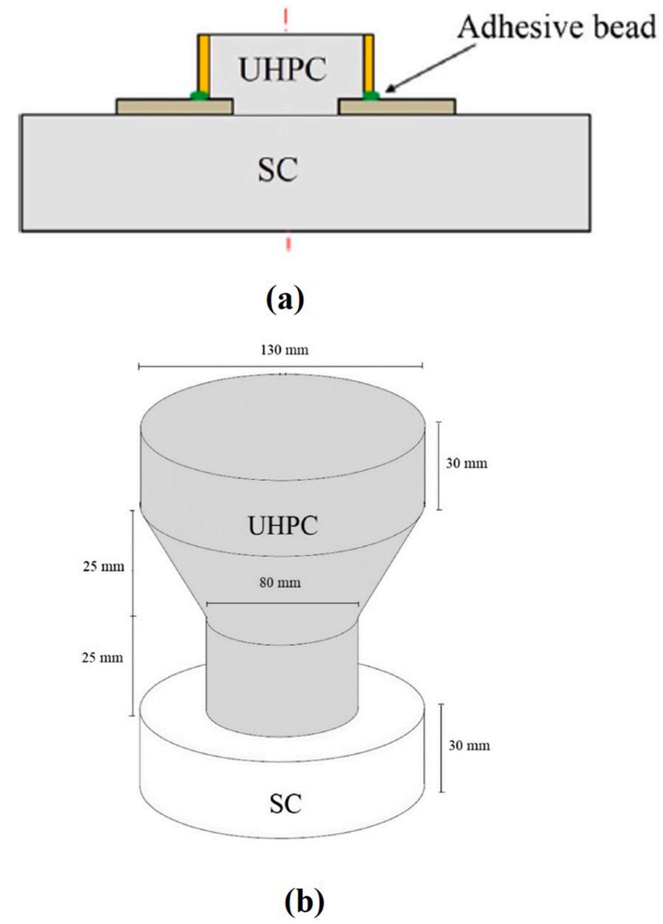


Fig. 7. (a) Modified pull-off test setups. The diameter of UHPC sample is 51 mm at the top and 38 mm at the interface. The thickness of sample is 51 mm; (b) developed debonding test for composites including UHPC overlay. Adapted with permission from [35].

4.4. Slant shear test (SST)

The slant shear test (SST) is one of the most widely used tests to evaluate the interfacial bond strength, mainly owing to its simplicity and high sensitivity to factors such as interfacial surface condition, specimen geometry, and differences in the properties between concrete layers [28,76,77]. In this method, the specimen is subjected to compressive loads from both ends, inducing a combination of compressive and shear stresses on the inclined interface (Fig. 6). This mixed state of shear and compressive stresses enhances the interfacial friction, resulting in higher shear bond strength compared to that obtained with pure shear test [28,32]. One of the major difficulties associated with this test is the fixed angle of bond plane. While the inclination of the bond plane angle is recommended to be 30°, the critical angle (the angle leading to the lowest failure stress) may be smaller in composites with higher interfacial roughness [58,78], leading to non-conservative estimations (Fig. 9). It was shown that the sensitivity of the test to interfacial roughness also highly depends upon the bond plane angle (CD > AB, see Fig. 9) [57]. It is therefore recommended to perform SST with varying bond plane angles to get a deeper insight into the behavior of the bond.

Moreover, cohesive failure may occur in SST, preventing a true assessment of the bond strength. To address this, Saldanha et al. [55] proposed a modified version of SST (see Fig. 10), in which specific stirrups were introduced into both overlay and substrate, enforcing the occurrence of adhesive failure. In another attempt, Tong et al. [79] developed a modified SST for UHPC-NC composites in which they used a larger cross-section (150×100 mm^2) for UHPC and a smaller one (100×100 mm^2) for the NC part wrapped with FRP strip. With this setup, they were able to force the occurrence of debonding failure and obtained a bond strength value.

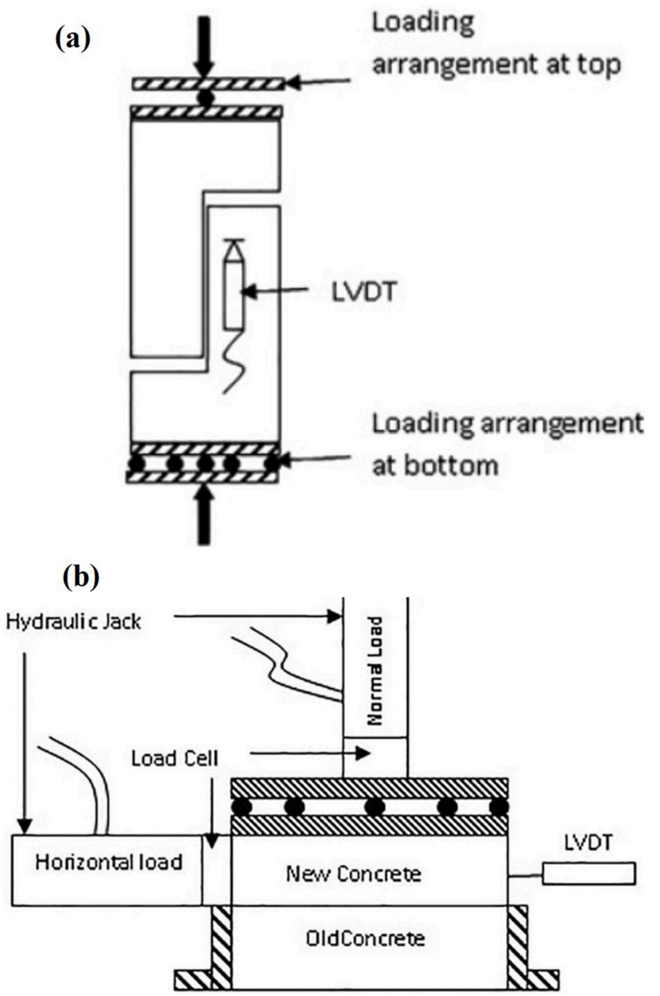


Fig. 8. Typical direct shear test methods; (a) conventional L-shape push-off test, (b) modified push-off test with additional normal stress. Adapted with permission from [74].

4.5. Wedge splitting test

The wedge splitting test (WST) (Fig. 11) was originally introduced by Linsbauer & Tschegg [80] and was further developed by Brühwiler & Wittmann [81]. In this test, the compression load is applied to a stiff wedge (wedge angle 15°) placed in the groove of the composite between load transmission pieces. While pushing down the wedge, the roller bearings in contact with the wedge directly convert the vertical compressive load into a horizontal splitting load with negligible friction, inducing the Mode I fracture to the pre-notched composite [82]. WST has been widely used to measure the fracture properties of quasi-brittle materials, including concrete. Stable crack growth, small sample size, easy load application and minimized elastic energy stored in the testing machine are the main advantages of WST [59,81]. It has also been reported that the higher ratio of sample fracture area to volume leads to low variability in the WST bond strength results [82]. Considering the great importance of using a reliable traction-separation law in the simulation of debonding behavior, Amidi and Wang [83] proposed a novel technique based on WST to characterize the traction-separation law (Mode-I) and long-term durability of concrete-epoxy interfaces. Specifically, they expressed the concrete-epoxy interface traction as a

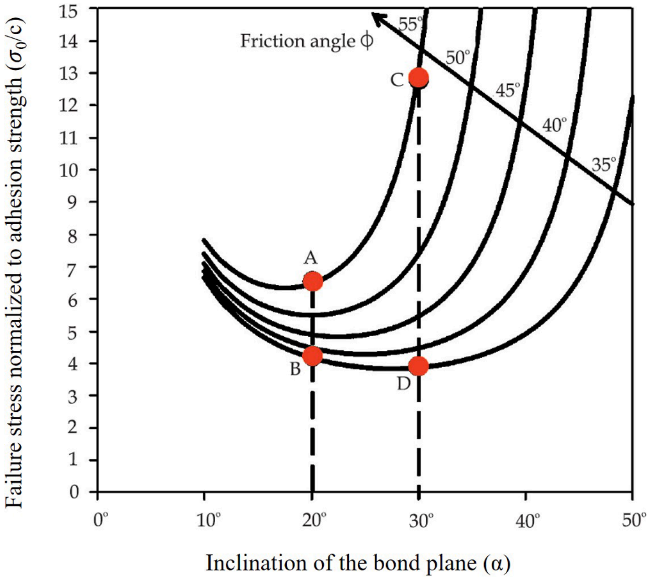


Fig. 9. Stress failure as a function of bond angle for interface roughnesses having internal angles of friction varying from 35 to 55°. μ is the interfacial coefficient of friction, c the adhesion strength and ϕ the internal friction angle defined as $\tan^{-1}(\mu)$. Figure adapted with permission from [58,78].

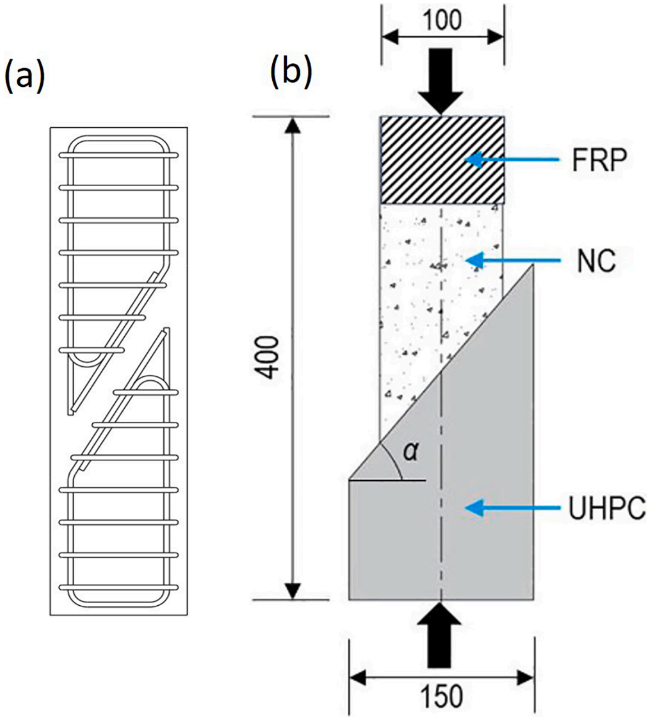


Fig. 10. Modified SST setups; (a) Reinforced with stirrups, (b) Varied cross-section. Figures adapted with permission from [55,79].

function of the applied load and crack mouth opening displacement, using a rigid body moment assumption. Wang and Petru [62] assessed the freeze-thaw resistance of epoxy-concrete interface through WST and demonstrated the relevance of this test to directly measure the traction-separation law of epoxy-concrete interfaces that were submitted to various freeze-thaw cycles, interface treatments and environmental conditions.

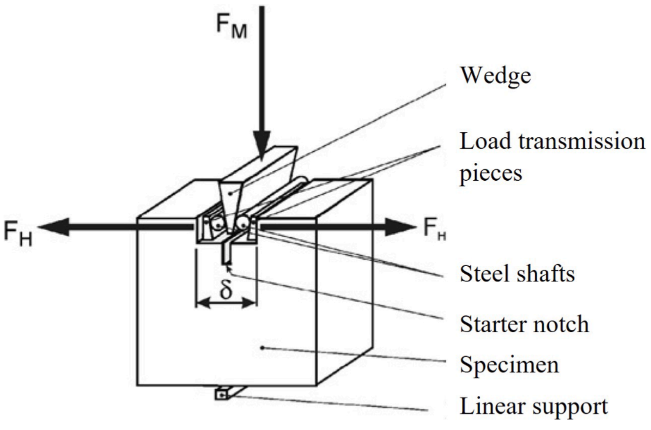


Fig. 11. Wedge splitting test setup. Figure adapted with permission from [84].

4.6. Beam bending test

Beam bending tests are reliable and easy to perform, making them one of the widely used methods to measure the bond strength between concrete layers [63]. Various configurations have been developed, all based on concrete-concrete composite beams subjected to a flexural load. In general, two different interface orientations (horizontal and vertical) have been used to evaluate fracture resistance of interfaces (Fig. 12). Kamada and Li [85] used a beam specimen with a *T*-shaped notch, forcing the early propagation of cracks to occur at the interface between the overlay and the substrate, as shown in Fig. 12(a). By applying a four-point loading, a stable crack propagation along the

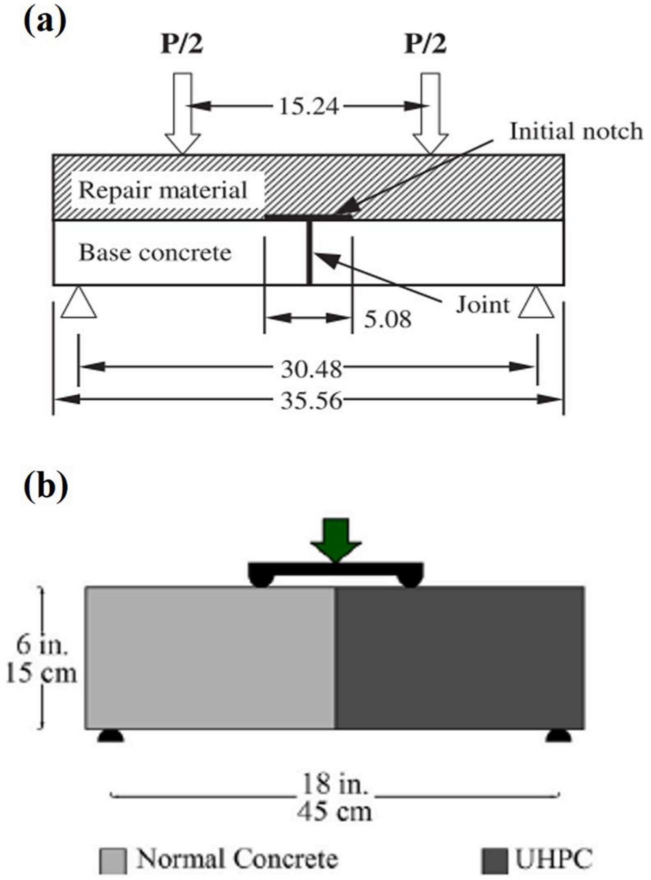


Fig. 12. Various bending beam test methods. Figures adapted with permission from [63,85].

interface occurs and, depending on the overlay properties, the crack may proceed further along the interface or kinked out into the overlay [85]. The *T*-shaped test was shown to be sufficient to investigate the effect of interface roughness and kink-trapping mechanism in engineering cementitious composite (ECC) overlay [85]. In this regard, Tong et al. [79] investigated the flexural behavior of NC-UHPC composites through four-point bending without an initial notch. Depending on the thickness of UHPC substrate and NC overlay, they observed three different types of failure, including flexural fracture (one main crack turning the composite into halves), combination of NC overlay flexural failure and debonding, and combination of NC overlay shear failure and debonding. Farzad et al. [63] studied the bond performance of UHPC-NC composites through a three point bending test where the interface was vertical, favoring the propagation of the crack along the interface, i.e. promoting debonding failure (Fig. 12 (b)). Moreover, comparing the performance of direct shear, SST and three-point bending tests, they observed that the three-point bending test produces more consistent results, with the lowest standard deviation. Compared to other test methods, the beam shape specimen enables the measurement of interface delamination and surface cracking in a simpler way [86].

4.7. Failure envelope approach

Due to varying concrete properties and failure modes, it is not always feasible to directly assess and compare the bond performances of different concrete-concrete composites. To address this issue and provide a more explicit description of bond conditions, Robins and Austin [87] proposed a bond failure envelope solution based on the normal and shear stress data obtained from a variety of test methods. This failure envelope includes the results of pull-off, patch [88], and slant-shear (both in compression and tension) tests, covering a wide range of pure tension and compression/shear stress combinations. The bond failure envelope offers advantages. First, it can be used as a reliable tool to compare bond strength values obtained from different tests. For instance, the pure shear and tensile strengths of the bond can be extracted from the failure envelope and directly compared. Secondly, collecting wide ranges of strength values and combinations can be used to predict the bond strength in a variety of repair/strengthening systems. Finally, the application of material failure theories such as Mohr-Coulomb and Griffith support further investigation of the bond strength contributing mechanisms. As shown in Fig. 13, the bond failure envelope is gained through data fitting by means of the Mohr-Coulomb linear or other semi-empirical approaches that can be used to extrapolate cohesion and friction coefficients.

To assess the bond performance, the simplicity, ease of use and quick performance of the test is of great importance. In this regard, specific conversion factors have been developed, correlating the results of simple test methods such as pull-off or splitting test to the shear bond strength [12,40,113]. Nevertheless, these conversion factors highly depend on the type of concrete overlay and substrate and should therefore be determined in each specific case.

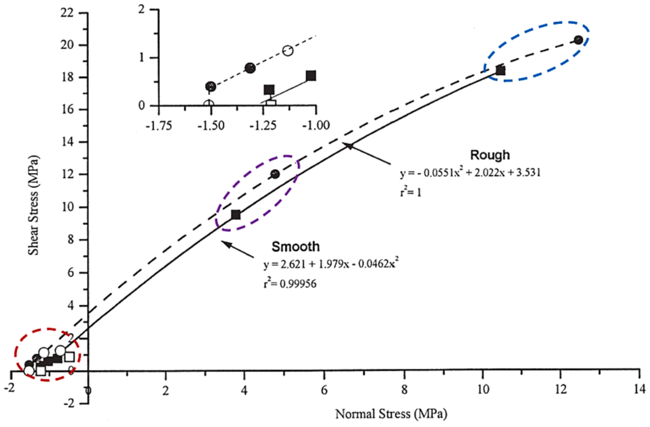


Fig. 13. An example of bond strength failure envelope based on the results of slant shear, patch and pull-off test. Figure adapted with permission from [78].

4.8. Emerging technologies: non-destructive techniques

The common test methods used to assess the structural performance of the bonded concretes are destructive, local (only limited to number of examined points), time consuming, and expensive (making them ill-suited for the evaluation of large areas). This drove interest towards employing non-destructive test methods capable of assessing the interface condition. Impact-echo (IE), impulse response, ultrasonic pulse velocity (UPV), and 3D laser scanning tests have been employed to evaluate the interface condition and bond strength [89–94]. Most of the common methods used for profilometry and assessing the roughness of concrete surface must be carried out before placing the overlay. However, the condition of the interface after the overlay placement is important to ensure it meets the design values. In this regard, Santos et al. [94] investigated the applicability of ultrasonic methods to characterize the surface of concrete substrates with different levels of roughness after an overlay is placed. Their numerical investigations confirmed that through the excitation of concrete-concrete composites by ultrasonic waves, it is feasible to identify various waves generated inside the concrete and along the interface. By applying a 500 kHz frequency and assuming a homogeneous concrete, they could show that the intensity of reflected pulses at the interface inversely correlates with the interface roughness [94], providing important information. However, the technique shows limitations in the case of very rough surfaces or highly heterogeneous concretes, due to high noise-to-signal ratios [89,90,94]. On the other hand, the impact echo and impulse response techniques are less influenced by heterogeneities in the concrete and show promise for interface and bond assessment [90,91]. In these methods, the stress waves are generated by the impact of an object (steel ball, striking hammer) on the concrete surface and the reflected responses are measured and analyzed at adjacent points. It was shown that the impulse response method could characterize defects in concrete-concrete composites including interface delamination and debonding in-situ [91,95]. Trying to use a faster testing speed and greater detectability compared to impact echo and impulse response method, Wang et al. [96] used some of the NDT techniques (resonant frequency, hammer percussion, and modified chain drag methods) to characterize the flexural strength of the bond after exposing to freeze thaw cycles. Their investigation showed reliability of these NDT methods to detect freeze-thaw damage as well as to predict flexural capacity of repaired bonded concrete after freeze–thaw (FT) exposure [96].

X-ray microtomography is another NDT tool that has been increasingly used to characterize the interfacial zone in concrete-concrete composites. With this method, researchers could capture the interface microstructure and its evolution during the first days, specifically pore content, distribution and connectivity, as well as any defects such as micro cracks which were shown to directly impact the structural performance and bond strength of multi layered concrete composites [97,98]. The local micromechanical characteristics of the interface can also be investigated through nano-indentation, and it was shown that the modulus values obtained from this method show similar tendencies to the results of pull-off and splitting tensile tests [99,100].

Attempts have also been made to characterize the interfacial bond strength using non-destructive techniques coupled with artificial neural networks (ANNs) [101,102]. Sadowski and Hola [103], and Czarnecki et al. [104] developed a concept for non-destructive identification of the pull-off bond strength value in layered concrete floors based on parameters obtained from three non-destructive tests, namely 3D laser scanning method (morphology of surface of substrate before overlay placing), acoustic impulse and impact-echo response (on the surface of overlay). Collecting several hundreds of datasets, they showed that their

ANN-based algorithms could predict the pull-off bond strength from the three test results mentioned above with a linear correlation coefficient value above 0.97.

Considering the variety of proposed test methods, one can conclude that the result of only one test method may not be sufficient to properly assess the bond strength of an interface, and could even lead to misleading information. A more reliable assessment is achieved when the results of different experimental test methods, semi-empirical approaches, and predictive models are compared and interpreted [12,77,87]. In fact, different methods give information on the bond or the interface at different scales, namely macro, *meso*, micro, and nano scales (see Table 2 from [105]), and mixing these methods and the scales of description provides a more detailed characterization of the interphase zone.

5. Influencing factors

The interface bond strength and durability of concrete-concrete composites, results of the aforementioned bonding mechanisms, depend upon several factors, and the main ones are summarized in Table 3. In the following subsections, a review of these major factors is presented.

5.1. Moisture condition

The moisture condition near the interface at the time of casting plays a pivotal role on the interfacial bond strength. A dry substrate may quickly absorb water contained in the fresh concrete overlay, inducing high shrinkage, delamination, and consequently lower bond strength. On the other hand, introducing excessive amounts of water may negatively affect the bonding, owing to the formation of a high water-to-cement ratio (w/c) concrete layer near the interface, and in turn may weaken the bond (the adhesion and friction components).

As a matter of fact, there is no universally accepted recommendation on the appropriate moisture condition of the substrate, but three schools of thought exist instead. A first group recommends the substrate to fulfill the saturated surface dry (SSD) conditions, in which the concrete is saturated with water, filling the accessible voids in the substrate, while the surface is devoid of free water [6,32,98,109]. A second group favors dry substrates [8,110,111]. Santos et al. [42] measured the shear bond strength of normal concrete-normal concrete (NC-NC) composites using bi-surface shear tests and measured a bond strength twice as high when the overlay was casted on a dry substrate compared to an SSD one. Bentz et al. [112] studied the microstructure of the interface zone and showed that the overlay concrete was denser near the interface in the case of dry substrates, providing a plausible explanation for the increase in bond strength under slant shear, where friction plays an important role. In pull-off testing, on the other side, cohesion dominates, and SSD conditions may lead to higher content of hydration products due to water availability, creating better connections between layers at the atomic scale, leading to higher bond strength. The third group offers an intermediate view, recommending to avoid too dry or too wet moisture conditions, and proposing instead a saturation level of between 50 and 90 % as a proper interfacial moisture condition [34,113].

Table 2

Summary of the test methods and their suitability in different scales [105].

Category	Test method	Scale
Tensile	Pull-off	Macro, *meso*
	Splitting tensile	*Meso*
shear	Direct shear	Macro, *meso*
	Push off	Macro, *meso*
	Bi-surface shear	*Meso*
Mixed mode	Slant shear	*Meso*
	Wedge splitting	*Meso*
	Beam bending	Macro, *meso*
Non-destructive	Impulse response	Macro
	Impact echo	Macro, *meso*
	3D laser scanning	Macro, *meso*
	Profilometry	*Meso*
	X-ray micro CT	Micro
	SEM	Micro, nano
	Optical microscopy	*Meso*, micro
	Nano indentation	Micro
	Sand patch	*Meso*

Several authors argue that the optimum moisture content depends upon the materials chosen for both substrate and overlay [70]. Farzad et al. [63] showed that wetting the interface (sprinkling the substrate surface followed by wiping with a damped cloth 10 min before overlay pouring) increases the bond strength of normal concrete (NC) parts, while keeping the interface dry was more beneficial in the case of ultra high-performance concrete (UHPC) overlays.

In conclusion, despite numerous studies carried out so far, the driving mechanism is still unclear. Further detailed investigation could involve fluid-solid interaction studies and micromechanics tools.

5.2. Surface preparation and treatment

The skin of concrete is defined as the thin layer near the surface of the substrate which is formed mainly due to bleeding and segregation [34,119]. This layer was shown to have a different composition than the bulk cementitious material of the concrete substrate, resulting in a lower hardness, weak frost resistance, and high chloride diffusion [119,120]. Surface treatment refers to the techniques used to partially/fully remove this layer as well as to provide higher surface roughness. Application of appropriate surface treatment methods such as polishing and silicate-based impregnation products may improve the issues associated with the skin of concrete such as water penetration and abrasion resistance [121,168]. In general, increasing the roughness of concrete substrate surface results in greater interfacial bond strength mainly due to higher interfacial shear friction and mechanical interlocking between concrete layers [39]. It must be pointed out that the benefits brought by roughness highly depend upon the applied stress. In a pure shear condition, a rough interface can shift the location of failure from the interface to the bulk concrete (overlay and/or substrate) and causes a localized material failure with a higher cracking resistance compared to the untreated interface [78]. Unsurprisingly, the advantages brought by surface roughness on the tensile bond strength, as measured via pull-off test, are almost negligible, mainly due to the limiting contributions of interlocking [28,114].

Among various surface treatment techniques, hydro-demolition and sandblasting are widely used due to their superior performance compared to other techniques [43,111,115]. Tayeh et al. [41] showed that sandblasting the substrate, purposely exposing aggregates, doubled the shear bond strength of ultra-high performance fiber concrete-normal concrete (UHPFC-NC) composites compared to the left-as-cast ones. Nevertheless, Costa et al. [31] indicated that the beneficial effect of roughness on shear and tensile bond strengths has limits and plateaus above a certain roughness level (they measured the optimal mean valley depths to 2.3 and 3.6 mm for shear and tensile bond strengths, respectively). In some cases, applying excessive surface roughness may even have a negative effect [190]. Zhou et al. [116] analytically showed that excessive interfacial roughness may further restrain the overlay shrinkage, inducing higher tensile and shear stresses on the overlay and interface, increasing the risk of overlay cracking or interface debonding. In fact, smooth surfaces may in some cases provide more desirable performance linked to a better control of the crack pattern and crack widths. In carefully designed engineered cementitious composite-normal concrete (ECC-NC) composites for example, the interface cracks may kink into the ECC overlay and get trapped there. This

Table 3
Summary of the factors affecting the interfacial bond strength.

Category	Factor	References
Interface	Moisture condition	[6,8–10,32,34,42,63,70,98,106–113]
	Surface treatment and skin of concrete	[28,31,34,39,41,43,70,78,85,111,114–121]
	Bonding agent	[6,8–10,32–34,36,42,43,63,70,98,106–113,122–127]
	Crossing reinforcement	[20,27,43,77,128,129]
Concrete overlay/Substrate	Strength and elastic modulus	[7,33,34,44,78,111,116,130–132]
	Shrinkage, age, curing	[32,39,41,44,133–136]
	Type and composition	[30–33,41–44,57,85,118,129,137–155]
	Admixture	[152,156–159]
	Fresh properties	[56,63,135,160]
	Exposure condition	[30,127,156,157,161–167]

mechanism eliminates common types of failure such as spalling and delamination. Kamada and Li [85], in particular, studied the effect of surface preparation on the crack trapping performance of ECC used as concrete repair. They showed that a smooth surface favors the propagation of multiple small cracks along the interface and into the ECC, where the cracks get arrested. A rough interface, on the other hand, opposes the propagation of cracks at the interface, promoting the propagation of a single macro crack through the ECC, and leading to early fracture. These results explain the benefits of a smoother interface in the case of ECC, where multiple small cracks help redistributing the load over a wider area, leading to higher deflection at peak load and greater strain-hardening behavior. The aggressiveness of the surface treatment method is an important factor that should also be considered. Indeed, harsh methods such as jack hammering and chipping can cause much higher (at least two times greater) densities of micro cracks near the substrate surface (to a depth of 20 mm) than that of other methods like sand blasting [34,70]. This, in turn, can lower the tensile strength of the concrete and hence the bond. It must be pointed out, however, that such aggressive surface treatments may be beneficial in the case of high strength concrete substrates [34]. Other unexpected positive effects can come into play. In steel fiber modified overlays for instance, the larger depression in rough interfaces can lead to an orientation of steel fibers perpendicular to the shear plane, creating a dowel effect that contributes to the higher shear bond strength [117]. Rough interfaces can also be advantageous against the interface erosion resulting from salt freeze-thaw cycles [118]. Regarding the resistance of concrete repair to permeability of chloride, gas and water, results showed the choice of overlay material is key, and the roughness or surface treatment of the surface has negligible effects [41]. Among surface texturing methods, brushing, grooving, acid etching, dragging jute, and leaching of cement paste have been discussed [119].

The morphology of the surface of concrete substrates can be characterized via qualitative and/or quantitative approaches. Most design codes classify surfaces based on a visual qualitative assessment, making it subjective to the inspector's view. To overcome this issue, various quantitative assessment methods have been developed to support the characterization of surface texture using roughness parameters (e.g., peak height, valley depth and spacing between peaks and valleys). Santos et al. [169] identified maximum peak-to-valley height, total roughness height and maximum valley depth among the roughness parameters that best correlate with shear and tensile bond strengths. In fact, based on the results from two different profilometer techniques, maximum valley depth shows the highest coefficient of correlation (over 0.99) with shear and tensile bond strengths and has been proposed as an appropriate indicator for estimating the shear and tensile bond strength values [38]. Sand patch test (SPT) and concrete surface profile (CSP) are among the simplest and most widely used roughness assessment methods. Poor repeatability and direct influence of user expertise are however the main reported drawbacks [11]. A comparison between the SPT and some laser-based profilometry methods revealed that SPT was not able to clearly distinguish between different surface textures, especially those with low roughness [170]. Moreover, the SPT is only applicable to horizontal top surfaces [170]. The new generation of improved roughness quantification methods, and in particular those based on optical and laser techniques (such as 3D laser scanning), are promising to accurately characterize surface roughness, with the possibility of doing in-situ and non-destructive measurements [11,93].

5.3. *Adhesive bonding agent*

Adhesive bonding agents are commonly used to provide greater interfacial adhesion, impermeability and bonding strength [9,32,42,106]. The compatibility with concrete parts, their physical and chemical properties, thermal expansion, viscosity and shrinkage are the main factors controlling the efficiency of the bonding agent and hence dictating its choice [6,10,42]. Epoxies and cement-based slurries are among the most widely used bonding agents. Although cement-based adhesives have been employed to retrofit concrete parts, their weak mechanical properties, including compressive and tensile strengths compared to the epoxy bonding agent, limit their broad application [171]. This section focuses on epoxy bonding agents, due to their prevalence in applications despite their high cost. The effectiveness of epoxy adhesives relies on their chemical structure, method of application, concrete surface state and environmental factors [43,122]. In particular, the humidity at early times should be watched. Park and Kim [123] showed that exposure to water substantially impacts the epoxy bonded concretes. They found that upon increasing the exposure time to tap water from 0 to 90 days, the pull-off strength decreases up to 50 %, with noticeable changes within the first 7 days of exposure. Temperature is also a key factor impacting the interfacial bond of epoxy bonded concrete composites. More specifically, casting and curing temperature significantly affects the structural performance of the epoxy bonded concretes such that increasing temperature from 5°C to 55°C results in a drop in bond strength by up to 65 % [36]. This originates from the remarkable decrease in setting time of epoxy compared to the setting time of cementitious materials at elevated temperature, preventing chemical bonding between the epoxy and the concrete overlay [172]. Such a decrease was also observed when an acrylic modified bond coat was allowed to set/dry before applying the repair overlay [70]. To a lesser extent, the decrease in epoxy thickness due to material loss in microcracks and pores [36] and the inferior mechanical properties of epoxy at high temperature contribute to this drop. The use of nanomaterials including carbon nanotubes (CNT), carbon nanofibers (CNF), graphene oxide (GO), graphene nanosheets (GNS) and graphene nanoplatelets (GNP) can improve mechanical and thermal properties of the epoxy adhesives [173–175]. In particular, it was reported that the addition of nanomaterials (0.05 to 5 % by weight of adhesive) into bonding agents, including epoxy and cement based adhesives, could improve their mechanical and thermal properties by up to a factor 4 [171]. Expectedly, the performance of bonded concretes depends not only on the properties of the epoxy adhesives, but also on the characteristics of the constituting concrete layers. Previous work showed that, in the case of concrete layers with low strength (below 50 MPa), the properties of the epoxy adhesive play a negligible role, while upon using higher strength concrete layers (above 60 MPa), the mechanical characteristics of the epoxy become crucial, mainly due to a shift in failure mode from rupture to adhesive [124]. In this case, the application of an epoxy layer helps to mitigate brittle and fast propagating ruptures that may happen when no bonding agent is used [124]. Moreover, the beneficial effects of epoxy highly depend on the substrate surface texture. Júlio et al. [125] showed that epoxy improves both shear and tensile bond strengths on smooth substrates. On rough surfaces instead, the effect of epoxy may become detrimental since the irregularities (peaks and valleys) are filled with epoxy resin, which diminishes the effective contribution of mechanical interlocking [43,125]. In this regard, Randl [20] recommends a minimum mean surface roughness value ($R_t > 1.5$ mm) for a sufficient aggregate protrusion that would generate mechanical interlocking. The applied quantity of the bonding agent also affects the interfacial bond strength. The optimum thickness of bonding agent depends both on concrete properties and state of stress. Inadequate thickness of adhesive negatively impacts the bond strength [108,122]. Moreover, an excessive thickness of adhesive layer can lead to a lower bond strength due to an early failure caused by high deformation and creep [122,127].

Although an improved bond strength can be achieved, there is no consensus among researchers regarding the overall benefits of using bonding agents. In addition to the poor creep properties of epoxies, the induced vapor barrier at the interface may also lead to a lower bond strength and earlier failure [6]. Inferior fire resistance (reaching failure point within 5.5–6 min under standard fire exposure) and emission of toxic fumes and steroids are among other reported disadvantages of epoxy adhesive bonding agents [171,176].

5.4. *Crossing reinforcement*

The behavior of the unreinforced joints is typically brittle and failure occurs at relative slips lower than 0.05 mm if clamping stresses, due to external loads, are not significant enough [20]. In concrete-concrete composites, the load transfer capacity of the interface may be enhanced at higher slips by using steel connectors crossing the interface. In this case, the relative slip between concrete layers induces bending, tensile and shear stresses in the crossing steel reinforcement and activates their contribution to load transfer at the interface [20]. Dowel action is a term that refers to the bending resistance of these steel connectors. Depending on the amount of reinforcement and interfacial roughness, a more ductile behavior is observed in the case of reinforced joints, with relative slips between 0.5 and 1.5 mm, as shown in Fig. 14. Julio et al. [77,177] indicated that interfacial shear strength and the post-debonding behavior of the interface is highly dependent on the number of steel connectors, adequate anchorage of steel reinforcement and the concrete compressive strength (to resist localized crushing near the steel-concrete interface). Along this line, anchoring longitudinal rebars in the overlay to the ones in the substrate has been shown to enhance the interfacial shear strength by up to three times compared to that of reference specimens [27].

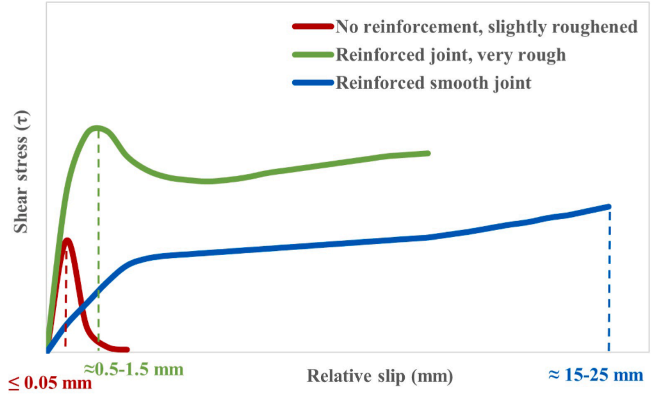


Fig. 14. Typical load-displacement curves of a concrete-concrete composite under shear loading. Influence of crossing steel connectors and surface roughness, after [20].

5.5. *Differential (mismatch) properties*

In concrete-concrete composites, the properties of both overlay and substrate should be taken into consideration not only as individual characteristics but also as relative properties. In most cases, the properties of the concrete overlay and substrate are distinct, mainly due to their different mix designs and times of casting. In this section, the potential effects of these differential properties on the interfacial bond strength are discussed.

5.5.1. *Strength and elastic modulus*

In general, increasing the compressive strength of concrete overlay results in greater structural performance of the concrete-to-concrete composite and bond strength, accompanied by shifting the failure mode from adhesive to cohesive [7,44,111,190]. A numerical analysis on slant shear test samples revealed that using a stronger overlay induced a higher normal stress at the interface for a given shear stress, leading to higher friction and hence interfacial shear strength [7]. The influence of overlay elastic modulus on the bond strength is more controversial. On one hand, some studies have shown that employing a low elastic modulus overlay enables a higher relaxation of the stresses induced by drying shrinkage, and hence reduces the risk of overlay cracking and interface delamination [131]. On the other hand, other studies reported that a low elastic modulus overlay is unable to redistribute and transfer shrinkage strains to the stiffer substrate (lower effective structural interaction), and hence remarkable shrinkage strain is restrained by the substrate, increasing the possibility of overlay cracking [116,132]. Also, remarkable modulus mismatch among concrete layers results in higher local stress concentration at the edges of the interface, compared to the central points, fostering the development of shear stresses and resulting in early failure of the bonding [78]. This agrees with the observation of Shah et al. [130] who reported that increasing the mismatch in compressive strength and elastic moduli of concrete layers resulted in a decrease of the bond fracture toughness (opening mode) and critical energy release rate, increasing the vulnerability of the composite to cracking and failure for the same loading configuration.

5.5.2. *Shrinkage, age, curing*

Drying shrinkage, a self-contracting phenomenon in concrete due to the loss of capillary water, is restrained in overlays by the concrete substrate. This results in the development of tensile stresses in the overlay, as well as shear (friction) and normal (delamination) stresses at the interface [133]. Besides drying shrinkage, autogenous shrinkage, an internal volume reduction of the cement/water mixture in the course of the hydration process [178], can also generate internal stresses. Differential shrinkage between concrete layers is one of the most critical time-dependent parameters and is being largely responsible for overlay cracking and/or interface debonding, affecting the durability and service life of concrete-to-concrete composites. As a rule of thumb, the younger the substrate, the lower the differential shrinkage and resulting stresses. The age of the overlay also plays a role. For example, UHPC-NC composites exhibited a high interfacial bond strength at early ages (3–7 days) that gradually increased until 28 days. However, upon further drying from 28 days to 90 and 180 days (at normal lab temperature curing), the interfacial bond strength slightly decreased by 1.5 % and 2.7 %, respectively, attributed to overlay shrinkage [32,41,44]. Curing condition could also impact the bond strength. Although high curing temperatures are often used to enhance mechanical properties of

UHPCs, care must be taken in the case of composites containing UHPC overlays. In this regard, Zhang et al. [32] studied the impact of different curing conditions including normal lab temperature and steam curing (60°C for 72 h, and 90°C for 48 h), on the interfacial bond strength of UHPC-NC composites. They observed a reduction in bond strength values by up to 30 % upon increasing the curing temperature to 90°C. This was attributed to the rapid and significant shrinkage of the UHPC overlay in the latter curing condition, inducing remarkable interfacial shear stresses at early ages, while the bond is still weak, and eventually leading to early bond failure [32]. Furthermore, fluctuations in temperature and humidity affect the bond strength, cautioning researchers and practitioners that results obtained in well-controlled labs may not be applicable to outdoor job site conditions [39]. It must be pointed out that not only the differences in the age of the concrete overlay and the substrate impact the structural performance of multi-layer composites, but also, in the case of large-scale constructions, the potential delay time between every successive layer/part of overlay, which can result in cold joint, jeopardizing the durability of the composite. In this regard, it was shown that increasing the delay time between successive layers of a self-compacting concrete (SCC) overlay from 0 to 60 min results in a decrease by up to 50 % of the interfacial flexural strength [135]. To address the interface cracking caused by this time interval, Qian an Xu [136] recommended to control the delay time between layers such that it always falls within the initial setting time of the poured mixture.

5.6. Concrete type

As mentioned before, the properties of the concrete, and especially the overlay, can significantly impact the interfacial bond strength and general performance of the composites. This has raised an increasing interest toward using modified concretes. In this section, UHPC, recycled aggregate concrete (RAC), light weight aggregate concrete (LWAC), fiber reinforced concrete, and SCC are presented and their use in concrete-concrete composites are discussed.

5.6.1. Ultra high-performance concrete (UHPC)

Harsh environmental conditions and excessive mechanical loading often compromise concrete-concrete composites, making UHPC, a high-strength and low permeability material, a great candidate under such conditions. Permeability indeed plays a key role, as gases, water and other deleterious agents may penetrate the overlay and reach not only the interface but also the embedded reinforcing steel. This could result in the deterioration of the interfacial bonding as well as the corrosion of steel reinforcement [162,163]. When using resin at the interface, moisture absorption can also degrade its structure and hence deteriorate mechanical properties [127]. Numerous studies have shown the superiority of UHPC to enhance the durability and performance of the existing structural elements. UHPC, with its tight microstructure, can resist against chloride, gas, and water permeability when used as an overlay [41]. Tayeh et al. [30] observed a 54 % reduction of the total charge passed in the rapid chloride permeability test (indicating a higher resistance of the specimen to chloride ion penetration) in UHPFC-NC composites. On top of impermeability, the use of UHPC overlay can provide great structural strengthening, resistance to abrasion, and allow additional dead load on the structure while reducing the material volume [137]. UHPC overlays are typically used with thickness between 25 and 50 mm [179]. Previous studies showed that employing UHPC as an overlay on a NC substrate can result in an increase in bond strength by up to two times compared to using NC overlay [42,43]. This is mainly attributed to the formation of a denser ITZ linked to a lower w/c ratio, with less pore accumulation and reduced production of large crystal hydration products [32,41]. The rough surface of concrete substrates and thus exposed aggregates can also provide a source of $Ca(OH)_2$ for immediate pozzolanic reaction with silica fume (or other supplementary cementitious materials) present in UHPC [41]. Tayeh et al. [30] showed that a great interfacial mechanical bond (obtained by appropriate surface preparation) could further mitigate the chloride ion penetration, resulting in a more durable and robust bond performance in UHPFC-NC composites.

The presence of fibers in UHPC can further improve the bond performance and is recommended as a material additive for structural element repair [138–140]. A comprehensive review by Zhu et al. [141] indicates that fiber reinforced UHPC applied as an overlay on concrete beams and slabs could increase the flexural strength by up to 400 %. Based on their database, the optimal UHPC thickness and steel fibers content was found to be 50 mm and 3 %, respectively [141]. In the beams overlaid with thicker reinforced UHPC (above 50 mm), a lower tensile strength and softening behavior was observed as a result of fiber segregation (i.e., fewer fibers near the top surface) [141,180]. Moreover, when time is a constraint, Delatte and Sehdev [144] showed that high-strength concrete is a better option for the overlays that have to be opened to traffic in less than 24 h, compared to NC for which the traffic loading should be delayed for 48 or 72 h. To address the higher cost of high-strength concrete in very large-scale projects where paving lasts over several days, they recommend the application of normal strength concretes within the time period permitting sufficient curing time prior to the traffic loading (at least 48 to 72 h), followed by the use of high-strength concrete for the last day of construction.

5.6.2. Recycled aggregate concrete (RAC) and light weight aggregate concrete (LWAC)

Liu et al. [129] investigated the shear transfer behavior between a substrate made of RAC and a NC overlay by means of push-off tests. They showed that replacing coarse aggregates by recycled aggregates (RA) by up to 50 % by weight results in a negligible adverse effect on the interfacial shear strength. In case of using RAC in the overlay, Ceia et al. [145] indicated that although the shear bond strength in the RAC-NC composites exhibited adequate mechanical properties for structural use, increasing the RAC replacement rate resulted in a decline of the shear bond strength by up to a factor two, mainly owing to the reduced shear and tensile strengths of the RAC layer and the induced differential stiffness between concrete layers [146,147].

To benefit from high durability and mechanical properties of high performance concrete on one hand, and reduce its environmental and economic issues on the other hand, Robalo et al. [181] proposed a novel functionally graded concrete called “intelligent super skin” which consists of low cement content recycled aggregate concrete (LCRAC) in the core of structural elements and an ultra-high durability concrete (UHDC) in the outer layer as an protective layer. According to their experimental results, the LCRAC-UHDC exhibited a higher interfacial strength (up to 2.5 times) compared to that of NC-UHDC. This was mainly attributed to the higher binder matrix strength in LCRAC compared to NC despite having the same compressive strength. Moreover, they showed that the way the UHDC super skin is applied (prefabricated substrate or cast-in-place overlay) does not impact the interfacial shear strength, expanding its application in both new construction and rehabilitation of existing structures.

It should be noted that the fib Model Code 2010 provides the most accurate results compared to standard codes (*ACI* 318–14, Eurocode 2 and CSA A23.3–04), although all of these design codes give conservative results [129,145].

Due to the weight advantage of light-weight aggregate concrete (LWAC), there has been an increasing interest towards employing them in concrete overlays. In general, it is expected that both the shear and tensile bond strengths decrease upon reducing the density and strength of LWAC overlay [31,148]. In this regard, Costa et al. [31] studied the effect of concrete overlay density on the interfacial bond strength of composites including different interface roughness conditions. They observed that shear and tensile bond strengths are mainly influenced by the strength of the overlay binding matrix (cement paste) in smooth interface conditions. According to their LWAC-NC and NC-NC composite characterization, the LWAC overlay with density of 1500 kg/m^3 and compressive strength of 44 MPa exhibited higher shear strength (by up to 110 %) and tensile bond strength (by up to 50 %) compared to NC overlay with a density of 2350 kg/m^3 and compressive strength of 52 MPa. This is attributed to higher binding matrix strength of LWAC (90 MPa) compared to that of NC (50 MPa). However, the aggregate strength and stiffness, and hence concrete overlay density, played a pivotal role when a rough interface was employed. Here, the NC-NC composites outperform LWAC-NC in terms of shear and tensile bond strength. Raths [149] proposed to introduce a correction factor of concrete density in the design expression of the ultimate longitudinal shear strength by incorporating the values of 1, 0.85, 0.75 for normal weight concrete, sand-lightweight concrete, and lightweight concrete, respectively. However, it must be emphasized that the major design codes such as Eurocode 2 and fib Model code 2010 are developed based on normal aggregate concrete properties, and the effect of concrete density is typically not taken into consideration.

The shape and size of aggregates also affect the mechanical interlocking along the interface as well as the concrete overlay shrinkage. As shown by Momayez et al. [44], the use of larger aggregates, with maximum size of 16 mm, could be associated to an increase in interfacial shear bond strength by up to 7 % compared to that of 4.75 mm.

5.6.3. *Fiber reinforced cement-based composites*

Reinforcement of cement-based overlays with various types of fibers, namely metallic, synthetic, and natural, has become common practice to enhance the structural performance and durability of concrete-concrete composites. The addition of fibers typically results in enhanced crack growing resistance, reduced overlay shrinkage, and decreased porosity near the interface [57,150]. The degree of improvement depends upon the type, stiffness, orientation, and volume fraction of the fibers. High performance fiber reinforced concretes (HPFRC) dominate the field in this regard. Engineered cementitious composites (ECC), in particular, offer large tensile strain capacity (up to 6 %, i.e. about 600 times that of NC) and pseudo-strain hardening behavior resulting from fiber networks that promote the occurrence of multiple micro-cracks. The use of ECC in overlays was first proposed by Lim and Li [182]. In their experiments, they observed that the common spalling or delamination failures in repaired NC systems can be eliminated through the use of ECC, which promote the formation of multiple kinked microcracks that get arrested [85]. Tests using *T*-shaped notch bending specimen confirmed that ECC-NC composites outperform NC-NC ones with a higher peak load (by a factor 2) and deflection at peak load (one order of magnitude) [85]. Moreover, avoiding wide macro-cracks and favoring multiple micro-cracks in ECC (width < 100 μm) result in limiting or even preventing the ingress of deleterious agents. The resistance to chloride penetration and sulphate attack is enhanced, protecting underlying structural parts [153]. In this regard, sulfate corrosion resistance and degradation degree of interfacial bond strength in ECC/NC composites was assessed through coupling action of Na_2SO_4 sulfate (5 %) exposure and wet-dry cycles by Gao et al. [155]. Their results proved the great sulfate corrosion resistance of ECC-NC composites, showing less than 40 % reduction in tensile and shear bond strength after 120 cycles, in comparison with the NC-NC composites, which completely degraded after 90 cycles. In case of ECC reinforced with polyethylene (PE) fibers, the retrofitted structural elements have demonstrated greater impact resistance, moisture resistance, fatigue performance, ductility and energy dissipation capacity compared to that of plain concrete [69,183]. Nevertheless, the addition of PE fibers decreases the slump of the cementitious composites, and increases the air void, drawbacks that can be mitigated through a specific vibration mixing and production process [183,184]. The influence of ECC strength grade on the interface shear strength degradation of composites subjected to freeze–thaw (FT) salt cycles was studied by Tian el al. [118]. They found that using a lower strength ECC always resulted in earlier decrease of interface shear strength. A life cycle analysis demonstrated that the use of ECC overlays can provide higher service life (up to two times), less frequent repair events, thinner overlay thickness and reduced construction requirements and time compared to unbonded NC overlays [154]. This leads to a reduction by up to 40 % in total cost and greenhouse gas emission, making ECC an ideal sustainable alternative to NC as a repair material [154]. Fire safety of ECC overlays has also been studied. Gao el al. [185] studied the bond performance of NC and ECC reinforced with polyvinyl alcohol (PVA) fibers on NC substrates. They simulated the effect of fire in two scenarios; (i) the NC was first subjected to temperature, cooled down and then repaired with ECC, (ii) the NC was repaired with ECC and then subjected to temperature. Temperature effects were explored between room temperature and 800 °C. Their results show that ECC overlays behave better than NC overlays in all cases. In fact, when ECC was used as a repair material on previously heated NC substrates, the sample slant shear and splitting strengths increased after temperature exposures of 200 and 400 °C compared to room temperature. In specimen that were exposed to higher temperatures after repair, several NC-NC composites burst during the heating stage while none of the NC-ECC did. Authors attributed the superior performance of NC-ECC to the presence of slag and its post-reactivity with hydrates at high temperature, as well as the presence of melted PVA fibers that provide path for the evacuation of evaporating free/capillary water in the sample during heating. Kabiri Far and Zanotti [150] studied the effect of PVA and steel fiber addition in cement-based overlays. Theirs results revealed improved Mode-I crack grow resistance at the interface by increasing the peak splitting load and the critical stress intensity factor. Zanotti et al. [57] showed that the PVA fibers would not mitigate the destructive effect of wet and dry cycles on the bond strength and also does not remarkably affect the angle of internal friction since it is mainly controlled by the surface roughness. Moreover, it was shown that excessive addition of carbon fibers into a latex modified concrete overlay led to inferior workability, interfacial adhesion and hence a weaker bond strength [160].

5.6.4. *Modified concrete overlays (polymer admixture, granite powder, nanoparticles)*

Numerous studies have shown that the incorporation of polymer-based admixtures into the overlay greatly enhances the structural performance of concrete-to-concrete composites, their interfacial adhesion, impermeability, and their chemical resistance [156,157]. Guo et al. [158] studied the influence of aqueous epoxy resin addition on the mechanical properties and structural bond performance of ordinary portland cement (OPC)-based overlay mortar. They identified an optimum dosage of 5 % of epoxy, leading to increases of 17 %, 30 %, and 7 % of the interfacial flexural bonding strength, direct interface shear strength, and interface tensile strength of the composites, respectively. Authors attributed these results to the reduced crack width (pore filling and bridging effect by epoxy resin particles) and/or the enhanced integrity of the binder matrix (formation of polymer films covering/binding hydration products and fine aggregates) that eventually improve the microstructure of OPC mortars and toughness of the binder matrix [158]. It was shown that the epoxy-modified overlays provide increased resistance against thermal stresses, freeze–thaw (FT) cycles and carbonation, leading to great durability and hence an enduring robust bond strength [159]. Mirza et al. [157] reported that repairing materials modified by two types of polymers (i.e., styrene butadiene rubber and acrylics) showed at least 50 % less mass loss after 300 FT cycles compared to plain cement-based mortars. Considering the effect of overlay polymer modification, Assaad et al. [166] found incorporating styrene-butadiene rubber (SBR) latex is more efficient than air-entraining agent mainly through improving the flexibility of the materials to better accommodate the deformations along the interface, leading to a lower bond strength drop over FT cycles compared to air-entrained overlays. In this regard, Sadrmomtazi and Khoskbijari [161] showed that overlay mixtures containing a SBR-based polymer admixture and 5 % silica fume leads to improved durability performance against FT cycles, mainly due to the efficient reduction in shrinkage in these repair overlays.

Chajec et al. [186] studied the performance of cementitious overlays modified with waste granite powder (D50 ≈ 32 μm and Blaine specific surface area of 3650 cm^2/g) used as a partial replacement for cement. They observed that the modified overlays exhibit comparable consistency, lower water absorption and porosity along the interface, and promising mechanical and bond performance compared to that of reference samples. This enables to replace the cement by up to 10 %, and reduce the concrete environmental footprint. This result was mainly attributed to the fineness of granite powder leading to the optimized arrangement of particles and packing density. Along these lines, several studies have been carried out to investigate the effect of nanoparticle admixtures on the performance of cementitious overlays. Szymanowski and Sadowski [187] added different percentages of aluminum oxide (Al_2O_3) to various overlay mixtures and reported that the addition of 0.5 % of Al_2O_3 (by weight of cement) resulted in an increase in pull-off bond strength by up to 16 %, as well as higher overlay hardness and abrasion resistance, compared to the reference samples. This is primarily attributed to the formation of a denser micro-structure, as established by SEM images, including an estimated reduction of 18 % in fractional share of capillary pores near the interface. Similar effects were observed upon addition (0.5 %) of other types of nanoparticles, namely tetragonal crystalline titanium oxide (TiO_2) and amorphous silica (SiO_2) nanospheres [188,189].

5.6.5. *Self-compacting concrete (SCC)*

Diab et al. [56] showed that the appropriate application of SCC as an overlay can provide slant shear bond strength increase by up to 70 % compared to that of conventional concrete overlays. Appropriate workability of the overlay not only eases proper application and spreading on the substrate but also provides a better filling of the substrate surface cavities and pores, leading to a greater anchorage and bonding [63,135]. This highlights the importance of overlay fresh properties. To maintain the remarkable effect of flow when using overlay mixtures containing fibers, Diab et al. [56] used a type G water reducing agent in an SCC containing polypropylene fibers and measured an increase in bond strength by up to 14 %.

6. Summary and conclusions

Over the last three decades, concrete-to-concrete composites have been used in a broad range of applications. The extensive literature published in this period demonstrates the importance of the repair techniques, but may also present confusing and even contradicting results. This paper aims at providing an accessible analysis of the literature through (1) a comprehensive summary on the test methods used for the evaluation of the performances of concrete-to-concrete composites and (2) a systematic review of the factors that affect these properties. The main findings can be summarized as:

- Mechanical tests to characterize concrete-to-concrete composites include slant shear tests, direct shear tests, bi-surface shear tests, pull-off tests, splitting tensile tests, three-point bending tests, wedge splitting tests, and failure envelope approach. More recently, non-destructive tests have also been given attention. The use of a combination of test methods, instead of a single test, is recommended to obtain a more representative assessment of the performance of a concrete-to-concrete composite.
- The failure mode is typically categorized as either cohesive or adhesive in concrete-to concrete composites, depending on the location of the main crack path. Increasing the bond strength can shift the failure mode from adhesive to cohesive.
- Many factors affect the performance of concrete-to-concrete composites. Discussed in this review are: moisture condition, type and properties of adhesive agent, roughness, crossing reinforcement, mismatch in the properties/behavior of concrete layers (including shrinkage), concrete type (UHPC, ECC, RAC, SCC, LWAC).
- The application of bonding agents such as cement-based slurries and epoxies on smooth and slightly rough interfaces is beneficial. The mechanism of bonding varies among these materials (primary bonding forces, Van der Waals forces). Polymer based bonding agents are sometimes selected, despites their costs, for their ability to provide an impermeable layer, preventing the penetration of deleterious agents.
- The use of HPC and in particular ECC in overlays have shown to greatly improve mechanical integrity, lifetime and fire resistance of concrete-concrete composites.

7. Recommendations for future research

The findings of this systematic literature review revealed future research directions that could support researchers and engineers to move towards improved concrete-to-concrete composites, including:

- More environmentally friendly materials should be investigated. Nanomaterials, supplementary cementitious materials, and rapid setting cements could improve mechanical integrity and durability of concrete-to-concrete composites while offsetting their CO_2 footprint.
- Evidence-based guidelines for the selection of the appropriate test methods should be developed. Correlations between different test methods should be further explored.
- The mechanisms of bonding between concrete layers have been extensively discussed. These mechanisms involve adhesion, aggregate interlock, shear friction, and dowel action. Despite this understanding at the macroscopic level, the behavior of a concrete-concrete composite formed with a novel material is, for example, difficult to predict by codes. This prompts the need for future research at an even smaller scales to further a bottom-up approach.
- More informed guidelines on the appropriate selection of bonding agents and method of application for smooth and slightly rough interface surfaces from a practitioner point of view can be written using the up-to-date published research.
- The effect of sample size on the mostly detrimental effect of restrained shrinkage could be tested and discussed further. The presence of a polymeric bonding agent and its mitigation effects could also be further examined.
- The use of artificial intelligence and machine learning techniques to develop comprehensive predictive models would be recommended in future studies, given the extensive number of studies available. The extensive but complex published literature could be scavenged to feed such models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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