

**INTERFACIAL BOND BEHAVIOR BETWEEN ULTRA
HIGH-PERFORMANCE CONCRETE (UHPC) AND
DIFFERENT CONCRETE SUBSTRATES**

BY

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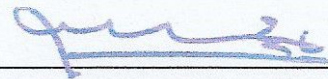
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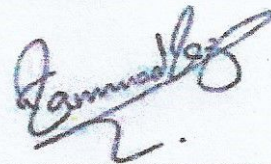
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Dedicated to
My beloved parents, my wife, and my sisters |

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LIST OF ABBREVIATIONS

AC	:	As cast
ACI	:	American Concrete Institute
ASTM	:	American Society for Testing and Materials
CDP	:	Concrete Damage Plasticity
EXP	:	Experimental
DH	:	Drill holes
FEM	:	Finite Element Model
LVDT	:	Linear Variable Differential Transformer
NC	:	Normal concrete
SB	:	Sandblast
SC	:	Screed concrete
SSC	:	Self-compacted concrete
UHPC	:	Ultra-high performance concrete
UTM	:	Universal Testing Machine

|

ABSTRACT

Full Name : Mohammed Khaled Almadani
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Ultra-high performance concrete (UHPC) can be used as an excellent material to repair or strengthen the reinforced concrete structural elements since the UHPC possesses excellent properties such as very high compressive strength, high tensile strength, serviceability, and incredibly very high durability. However, the effectiveness of repairing and strengthening by applying the layers of smart materials on the surface of substrate concrete depends on whether the interface between overlay and substrate ensures adequate bonding performance over the entire life span under different loading and exposure conditions.

In this research, the interfacial bond strength between UHPC and different types of concrete substrates was investigated experimentally and numerically. The comprehensive experimental program included casting of two hundred ninety-seven different specimens following an experiment design that considered different variables: (i) concrete mixtures as substrates, (ii) methods used for surface preparation of the substrate, (iii) curing conditions, and (iv) environmental exposure conditions of concrete. Four different tests were conducted to evaluate the bond strength, namely, slant shear, bi-surface shear, splitting tensile, and third-point flexural tests. The analysis of the test results revealed that the UHPC overlay obtained superior interfacial bond performance to rehabilitate different concrete elements.

A numerical non-linear finite element model (FEM) using the Abaqus package was developed to simulate the bond behavior between UHPC and concrete substrates. A surface-based cohesive behavior model was used to investigate substrate surface roughness behavior.

Finally, a parametric study using a validated model was developed to study the effects of surface contact between the UHPC and substrate interfaces. The numerical studies from the surface-based cohesive behavior were most suitable and showed good agreement with the experimental results to simulate the bond between UHPC and concrete substrate.

|

ملخص الرسالة

الاسم الكامل: محمد خالد عبدالله المدني

عنوان الرسالة: سلوك الروابط البينية بين الخرسانة فائقة الأداء (UHPC) وأنواع مختلفة من الخرسانة الأصلية

التخصص: الهندسة المدنية

تاريخ الدرجة العلمية: ديسمبر 2020م

إن الخرسانة فائقة الأداء المسماة (UHPC) يمكن أن تستخدم كمادة ممتازة لإصلاح أو تقوية عناصر الخرسانة المسلحة الهيكلية نظراً لأن هذا النوع من الخرسانة UHPC يمتلك خصائص ممتازة مثل قوة تحمل الضغط العالية جداً ، وكذلك قوة الشد العالية ، والمتانة العالية جداً أيضاً ، كما أنها تعطي خدمة أفضل بكثير من الخرسانة العادية من ناحية التقليل من قيمة التشوهات والشروخ المحتملة. ومع ذلك، فإن فعالية الإصلاح والتقوية من خلال تطبيق هذا النوع من المواد الذكية على سطح الخرسانة الأصلية تعتمد بشكل أساسي على نوع التماسك وقوة التلاصق ما بين هذه الطبقات والخرسانة الأصلية والتي قد تضمن أداء ترابط وتماسك مناسبين طوال فترة حياة المنشأة بأكملها وفي ظل ظروف تحميل وتعرض مختلفة ومتنوعة.

في هذا البحث ، تمت دراسة قوة الروابط البينية بين هذا النوع من المواد الذكية UHPC وأنواع مختلفة من الخرسانة العادية والمستخدمة بشكل كبير في مواقع العمل وهذه الدراسة تمت مختبرياً من خلال اختبارات وتجارب معملية وكذلك عددياً باستخدام برامج الحاسوب. تضمن برنامج التجارب المعملية صب مائتين وسبعة وتسعين عينة مختلفة وذلك بعد الأخذ في الاعتبار عدد من المتغيرات المختلفة والتي يمكن تلخيصها في النقاط التالية: (أ) نوع الخرسانة العادية المستخدمة كخرسانة أصلية ، (ب) الطرق المستخدمة لإعداد وتجهيز سطح الخرسانة الأصلية ، و (ج) شروط معالجة الخرسانة و (د) تعرض الخرسانة لظروف بيئية مختلفة. تم إجراء أربعة اختبارات مختلفة لتقييم قوة الترابط ، وهي اختبار القص المائل، واختبار القص ثنائي السطح ، واختبار الشد الانشقاقي ، وكذلك اختبار الانحناء من النقطة الثالثة. أظهرت نتائج تحليل الاختبارات المعملية أن أداء الروابط البينية بين الخرسانة UHPC مع الخرسانة الأصلية كان عالياً وفعالاً مما يجعله مناسباً لإعادة تأهيل وتقوية العناصر الخرسانية المختلفة.

تم تطوير نموذج رقمي غير خطي للعناصر المحدودة (FEM) باستخدام حزمة برنامج Abaqus لمحاكاة سلوك الترابط بين مادة UHPC والخرسانة الأصلية ولقد تم استخدام نموذج السلوك المتماسك السطحي لمحاكاة قوة الترابط و للتحقق من سلوك خشونة السطح ما بين نوعي الخرسانة المستخدمة في التجارب المعملية.

أخيراً ، تم عمل وتطوير دراسة حدودية عديدة باستخدام النموذج السابق وقد تم التحقق من صحته لدراسة تأثيرات التلاصق السطحي بين واجهات مادة UHPC والخرسانة الأصلية. لقد كانت هذه الدراسات العددية الناتجة عن استخدام نموذج السلوك المتماسك السطحي هي الأنسب والأفضل ولقد أظهرت توافقاً جيداً مع نتائج التجارب المعملية لمحاكاة سلوك وقوة الترابط بين مادة UHPC والخرسانة الأصلية.

CHAPTER 1

INTRODUCTION

1.1 General

A significant number of current concrete structures worldwide need to be repaired or strengthened due to the deficiency in their structural performance and durability properties. These severe deficiencies could be due to adverse weather conditions and heavy mechanical loads. Early and severe degradation of reinforced concrete buildings is a global problem that may influence community safety and raise repair costs. Consequently, repair material's performance requirements must follow code and standard specifications [1]. The most significant characteristics of any repair and/or strengthening material are long-term performance, low-cost, non-hazardous, durability, stiffness, substratum consistency, and bond performance.

Several traditional methods are used in the repairing and strengthening of structural components, such as steel plate reinforcement [2], [3], fiber-reinforced polymers (FRPs) [4], [5], [6], [7], [8], concrete jackets, etc. Among these, FRPs have ideal properties such as high impact resistance, strength, stiffness, ease of handling, and the ability to carry structural component loads. However, FRPs, applied on the concrete surface as a repair/strengthening layer, has some bonding deficiencies, such as compatibility and low fire and weathering resistance. Thus, UHPC can be considered an excellent alternative to

improve the structural performance and durability of old concrete for repair and strengthen concrete structures [9].

The utilization of UHPC as an overlay for repairing/strengthening the reinforced concrete structural members might prove to be a promising option owing to UHPC's high serviceability, excellent compatibility, high strength-to-weight ratio, excellent ductility, and outstanding durability with low permeability and high corrosion resistance properties [10], [11]. The UHPC combines cementitious materials and steel fibers, having outstanding mechanical properties with a compressive and splitting tensile strength greater than 150 and 5 MPa, respectively [12], [13], [14], [15], as well as excellent durability in severe environmental condition [16], [17], [18]. However, specific bonding performance assessments are needed to ensure an efficient and effective repairing/strengthening of the concrete substrate using the UHPC [19], [20].

The concrete-to-concrete bond strength approach mostly adopted in retrofitting reinforcing concrete elements [21], [22]. However, it may be noted that the bond interface is typically a weak link of the repaired composite concrete structure. Moreover, the compressive, tensile, and other mechanical properties of the bond plane are significantly lower than the concrete mixture, especially in the harsh environments. Hence, a crucial factor deciding the lifespan of a repaired structure is the bond between the overlay and the substratum concrete. The interfacial bond properties are difficult to predict due to variations in the composition, material characteristics, surface conditions, and curing methods. Its performance in shear generally evaluates the bond strength of a concrete interface (e.g., bi-surface shear test), combined shear and compression (e.g., slant shear test), indirect tension (e.g., splitting tensile and third-point flexural test), direct tensile and pull-off test method

[20], [22], [23], [24], [25]. The shear bond strength's performance is primarily correlated with the mechanical interlocks, and the amount of the component hydration is significantly influenced by the degree of roughness of the interface. In contrast, the tensile bond's strength is due mostly to the hydration level of cementitious material [26].

1.2 Significance of this Research

The purpose of utilizing concrete-to-concrete composite members is to ensure the best load transfer, in which the adhesion between concrete layers is the principal factor. While numerous research studies have been conducted to determine the bond strength between old concrete (substrate) and UHPC (overlay), it can be observed that there is a lack of data regarding the bond performance with different types of exposed aggregate concrete interfaces. Also, there is a lack of information about the effect of different curing conditions and the effect of different aggressive exposure conditions on the performance of the bond. Despite the several studies that used various test methods to assess the bond strength between the concrete substrate and UHPC overlay, still the information pertaining to the comparison of the bi-surface shear and third-point flexural strength test to the relatively common tests (i.e., slant shear and split tensile strength tests), is lacking. Moreover, study on the simulation of the bond behavior using an accurate numerical model rather than a tie model that leads to overestimation and conservative, is rarely reported.

In this study, three types of composite concrete are used: UHPC-NC, UHPC- SC, and UHPC-SCC to investigate the bond strength's performance encountering different types of

concrete structural components. The various parameters were implemented, namely, interfacial bond roughness; as cast (AC), drill holes (DH), and sandblast (SB) of the substrate, different curing conditions of the composites; watering (W) and heating (H) and different exposure conditions; laboratory environment (N) and wet-dry and heat-cool cycles (R). Besides using the experimental data in evaluating the bond behavior, a numerical non-linear finite element model (FEM) using the Abaqus package was developed to simulate the bond behavior between UHPC and concrete substrates. A surface-based cohesive behavior model was used to investigate substrate surface roughness behavior.

1.3 Research Objectives

The main objective of this work was to investigate the bond behavior between UHPC and different concrete substrates (normal strength concrete: NC; screed concrete: SC; and self-compacted concrete: SCC) to develop a correlation between the bond strength and the types of concrete substrates that would enable to ensure an effective strengthening/retrofitting of concrete structures using UHPC overlays.

The specific objectives are as follows:

1. To study the effect of types of substrates (surface roughness and composition of the substrates).
2. To study the performance of the bond under different curing conditions.

3. To study the degradation of the bond under combined wet-dry and heat-cool cyclic exposure conditions.
4. To simulate the interfacial bonding between UHPC and substrate concretes in the ABAQUS environment to envisage the surfaces' performance and failure modes.
5. To validate the numerical models with the experimental results.
6. To carry out a parametric study using the validated model.

1.4 Thesis Structure

Eight chapters of this thesis are structured and reported. *Chapter 1* presents an introduction, objectives, and significance of this study. *Chapter 2* reviews the previous research works that have been conducted in the bond performance of UHPC rehabilitation. *Chapters 3* describe the experimental program; development of the concrete substrate and UHPC mixtures, preparation and repairing process, material properties, and bond test methods. *Chapter 4, 5, and 6* presents experimental results and discussions. All the results of the three concrete substrates to UHPC overlay conducted with different parametric studies under various test methods were discussed in detail. The bond results obtained from the experimental program then validated in *Chapter 7* using a numerical FEM model. Finally, *Chapter 8* outlines the conclusions and recommendations. |

CHAPTER 2

LITERATURE REVIEW

2.1 Outline

Ultra-high-performance concrete (UHPC) has recently been produced in accordance with four fundamental hypothesis standards, including porosity decreases, fine-structure improvements, consistency upgrades, and durability increases. Remarkably, UHPC generally increases its compressive strength up to 150 MPa, acceptable tensile ductility and hardness, and prevalent durability. A high number of subsidiary cement materials and a few doses of very fine particles regularly are used to increase the strength and sustainability of UHPC to supplant a portion of the paste and silica fume. Expansion of temperature curing is additionally embraced to quicken the hydration of paste and upgrade the subsidiary hydration among subsidiary cementitious materials and Calcium hydroxide. Both temperature increase and pressure recovery allow the overall characteristics of UHPC to be expanded.

A brief literature review is presented here to overview the UHPC properties' information as a superior repair material compared to CFRP's rehabilitation. Then, a background of conducted the bond strength between concrete layers. Finally, the bond performance between UHPC and normal concrete substrate was revised.

2.2 Rehabilitation by Carbon Fibre Reinforced Polymers (CFRP)

Wang et al. (2014) [27] evaluated the bond behavior between CFRP and high-strength concrete under dual-lab shear tests and subjected them to different wet-dry cycles and long-term loads. Based on his results, the ultimate bond load rises initially, usually decreasing with the rise in periods. In addition, the interfacial bond between the concrete and epoxy resin was the most significant failure occurring under the action of wet-dry cycles. However, long-term loads impact the failure mode of samples considerably and initiate an unexpected failure.

Mohammed et al. (2016) [28] examined the performance of near-surface mounted carbon (NSM) FRP repair using a pull-out test with innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) under high temperatures. The pull-out tests' findings indicate that the IHSSC-CA samples have less effect on high temperatures and preserve substantial residual bond strength as represented in Figure 2.1.

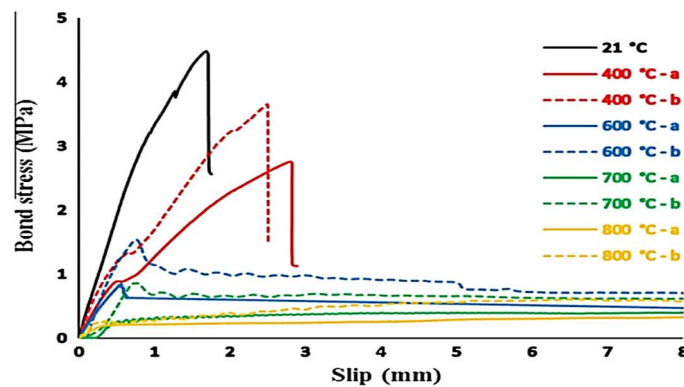


Figure 2.1 Bond-slip relations of tested samples [28]

Fazli et al. (2018) [29] investigated the pull-off tests with concrete slabs under different environmental conditions. As 3.5% of both immersion exposure and saltwater at 60 °C. This study's significance was to evaluate the influence of CFRP reinforced concrete sheets on bond quality over one-year of marine exposures. The test results showed that the 1-year treatment in the extreme environment had a small impact on epoxy quality between CFRP and concrete.

2.3 Ultra-High Performance Concrete

Azad et al. (2013) [17] studied the influence of UHPC tensile properties under wet-dry and heat-cooling cycles and different fiber contents. To aim that specimens are tested under flexural and split tensile strength. The process of heating-cooling cycles was exposed for two days at room temperature of 60 °C and then cooled down for the next two days. However, for wet-dry conditions, the proposed solution with a mixture of sodium chloride (NaCl) was tested for two days for wetting samples and then dried at 30 °C for the next two days. Based on his investigation, the UHPC mixture of 6.2 percent steel fiber is an outstanding cement material capable of achieving a strong tensile strength of approximately 31 MPa, with a maximum strength of 1.66 in proportion to its initiation cracking. Overall, UHPC does not indicate degradation of the tensile strength under wet-dry and heating-cooling conditions, which is a feature of these materials.

Ahmad et al. (2015) [11] established an optimal UHPC mixture utilizing resources of dune sand and other cementitious materials locally, as seen in Table 2.1. Based on his mixed design, the durability and mechanical properties were excellent in which the maximum

compressive and flexural strength was estimated nearly to 160 MPa and 30 MPa, respectively.

Table 2.1 Mix-design of UHPC [11]

Ingredients	Cement	Micro-silica	Fine sand	Water	Steel fibers	Superplasticizer-Glenium® 51
Proportions (kg/m ³)	900	220	1005	163	157	40

The UHPC's tensile and compression behavior has been studied by Shafieifar et al. (2017) [30], and comparisons have been made with NC in developing a numeric model to mimic UHPC's manner using finite elements (FE). The results revealed that the compressive strength of commercial UHPC was 3 to 4 times higher than normal concrete strength. In addition, higher elasticity modules of UHPC specimens were obtained (approximately twice) compared to NC. Furthermore, higher tensile resistance and ductility were observed for UHPC specimens than regular concrete (2 to 4 times higher). Overall, the results commonly coincide between numerical and the experimental outcomes, as shown in Figure 2.2 and 2.3.

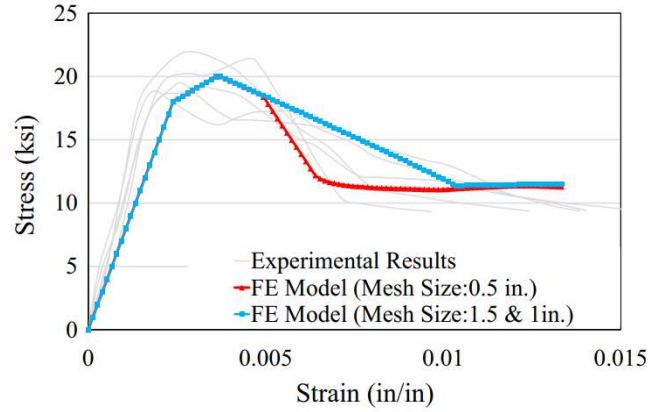


Figure 2.2 UHPC cylinder compression test results compared with the numerical result [30]

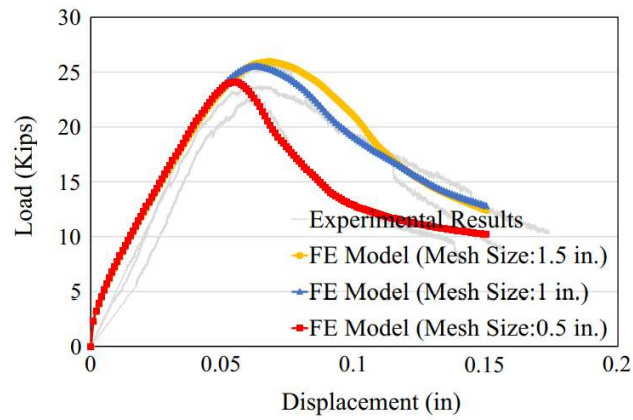


Figure 2.3 UHPC flexural strength test results compared with the numerical result [30]

2.4 Bond between different type of concrete to concrete layers

Widodo (2017) [31] evaluated the strength between the substratum lightweight fiber-reinforced concrete (HyFRLWAC) and the overlay SCC. As-casted and grooved, substrates were prepared. The pull-off test illustrated the strength, while an adjusted bi-surface shear test evaluated the concrete stability. Based on his study of friction, shear strength, the tensile strength of the concrete surface, the compressive strength of the

overlay, and the normal strength acting on the concrete interface will be influenced by the substratum's surface condition. Furthermore, the maximum interfacial tensile strength up to 60 MPa between HyFRLWAC substrate and SCC overlay. Also, a proposed formulation was established for the prediction of bond strength. The average interfacial tensile strength between the substratum and the overlaying concrete with a compressive strength of (30-60 MPa) can be expressed in Eqs. 2.1, and 2.2.

$$f_{pull-as-casted} = 0.03 f_{c_{top}} \quad 2.1$$

$$f_{pull-grooved} = 0.04 f_{c_{top}} \quad 2.2$$

Dybel and Wałach (2017) [32] investigated the interfacial bond strength between NC and high-performance concrete (HPC) under splitting tension test with varying age of test carried out to the composites. Based on his findings, the overlay transfer area was shown to have a prevailing interface deterioration mode when composite specimens are NC-NC and HPC-HPC. The attachment failure mode for NC-HPC samples was noted in the transfer overlay area and NC substrate. The greatest bond strength was noted on day 28 of curing: for composite HPC-HPC - 2.66 MPa, for NC-HPC - 2.13 MPa, and for composite NC-NC - 1.89 MPa, as shown in Figure 2.4.

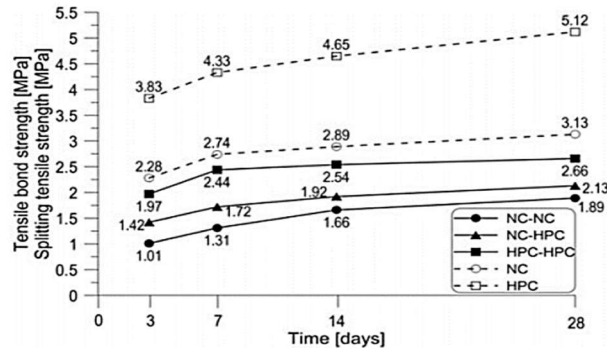


Figure 2.4 Tensile bond strength and splitting tensile strength development [27]

The effects of different repeated cyclic exposures are typical situations for old concrete frameworks in service [17], [18], [33]. The interfacial bond strength between the NC substratum and the UHPC surface was assessed by Carbonell Muñoz et al. [34]. The variable parameters used were the bond age, varying surface roughness, and exposure to freeze-thaw cycles. The slant shear tests indicated that the bond strength was greater than the actual concrete substrate strength at an early age of 8. Similarly, the pull-off test at an early age was greater than the minimum standard of ACI 546-06 at 28 days, independent of the surface treatment applied.

Regarding the split tensile study, regardless of substrate roughness or freeze-thaw cycle exposure, bonding performance was stronger even after the age of 6 months. Zuo et al. (2020) [35] studied new-old mortar interface bond strength and degradation after wet-dry and/or heat-cool cycles. The performance of the bond was assessed by slant shear and four-point flexural strength test. Based on the authors' findings, during combined wet-dry and heat-cool cycles, more severe degradation of the composite mortar interface is observed than the heat-cooling cycles, during seven cycles. In addition, the coupled cycles

substantially decrease the slanting shear strength of overlay mortars relative to a four-point bending strength test, as shown in Figure 2.5.

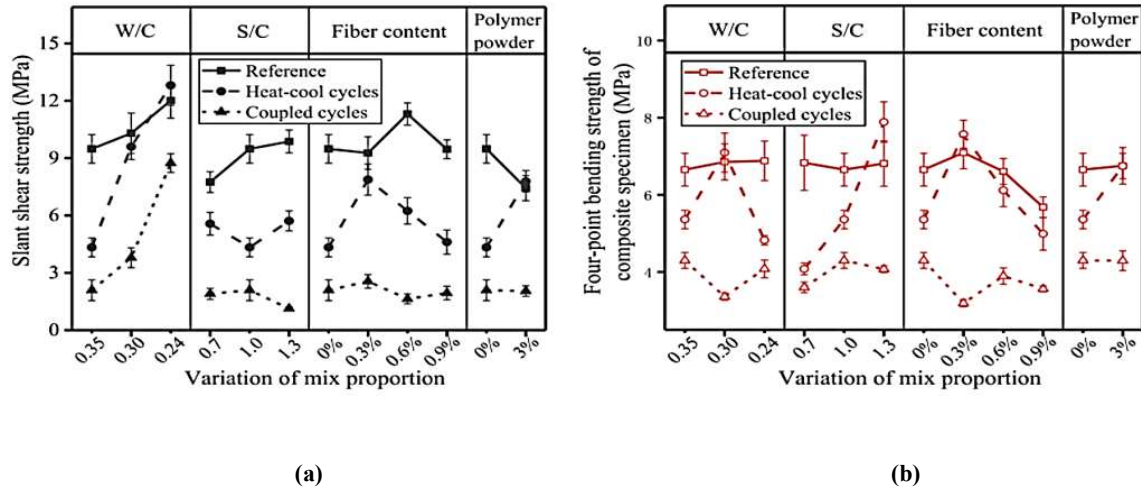


Figure 2.5 The degradation of the bond strength due to heat-cool cycles and coupled cycles: (a) slant shear strength; (b) four-point bending strength test results [35]

2.5 Bond performance between NC substrate and UHPC overlay

Harris et al. (2011) [19] examined the bond performance between UHPC as an overlay and NC substrate surface with different degrees of roughness under split tensile and slant shear stress applied to assess the bond strength of the composite specimen (Figure 2.6). The splitting tensile strength results demonstrated that the bond strength is not very sensitive to the surface preparation, but the slant shear test highly depends on the degree of roughness to assess the bond strength, as demonstrated in Figure 2.7.



Figure 2.6 Slant shear test specimens with different substrate surface preparation; grooved, chipped, smooth, and shear key [19]

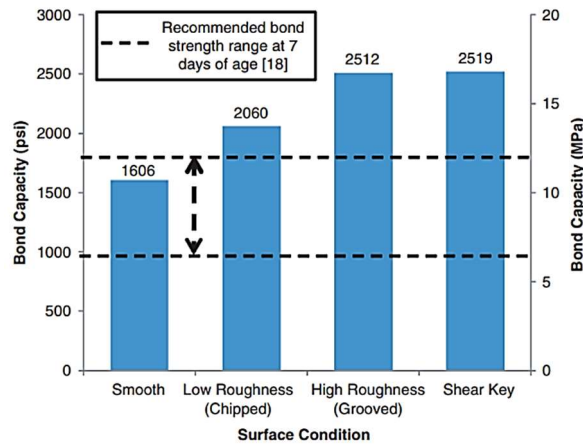


Figure 2.7 Average bond performance at ten days of age for different surface configurations [19]

Tayeh et al. (2014) [12], [20], [36] evaluated UHPC-NC interface bond performance and permeability characteristics. Interface bond strengths were evaluated through pull-off, splitting tensile and slant shear tests, water, gas, and rapid chloride permeability tests to assess permeability characteristics. The pull-off test results showed that any failure in the substratum occurred irrespective of the substrate's roughness. On the other hand, the results of splitting tensile and slant shear tests showed that the failure mostly occurred in the NC substrate when used sandblast preparation, as shown in Figure 2.8. Therefore, the UHPC-

NC witnessed a powerful bond performance. The permeability of the UHPC-NC interface was strong, and the concrete layer's impermeability was greatly increased.



Figure 2.8 Types of splitting tensile failure: (a) complete interfacial failure; (b) interfacial failure with partial substratum failure; (c) substratum failure [12], [20], [36]

Hong and Kang (2015) [37] studied the performance of the bond between UHPC as a substrate and overlaid by NC under splitting tensile and bi-surface shear tests. The variable parameters were the interface conditions and method of curing. The direct shear test results indicated that the bond strength decreasing by increasing the temperature through UHPC curing.

Li and Rangaraju (2016) [38] studied the influence of substrate concrete NC surface roughness on bond strength repaired by UHPC under various test methods to assess the bond performance. The third-point flexural test is more convenient and practical for the bond test, and 10 seconds of sandblasting treatment are essential to fulfill a needed bond performance of composite UHPC-NC even at the early age of casting the UHPC.

Baharuddin et al. (2016) [39] examined the bond performance between fire-damaged NC substrate and UHPC as a repair material under splitting tensile and slant shear tests. Three different curing conditions were implemented in this studied, such as wet, air dry, and saturated surface dry (SSD). Based on the authors' results, the superior bond strength was

witnessed by the SSD condition, as represented in Figure 2.9. The bond performance due to the slant shear test was weak in which displayed an interface failure compared to the highest bond strength under the splitting tensile test where the failure occurred in the NC substrate.

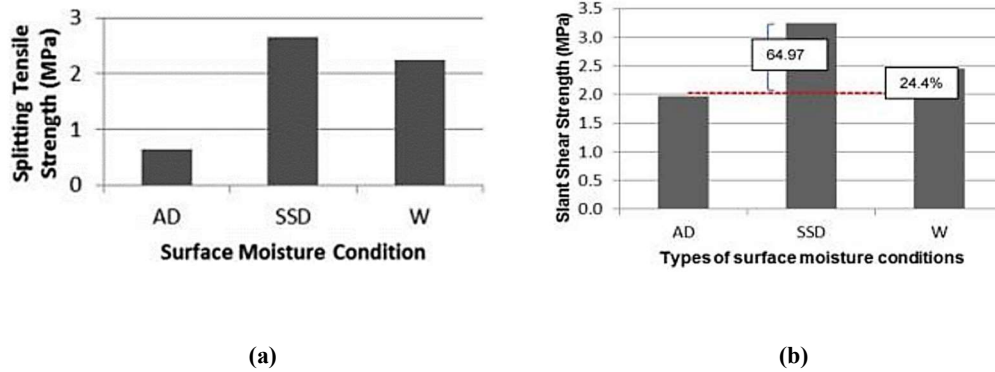


Figure 2.9 Average bond strength: (a) splitting tensile; (b) slant shear test [39]

Jang et al. (2017) [40] studied the shear behavior of normal concrete NC construction joints under push-off tests. The construction joint was incorporated with UHPC or NC and UHPC with different surface treatments. The coarse aggregate mechanism interlock played a crucial role in UHPC and NC's bond performance for the exposed aggregate as a grooved surface treatment.

ALHallaq et al. (2017) [41] investigated the bond performance between NC substrate and UHPC as an overlaid material. The authors conducted both slant shear and splitting tensile test to estimate the bond strength. NC substrate was treated with different surface preparation by as cast, wire brush, drill hole, and sandblasting methods. The results obtained from slant shear and split tensile tests indicate that sandblast surface preparation improved the bond strength by 251.8% and 153%, respectively, compared to as cast

interfacial surface, as shown in Figure 2.10. In addition, the results indicated that tension bond strength more relative to UHPC repair strength and less susceptible to the degree of surface roughness.

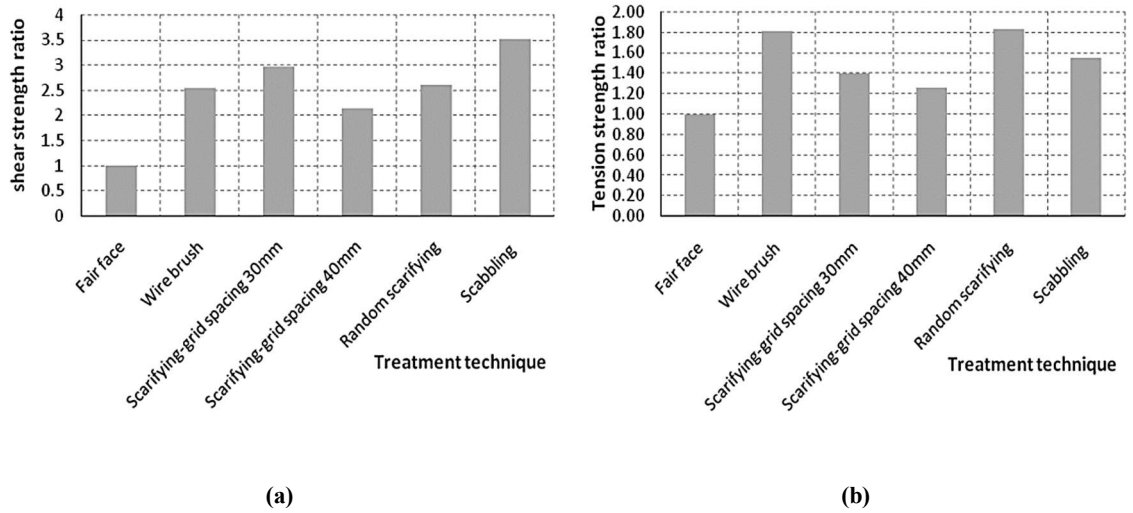


Figure 2.10 Normalized chart results: (a) slant shear (b) splitting tensile test results [41]

Al-Osta et al. (2017) [42] investigated experimental and numerical approaches for assessing the performance of two distinct techniques for repairing reinforced concrete beams using UHPC as a repair material. Various methods can be applied either on sandblasted RC beams or epoxy adhesive to bond prefabricated UHPC strips. Three distinct strengthening configurations were used to strengthen the bottom, two longitudinal sides, and three sides of the framework. Beam specimens strengthened on their three sides exhibited the highest strength increase, while beams repaired only on the bottom side showed the least increase in UHPC performance techniques. Finite element (FE) results indicated strong compliance with the experimental test results. The FM expected peak load and load-deflection behavior are consistent with the experimental test values.

Aaleti and Sritharan (2019) [43] studied different characteristics on bond performance of NC as a substrate and overlaid by UHPC, such as shear friction parameters, concrete strength, and interface roughness. The bond performance in the slant shear test depended highly on the interface roughness. A minimum roughness of 1.6 mm was sufficient to establish an appropriate bond strength between UHPC and NC interfaces.

Jafarinejad et al. (2019) [44] evaluated the bond strength between a conventional concrete substrate NC and UHPC overlay. According to his study, various surface roughnesses were implemented under slant shear, direct shear, and pull-off test methods to assess the composite specimen's bond strength. The test results show that sandblasting roughness's bond strength performance increased by four-times and almost three-times of pull-off and slant shear test, respectively, compared to the surface without any preparation, as shown in Figure 2.11.

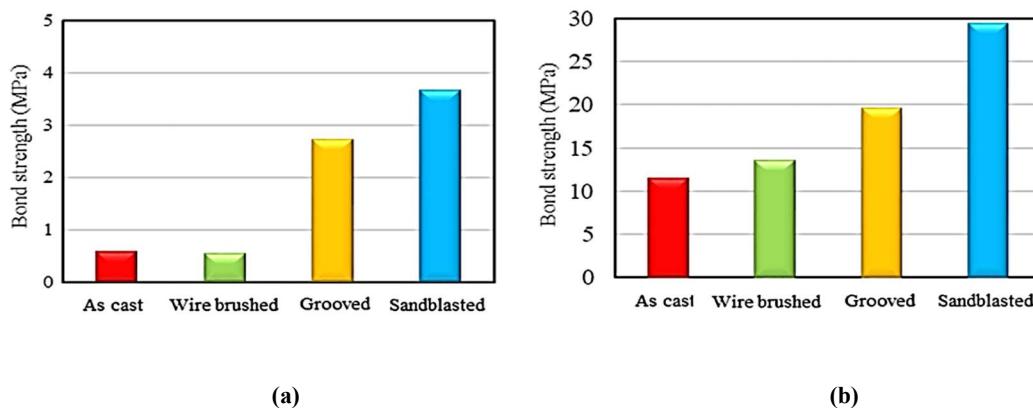


Figure 2.11 Average bond performance: (a) pull-off; (b) slant-shear tests [44]

Farzad et al. (2019) [14] studied the experimental and numerical bond strength of composite concrete UHPC-NC under different stresses applied (flexural, direct shear, and combined compression and shear loadings). The authors developed a recent numerical

approach that used the interface plane between the concrete layers to validate the experimental results, rather than the tie model that overestimated the load capacity. The study model's biggest mistake was 18 percent, whereas the 'tie model,' when shear and strain are on the bond, indicates more than 150 percent difference, as shown in Figure 2.12.

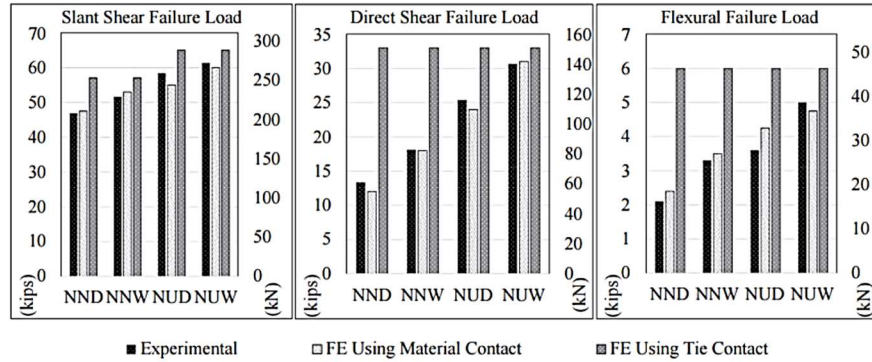


Figure 2.12 Experimental and numerical results of models associated with various conditions [14]

Zhang et al. (2020) [45] investigated the bond performance between NC substrate and UHPC as an overlay under splitting tensile, direct tensile, and slant shear tests. Various variable parameters studied the roughness of the substratum surface, the age of UHPC, the degree of moisture of the substratum, the curing conditions of UHPC-NC specimen, the grade of the NC substratum, the bonding and expansive agent were used to examine their effect on bond strengths and the UHPC-NC interfacial bonding mechanism. Results revealed that appropriate treatment of roughness, the substrate's grade, and full NC moisture before UHPC casting was required to ensure consistent bond performance.

Semendary and Svecova (2020) [15] applied pull-off, bi-surface shear, and slant shear test methods to investigate the bond strength between the NC substrate and UHPC as a repair material. The authors evaluate interfacial parameters such as cohesion, adhesion, and

coefficients of shear friction and perform a sandblast surface roughness to provide a reliable bond strength. The bi-surface shear results included a large coefficient of variation (COV) and did not seem accurate for achieving UHPC bond strength with rough surface preparations. However, the AASHTO LRFD interface parameters are reasonable and can be used when designing UHPC interfaces.

Valikhani et al. (2020) [46], [47] investigated the experimental and numerical bond strength between UHPC and NC's substrate. The researchers carried out a bi-surface shear test to assess the influence of different surface preparations. The results showed that the model's failure to the concrete substrate suggests a high bond strength than interfacial surfaces without preparation through an acceptable roughness for the interface surface with, or without, mechanical connectors. Compared to the model results with a fixed contact, the zero thickness model's numerical results indicate a strong alignment with the test results, which minimized error by 181% and 24% for as cast and sandblast interfaces, respectively, as shown in Figure 2.13.

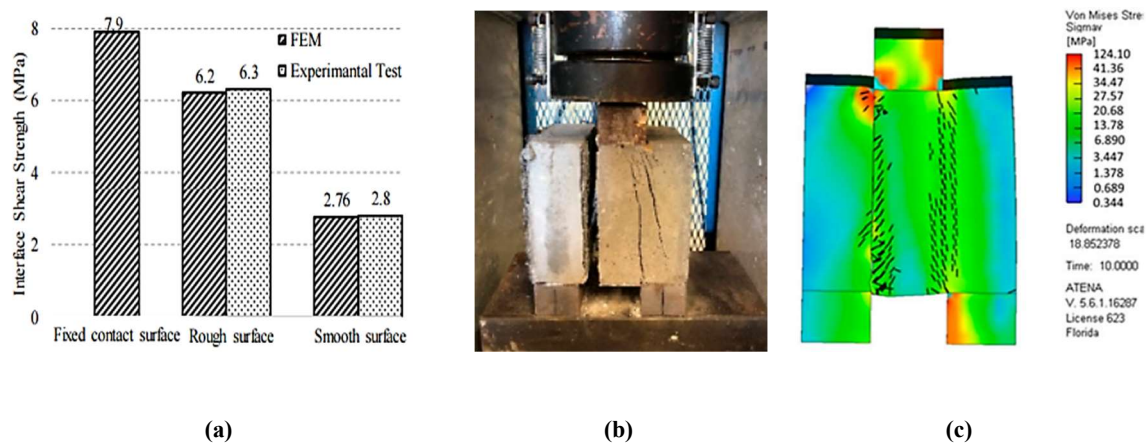


Figure 2.13 Bond strength numerical results: (a) Comparison between experimental and numerical model results of bond strength; (b) specimen failure; (c) stress distribution in the finite element model [46], [47]

Ganesh and Murthy (2020) [48] evaluated the experimental and numerical interfacial bond strength between UHPC as an overlay material and NC as old concrete conducted under slant shear, splitting tensile, and third-point flexural tests. The factors observed to assess bond performance are surface treatment (grooving and drill hole) and bonding nature (fresh and hardened UHPC). The slant shear results, splitting tensile, and third-point flexural strength of grooved harden specimen are increased by 12.2%, 60.3%, and 26.1%, respectively, relative to the chipped fresh surface state as shown in Figure 2.14 and 2.15. The overall percentage variance between the predicted and the resulting experimental values is less than 12%.

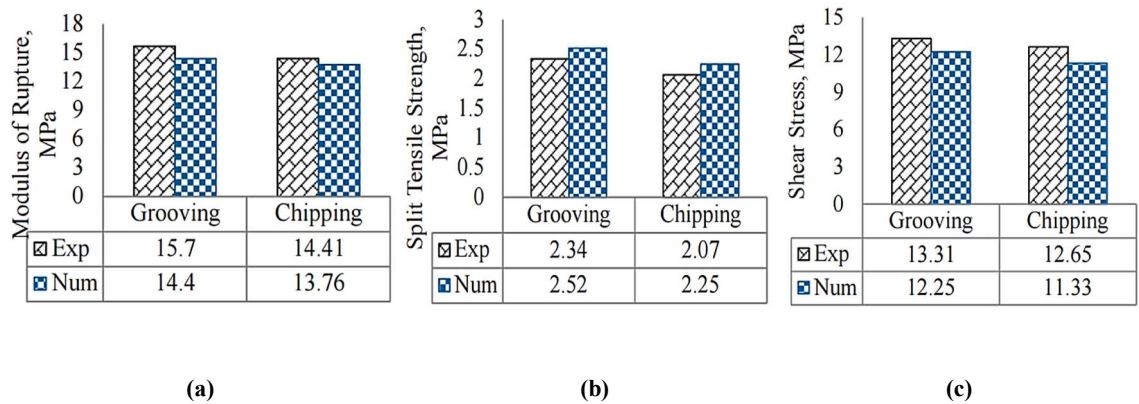
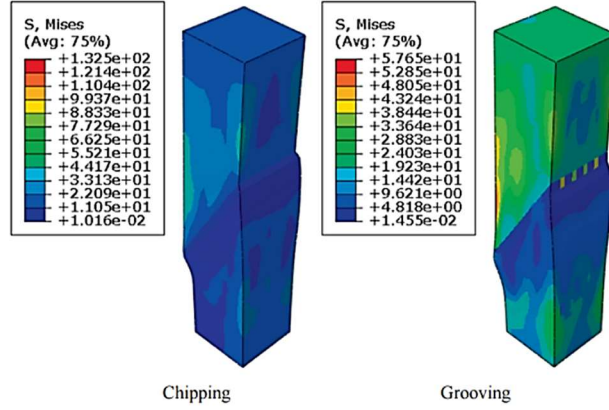


Figure 2.14 Experimental and numerical results: (a) Four-point bent; (b) splitting; (c) slant shear tests [48]





(c)

Figure 2.15 Deformed shape and stress distribution of composites: (a) Four-point bent; (b) splitting tensile; (c) slant shear tests [48]

Numerous research studies were performed to test the NC substrate's bonding strength with UHPC as a repair. However, it can be observed that there is a lack of data regarding the bond performance with different types of exposed aggregate concrete interface, the effect of different curing conditions, and the bond's performance under degradation to different exposure conditions. Furthermore, there is a knowledge gap that is related to numerical modeling. Therefore, this study investigates the effect of wet-dry and heat-cool cyclic exposure on the interfacial bond strength for the different concrete substrate surfaces. A non-linear finite element analysis is carried out to characterize the concrete substrate's interfacial properties and its effect on the bond strength between the two materials.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 General

In the present research, the effect of different key parameters were considered to holistically investigate the behavior of interfacial bond between different concrete substrates and UHPC overlay material. The studied parameters are summarized in Table 3.1. Three different substrate surface preparation methods (as cast, drill holes, and sandblasting) were considered together with two different curing conditions of the composite (water and heat curing) and two exposure conditions (laboratory environment and wet-dry/heat-cool cycles). For each specimen, four types of bond tests, i.e., slant shear, bi-surface shear, splitting tensile, and third-point flexural strength tests, were conducted. Hence, a total of 297 specimens were prepared as detailed in Table 3.2. All specimens are designated as X-Y, where X represents the curing conditions (W for the water curing and H for the heat curing). Y represents the exposure conditions (N for the laboratory environment and R for wet-dry and heat-cool cycles).

The following sections describe the details of experimental work such as materials used, mix design, formwork, surface preparation, curing regimens, the state of environmental exposure, and bond test methods.

Table 3.1 Parameters used in experiments studied

Parameter	Detailed approach
Strength of substrate	NC: Grade-50, SC: Grade-60 and SCC: Grade-80
Surface preparation of the substrate	As-cast (AC), drill hole (DH) and sandblast (SB)
Curing condition of the composite	Watering (W) and heating (H)
Exposure condition	Laboratory environment (N) and wet-dry and heat-cool cycles (R)

Table 3.2 Details of test specimens

Concrete substrate	Specimen ID	Surface condition			Total/ condition
		As cast (AC)	Drill hole (DH)	Sandblast (SB)	
NC	W-N	4 tests x 3 replicas	4 tests x 3 replicas	4 tests x 3 replicas	36
	H-N	4 tests x 3 replicas	4 tests x 3 replicas	4 tests x 3 replicas	36
	W-R	3 tests x 3 replicas	3 tests x 3 replicas	3 tests x 3 replicas	27
SC	W-N	4 tests x 3 replicas	4 tests x 3 replicas	4 tests x 3 replicas	36
	H-N	4 tests x 3 replicas	4 tests x 3 replicas	4 tests x 3 replicas	36
	W-R	3 tests x 3 replicas	3 tests x 3 replicas	3 tests x 3 replicas	27
SCC	W-N	4 tests x 3 replicas	4 tests x 3 replicas	4 tests x 3 replicas	36
	H-N	4 tests x 3 replicas	4 tests x 3 replicas	4 tests x 3 replicas	36
	W-R	3 tests x 3 replicas	3 tests x 3 replicas	3 tests x 3 replicas	27
Total/roughness		99	99	99	297

3.2 Material properties

3.2.1 Normal concrete substrate

The grade-50 normal concrete (NC) was prepared by using ordinary Portland cement (OPC, type I), coarse aggregate with maximum aggregate size and a specific gravity of 20 mm and 2.6, respectively, fine sand with finesses modulus of 2.5, water reducer (Arcrete D10) with a specific gravity of 1.12 at 20°C, superplasticizer (Fluidum PC 314) with a specific gravity of 1.1 at 20°C, and a water/cement ratio of 0.38. The mixture was obtained from a local precast concrete factory with the design mix proportions shown in Table 3.3.

Table 3.3 Mix proportions of the NC substrate (kg/m³)

Cement	Coarse aggregate	Fine aggregate	Water	Arcrete D10 (Arkaz)	Fluidum PC 314 (Arkaz)
400	1100	725	150	1.00	1.75

3.2.2 Screed concrete substrate

The grade-60 screed concrete (SC) was prepared by using ordinary Portland cement (OPC, Type I), micro silica with an average bulk density of 755 kg/m³, coarse aggregate with maximum aggregate size, and a specific gravity of 10 mm and 2.6, respectively, fine sand with finesses modulus of 2.5, superplasticizer (ADVA® 314) with a specific gravity of 1.106 at 20°C, plasticizer retarder (PR650-PLASTIMENT) with a specific gravity of 1.125 at 25°C, and a water/binder ratio of 0.34. The mixture was obtained from a local precast concrete factory with the mixing design proportions seen in Table 3.4.

Table 3.4 Mix proportions of the SC substrate (kg/m³)

Cement	Silica fume	Coarse aggregate	Fine aggregate	Water	ADVA314 (Grace)	PR650 (Sika)
425	25	1020	750	150	2.75	1.00

3.2.3 Self-compacted concrete substrate

The grade-80 self-compacted concrete (SCC) was prepared by selecting ordinary Portland cement (OPC, type I), micro silica with an average bulk density of 755 kg/m³, coarse aggregate with maximum aggregate size and a specific gravity of 20 mm and 2.6, respectively, fine sand with finesses modulus of 2.5, plasticizer-retarder (PR650 PLASTIMENT) with a specific gravity of 1.125 at 25°C, high-efficiency superplasticizer (ADVA® 314) with a specific gravity of 1.106 at 20°C, and a water/binder ratio of 0.31. The mixture was collected by a local concrete precasting factory with the proportions of the design mix in Table 3.5.

Table 3.5 Mix proportions of the SCC substrate (kg/m³)

Cement	Silica fume	Coarse aggregate	Fine aggregate	Water	ADVA314 (Grace)	PR650 (Sika)
465	35	976	750	150	5.50	1.00

3.2.4 Ultra-high performance concrete overlay

The UHPC mix proportion was chosen based on previous works [11]. It was prepared using a combination of cementitious materials such as Portland cement, micro-silica, fine dune sand, Glenium® 51 superplasticizer, water, and two different types of steel fibers. Straight

and hooked end fibers were used in a 1:1 weight ratio to improve the mixture's consistency. Straight fibers had a diameter of 0.2 mm, a length of 13 mm, and an aspect ratio of 65 with a tensile strength reaching 2500 MPa. While the hooked end fibers had a diameter of 0.35 mm, a length of 25 mm, and an aspect ratio of 71 with a tensile strength of 2500 MPa. Figure 3.1 and Table 3.6 indicate the proportion of the UHPC mix. Table 3.7 presents the chemical compositions of the binders used in UHPC mixtures.



Figure 3.1 Mixture components of UHPC

Table 3.6 Mix proportions of UHPC overlay materials (kg/m³) [11]

Cement	Micro-silica	Fine sand	Water	Steel fibers	Superplasticizer-Glenium® 51
900	220	1005	163	157	40

Table 3.7 Chemical compositions of cement and micro-silica (%)

Component	Cement	Silica fume
SiO ₂	20.5	88.66
Al ₂ O ₃	4.9	0.6
Fe ₂ O ₃	3.5	4.1
CaO	63.2	0.3
MgO	2	0.7
SO ₃	2.5	0.4
Loss on ignition (L.O.I.)	2.4	2.9
Insoluble residue (I.R.)	0.8	-
LSF	93.7	-
C ₃ S	53.6	-
C ₂ S	17.4	-
C ₃ A	6.9	-
C ₄ AF	10	-
Alkalies (Na ₂ O + 0.658 * K ₂ O)	0.5	-
C ₄ AF + 2C ₃ A + Cl	23.9	
Cl + P ₂ O ₅ + MnO + ZnO + Moisture	-	0.7

3.3 Preparation of specimens

3.3.1 Substrate casting and preparation

The summary of the preparation process of the substrate mixes is represented in Figure 3.2.

At the initial stage, the concrete substrate (NC, SC, and SCC) was cast into different molds (cube, beam, and cylinder). After 24 h, the specimens were de-molded and stored in a water

tank to undergo water curing for 28 days. Specimens were then put at room temperature 22 ± 2 °C up to 3 months. At the age of 3 months, substrate surfaces were prepared before casting of UHPC. Prepared surfaces using different techniques are shown in Figure 3.3 and 3.4.



(a) Preparing and mixing the materials



(b) Measuring the temperature and slump of the NC



(c) Measuring the temperature and slump of the SC



(d) Measuring the temperature and slump of the SCC



(e) Casting of the concrete substrates into different molds



(f) De-molding of the specimens



(g) Water curing of the concrete substrates (28 days)



(h) Specimens were then put at room temperature 22 ± 2 °C and relative humidity of 56% up to 3 months



(i) Cutting the cylinder with a water saw in accordance to slant shear and splitting tensile test methods

Figure 3.2 Process of preparing the concrete substrate mixture



Figure 3.3 Drill holes preparation; evenly spaced at 30 mm c/c distance and 5 ± 2 mm depth of the hole, and sandblast roughness; at 2 mm an average depth

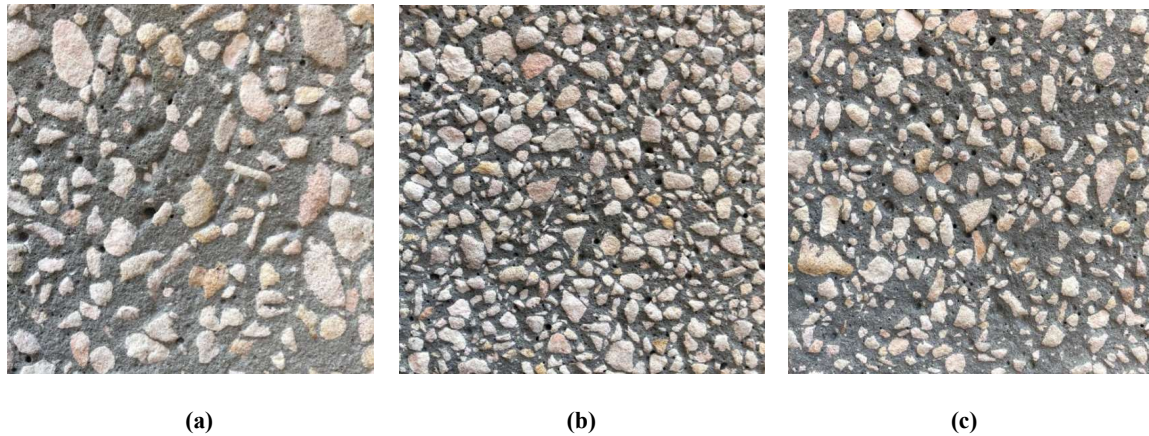


Figure 3.4 Sandblasting roughness: (a) NC; (b) SC; (c) SCC

3.3.2 UHPC casting and curing

After surface preparation, substrate specimens were moved to molds to cast the UHPC onto them. After 24 h of casting UHPC, the composite concrete specimens were de-molded and cured under two different conditions, such as water (W) and heat (H) curing. As for water curing (W), the specimens were placed back into the water tank at room temperature 22 ± 2 °C. On the other hand, for heat curing (H), the composite specimens could be sustained for 12 to 16 hours at 60 °C, immediately after de-molding. Finally, the specimens were cured for 28 days under respective curing regimes before testing. Figure 3.5 summarizes the UHPC casting and curing process.



(a) Cleaning the substrate interface



(b) Substrate positioned inside the mold before casting the overlay



(c) Casting of UHPC



(d) Covering of test specimens with plastic sheets



(e) Water curing condition (28-days)



(f) Heat curing condition (12-hour at 60 °C)



(g) The composites left to dry before testing

Figure 3.5 Process of preparing the composite of UHPC to different substrate concrete

3.3.3 Exposure condition

For exposure conditions, 81 water-cured specimens were put under coupled wet-dry and heat-cool cycles. These exposure conditions were selected based on literature-collected information [35], and details are given in Table 3.8. Following seven coupled cycles, the specimens were saturated in the water bath. By the end of wet-dry and heat-cool cycles, the specimens were kept to dry at room temperature 22 ± 2 °C before conducting the slant shear strength, bi-surface shear, and splitting tensile tests, as shown in Figure 3.6.



Figure 3.6 Process of wet-dry and heat-cool cycling exposures

Table 3.8 Procedure of wet-dry and heat-cool cycling exposures [35]

Cycle	Location	Temperature (°C)	Duration (h)
1	Oven drying	70-90	24
	Water bath	20-24	24
2	Oven drying	70-90	24
	Water bath	20-24	24
.	.	.	.
	.	.	.
.	.	.	.
	.	.	.
7	Oven drying	70-90	24
	Water bath	20-24	24
Saturation	Water bath	20-24	24

3.4 Mechanical properties

3.4.1 NC

The compressive and splitting tensile strengths were determined by testing cylinders (75 mm diameter and 150 mm height) in accordance with ASTM C39 [49] and ASTM C496 [50], respectively. The average values of compressive strength, split tensile strength, and modulus of elasticity, along with the NC substrate's fresh properties, are presented in Table 3.9. Figure 3.7 indicates the average stress-strain behavior of NC under compression.

Table 3.9 Fresh and hardened properties of the NC substrate

Property	Temperature “initial-30 Min” (°C)	Slump “initial-30 Min” (mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Modulus of elasticity (GPa)
Average value	27.3–26.5	245–175	61	4.9	36
Standard deviation	-	-	2.5	0.1	1.7
Coefficient of variation (%)	-	-	4.2	2.3	4.6

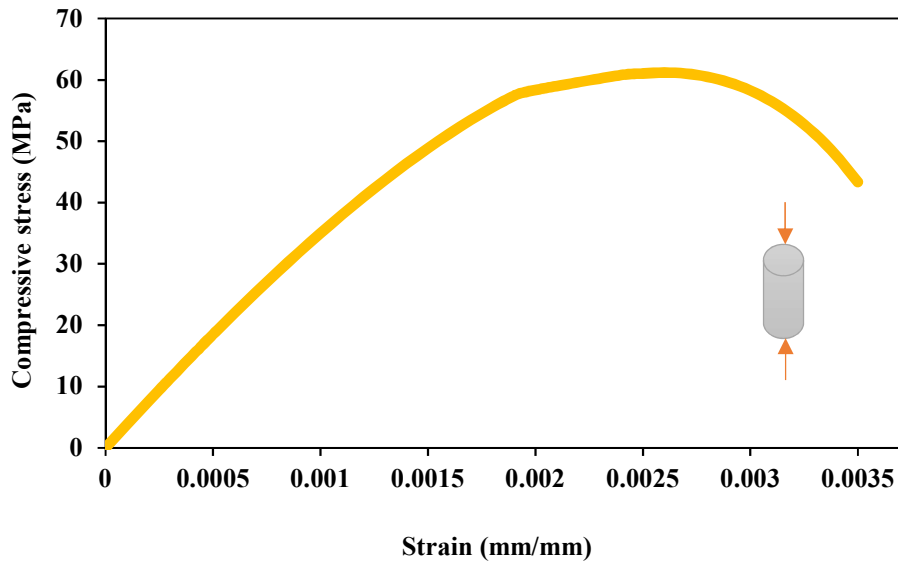


Figure 3.7 Uniaxial compression behavior of NC

3.4.2 SC

To ensure the freshly SC's quality, temperature and slump tests were implemented at “initial set and after 30 minutes” of the prepared mixtures. The average value was “22.6-23°C” and “230-205 mm” for temperature and slump test, respectively. The average values of compressive strength, split tensile strength, and modulus of screed concrete elasticity

are illustrated in Table 3.10, including the lowest, highest, standard deviation, and coefficient of variance values. Figure 3.8 represents the average compressive stress-strain behavior of the SC.

Table 3.10 Mechanical properties of the SC substrate

Property	Mix. value	Max. value	Average value	Standard deviation	Coefficient of variation (%)
Compressive strength (MPa)	65	69	68	1.5	2.2
Splitting tensile strength (MPa)	5	5.1	5.1	0.1	1.1
Modulus of elasticity (GPa)	37	39	38	0.4	1.1

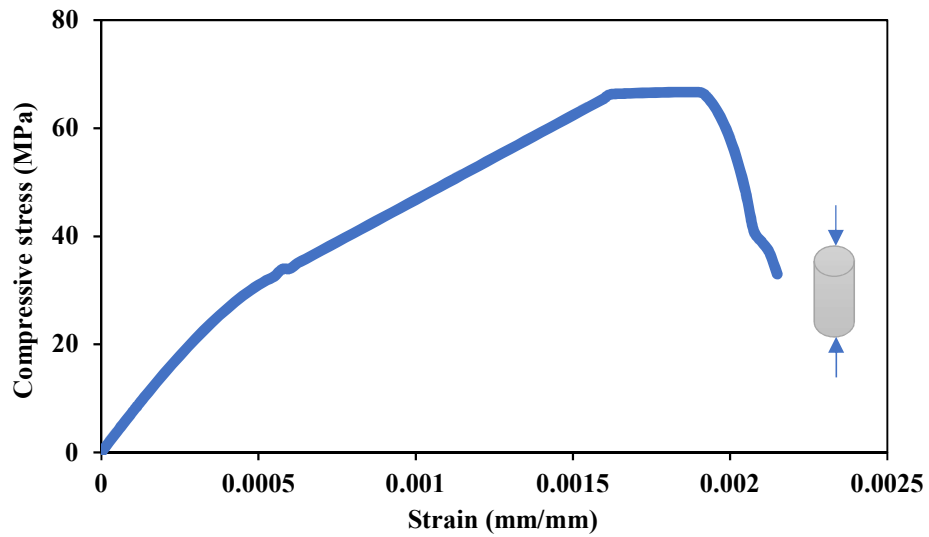


Figure 3.8 Uniaxial compression behavior of SC

3.4.3 SCC

Temperature and slump tests have been measured at the 'initial' and 'after 30 minutes' of the ready mix concrete to ensure the quality of a self-compacted concrete substratum. For the temperature and slump test, the average value was “27.3–26.5°C” and “245–175 mm.” The average values of compressive strength, split tensile strength, and modulus of SCC elasticity are shown in Table 3.11, including the standard deviation and coefficient of variation values. Figure 3.9 indicates the uniaxial behavior of the average SCC under compressive strength.

Table 3.11 Mechanical properties of the SCC substrate

Property	Compressive strength (MPa)	Splitting tensile strength (MPa)	Modulus of elasticity (GPa)
Average value	85	5.7	43
Standard deviation	2.3	0.1	0.6
Coefficient of variation (%)	2.7	1.5	1.3

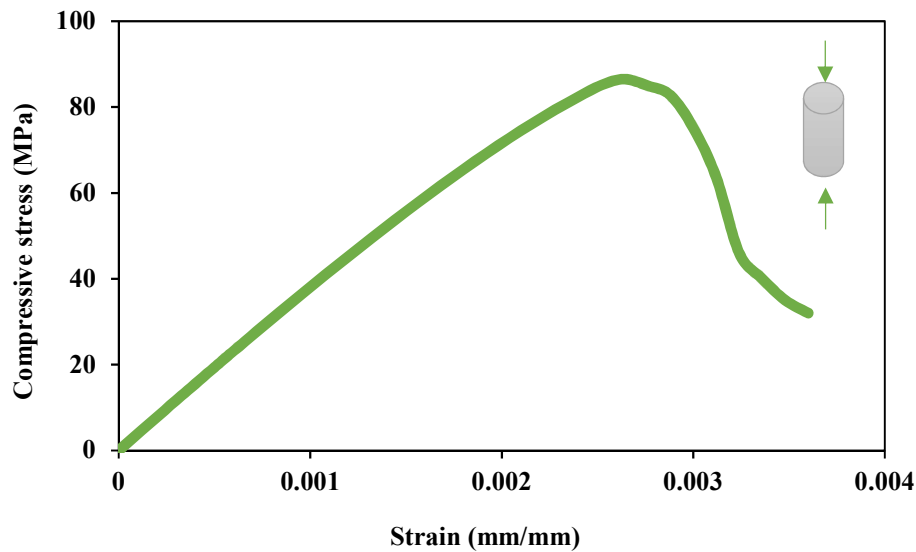


Figure 3.9 Uniaxial compression behavior of SCC

3.4.4 UHPC

The compressive strength tests for UHPC specimens were conducted on 50 mm cubes and 75 mm diameter and 150 mm high cylinders as assessed by ASTM C109 [51] and ASTM C39 [49], respectively. The tensile strength tests were performed on dog-boned specimens following ASTM D638 [52]. During compressive and tensile strength tests, the loading rate was 15 MPa/min and 0.5 mm/min, respectively. Figure 3.10 shows the test setup for compression and tensile tests. The average stress-strain curves under compression and tensile loading are shown in Figure 3.11a and b, respectively. From the test results, the average compressive strength of UHPC was found to be 156 MPa with 4.5% COV of the cubic specimen and 145 MPa with 3.6% COV of the cylindrical specimen. Moreover, modulus of elasticity, direct tensile strength, and Poisson ratio were calculated as 54 GPa, 6.7 MPa, and 0.2, respectively.

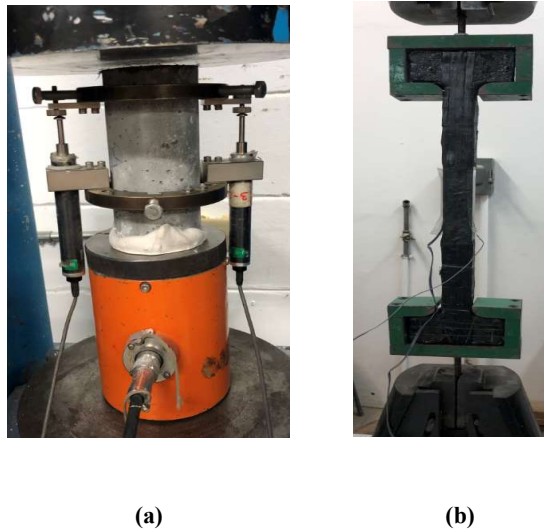


Figure 3.10 Test configuration (a) UHPC cylindrical uniaxial compressive test, (b) UHPC specimen dog-bone uniaxial direct tensile test (all measurements in mm)

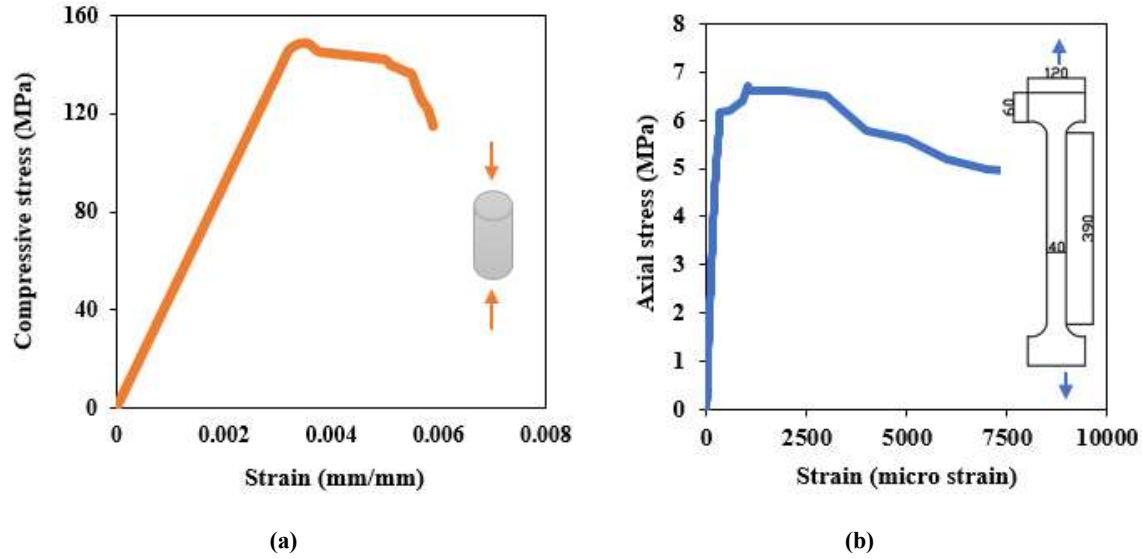


Figure 3.11 Uniaxial behavior of UHPC under compression (a) and tensile (b)

3.5 Bond strength tests

Four different bond strength tests were conducted in this study to assess the bond performance between UHPC and concrete substrates, namely, the splitting tensile, slant shear, bi-surface shear, and third-point flexural strength test. Standard test methods, sample fabrication, and test configurations are addressed herein.

3.5.1 Slant shear test

The slant shear tests were conducted according to ASTM C882 [53], in which the specimens are subjected to a combination of compression and shear stresses. To prepare a composite cylindrical specimen, the substrate was cast first as a cylindrical specimen. The substrate concrete samples of 75 x 150 mm were cut diagonally at 30° angle with a vertical plane by water saw to obtain a smooth surface. Before casting the overlay, the slant

interface was prepared for the drill hole and sandblast preparation. UHPC was then poured into the substrate samples, as shown in Figure 3.12. A 0.1 kN/s loading rate was applied using a Universal Testing Machine (UTM) of 3000 kN maximum capacity. The normal compressive stress (σ_n) and shear bond stress (τ_n) on the failure plane can be calculated according to Eqs. 3.1 and 3.2, respectively.

$$\sigma_n = \frac{P}{A_n} \cos^2(\alpha) \quad 3.1$$

$$\tau_n = \frac{P}{A_n} \cos(\alpha) \sin(\alpha) \quad 3.2$$

where P is the failure load (kN), A_n is the area of the inclined plane (mm^2) and α the angle of bonded inclined surface, i.e., 30° .

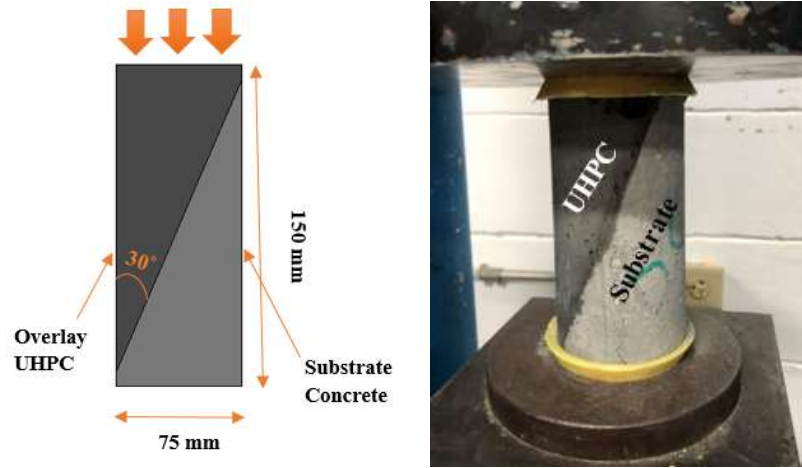


Figure 3.12 Configuration of the slant shear test setup

3.5.2 Bi-surface shear test

The bi-surface shear test method evaluates the bond strength under pure shear stresses [22], compared to the slant shear that, in addition to shear, considers the compressive force that increases the friction. Therefore, the direct shear test is more accurate to predict pure shear performance, is easy to create, and does not require special equipment to execute. The dimension of cubic specimens of 150 mm was constructed of the concrete substrate, and UHPC overlay is two-thirds and one-third of the length, respectively. The dimensions of the loading steel plates were 25 mm thick, 50 mm wide, and 150 mm long at the center of the test specimens, forming two shearing planes, one shear plane attached to the bonding interface, and that the other shear plane situated in the substratum concrete as defined in the Figure 3.13. The load rates were 0.1 kN/s, using UTM, and the bi-surface shear strength of the bond (v_{bs}) can be calculated according to Eq. 3.3.

$$v_{bs} = \frac{P}{2 b d} \quad 3.3$$

where P is the failure load (kN), b , and d are the width and depth of prisms (mm).

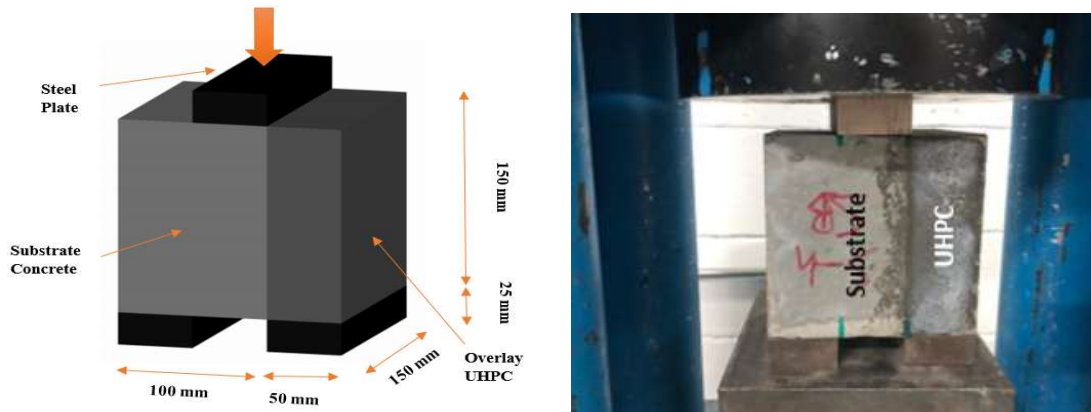


Figure 3.13 Configuration of the bi-surface test setup

3.5.3 Splitting tensile test

Tensile strength is one of concrete's critical and significant characteristics. Knowledge of its importance is needed for the design of concrete structural components. According to the ASTM C496 [50], a composite cylinder with a diameter of 75 mm and a height of 150 mm was prepared. The same slant specimen technique was applied to prepare the composite cylindrical specimen for split strength test with a split interface, consisting of one-half substrate concrete and one-half overlay UHPC, which is shown in Figure 3.14. The splits were loaded at the composite interface in the specimen's longitudinal direction with compression forces and UTM. The load rate was 0.5 kN / s. Eq. 3.4 was used to obtain the splitting tensile bond strength (f_{sp}).

$$f_{sp} = \frac{2P}{\pi A_s} \quad 3.4$$

where P is the maximum load at failure (kN), A_s is the area of the bond plane (mm^2).

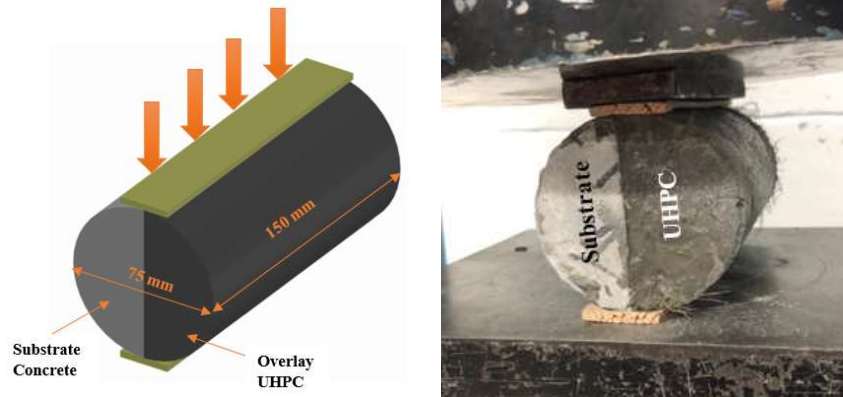


Figure 3.14 Configuration of the splitting tensile test setup

3.5.4 Third-point flexural test

The specimens for the two-point loading at the third points test were $150 \times 150 \times 500$ mm beams, in which half of the beam cast with the substrate and then repaired by UHPC overlay at a selected age. With an ASTM C78 third-point flexural test [41], a concrete joint's performance under tension was tested. Throughout this method, the failure occurs on the tension side inwards the middle third of the span length. Three linear variable displacement transducers (LVDTs) are used to estimate the maximum displacements at the middle of the beam 25mm near the substrate and overlay. The third one at the top of UHPC is to capture the slip near support, as shown in Figure 3.15. The loading rate was 0.1 kN/s, and the flexural bending strength (f_R) can be calculated according to Eq. 3.5.

$$f_R = \frac{3 P L}{4 b d^2} \quad 3.5$$

where P is the failure load (kN), L is the length of the supported span (mm), and b , d are the width and depth of specimen section (mm), respectively.

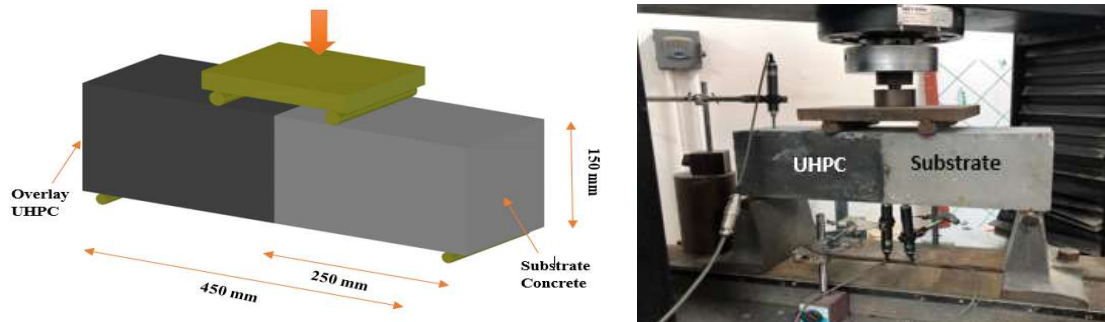


Figure 3.15 Configuration of the third-point flexural test setup

CHAPTER 4

RESULTS AND DISCUSSIONS FOR UHPC-NC

COMPOSITE SPECIMENS

4.1 General

The stresses corresponding to the failure load were recorded for all the tests, and the failure patterns were identified. According to the results, the performance of the bond was accessed. Since the failure normally occurs in the interfacial bonding zone, the failure strength is considered the composite specimen's bond strength. Alternatively, where the failure occurs in the concrete substrate, the bond strength is assumed to be higher than the substrate specimen's strength. In accordance with ACI 546-06 [1], the concrete repair guide defined the minimum acceptable direct shear and slant-shear bond strengths between the concrete substrate and the repair material. The minimum acceptable slant shear and direct shear bond strength values are listed in Table 4.1. Sprinkel and Ozyildirim [54] suggested the quantitative bond strength for indirect tensile stress, i.e., the bond strength exceeding 2.1 MPa, was labeled as "Excellent" (Table 4.2). Thus, an appropriate repair material for rehabilitating deteriorating concrete structures should be chosen based on the guide and assessment criterion of interfacial bond performance.

Table 4.1 Minimum acceptable requirements of bond strength (ACI 546-06) [1]

Description	Bond strength (MPa) at 28-days
Slant shear bond	14-21
Direct shear bond	2.8-4.1

Table 4.2 Quantitative bond performance for tensile bond strength for Splitting tensile and Third-point flexural Sprinkel and Ozyildirim (2000) [54]

Bond criteria	Bond strength (MPa)
Excellent	≥ 2.1
Very good	1.7-2.1
Good	1.4-1.7
Fair	0.7-1.4
Poor	0-0.7

4.2 Slant shear test results

The bond strength for slant shear was obtained by dividing the failure load by the bond area Eqs. 3.1, and 3.2. In general, the typical failure modes may be classified into four distinct types, namely, pure interface failure (A), interface and partial concrete substrate failure (B), interface failure and substrate fracture (C), and substratum failure (D) as shown in Figure 4.1. The overall test results, including the average bond strength, standard deviation (SD), coefficient of variation (COV) values, and failure mode corresponding to various specimen configurations, are illustrated in Table 4.3. Figure 4.2 shows the bond's performance across distinct surface preparation, curing conditions, and the effect of coupled cyclic exposure of wet-dry and heat-cool.



(a)

(b)

(c)

(d)

Figure 4.1 Failure mode under slant shear test. a: pure interface failure (A), b: interface failure and partially substrate crack (B), c: interface failure and substrate fracture (C), d: concrete substrate fracture (D)

Table 4.3 Summary of slant shear test results

Surface preparation	Specimen ID	σ_n (MPa)	SD (MPa)	τ_n (MPa)	SD (MPa)	COV (%)	Failure mode (%)
As cast	W-N	10.89	1.59	18.86	2.75	14.6	A:100
	H-N	11.71	0.42	20.29	0.73	3.6	A:100
	W-R	9.14	0.18	15.83	0.31	2.0	A:100
Drill holes	W-N	12.82	2.21	22.21	3.84	17.3	C:100
	H-N	12.47	0.88	21.60	1.52	7.0	A:100
	W-R	9.72	0.30	16.83	0.52	3.1	A:66.7, B:33.3
Sandblast	W-N	14.57	0.95	25.23	1.65	6.5	D:100
	H-N	14.88	0.88	25.77	1.53	5.9	D:100
	W-R	15.00	0.87	26.00	1.51	5.8	A:66.7, B:33.3

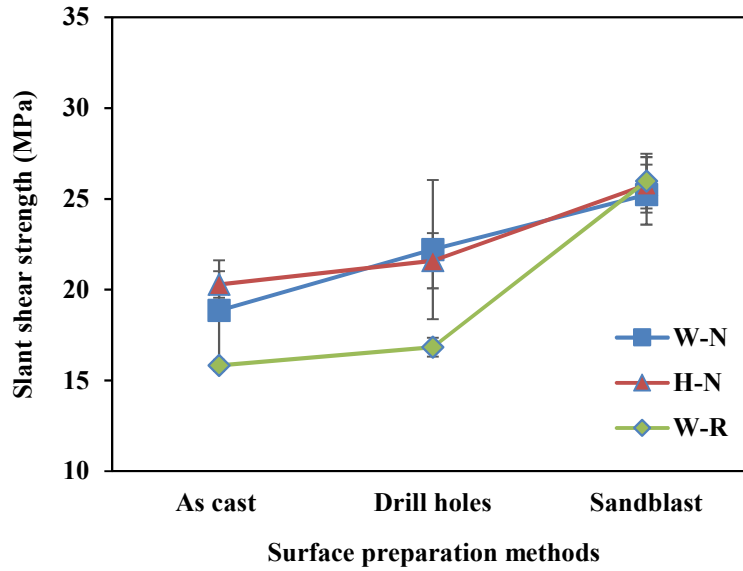


Figure 4.2 Evaluation of the average bond strength under slant shear test

For the group (W-N) with no surface preparation, the specimen failed in a pure interface (A), with an average shear stress of 18.86 MPa, SD of 2.75 MPa, and COV of 14.6%, as shown in (Figure 4.1a and Table 4.3). As for UHPC-NC with substrate roughness, the failure occurred in mixed interface plane and substrate fracture (C) with drill hole preparation (Figure 4.1c), while for sandblast composites, the failure falls within the substratum failure (D), which indicate a strong bond strength (Figure 4.1d). Moreover, Figure 4.2 illustrated that the surface roughened by drill hole and sandblast exhibits good bond strength of almost 18% and 34% higher, respectively, relative to the as cast surface.

For the group (H-N) with as cast, the specimen failed in a pure interface (A), with an average shear stress of 20.29 MPa, SD of 0.7 MPa, and COV of 3.61%, as shown in (Figure 4.1a and Table 4.3). As for UHPC-NC with drill hole preparation, the failure occurred similar to the as cast surface (A), while for sandblast roughness, the failure occurred within the substratum concrete (D), which similar to (W-N) group and indicated a strong bond

strength (Figure 4.1d). Figure 4.2 showed that the surface roughened by drill hole and sandblast exhibits good bond strength of approximately 6% and 27%, respectively, relative to the as cast surface.

For the group (W-R) with as cast surface, the specimen failed in a pure interface (A), with an average shear stress of 15.83 MPa, SD of 0.31 MPa, and COV of 2.0%, as shown in (Figure 4.1a and Table 4.3). For the surface preparation with a drill hole (DH) and sandblast (SB), 33.3% of UHPC-NC composite failed in both interfacial zone and partially cracks of the substrate (B), as shown in Figure 4.1b. However, 66.7% of composite failed in pure interface failure (A), as shown in Figure 4.1a. The average failure stress of UHPC-NC with (DH) treatment was found to be 16.83 MPa with a standard deviation and coefficient of variation of 0.52 MPa and 3.1%, respectively (Table 4.3). However, the average value of failure stress increased to 26 MPa for the specimen with (SB) preparation. This indicates that even with the effect of wet-dry and heat-cool cyclic exposure (W-R), the composite (UHPC-NC) with sandblasting treatment showed the highest performance of bond with the average 2% increase of the normal exposure condition (Figure 4.2). Besides, Figure 4.2 showed that the surface roughened by drill hole and sandblast exhibits a good bond strength of approximately 6% and 64%, respectively, relative to the as cast surface.

From the slant shear test results, it can be observed that for specimens with different curing conditions (W-N and H-N), the bond strength results were very close for all various surface preparation methods in which the maximum relative change is 7.5% (Table 4.3). As for the composite specimen exposed to coupled cycles of wet-dry and heat-cool (W-R), the average bond strength (UHPC-NC) went to decrease to 16% and 24% of AC and DH surfaces of the normal condition (W-N), respectively (Figure 4.2). In contrast, sandblasted

specimens' slant shear strength increased to 2% of the normal exposure condition. The possible reason is that the enhancement of the combined normal and shear bond performance might be generally accounted for from the coupled mechanisms of higher mechanical interlocking and improvements of the UHPC material at a certain degree of temperature from wet-dry/heat-cool cycles. It is worth noting that the slant shear test may lead to overestimation of the bond strength since combined with compressive force and due to friction [26]. At the normal water curing conditions (W-N), the bond strength variability evaluated by the coefficient of variation (COV) was higher when the concrete specimens were roughened using the drill hole technique by 2.7% compared to as cast specimens.

In comparison, the COV of the sandblasted specimens was lower by almost 8%. It is noted that the UHPC-NC composite with sandblasting treatment represented the smaller error bars and consistent bond strength even after repeated cycles, as seen in Figure 4.2. This can be attributed to the possibility that sandblasting surface preparation improved the adhesion between the substrate and the UHPC overlay.

The ACI concrete repair guide (ACI 546-06, [1]) specified a minimum acceptable bond strength of 14-21 MPa for the slant shear test performed at 28 days in the selection of suitable repair materials. Based on these requirements, it's obvious that almost all the results met or even exceed the range provided by ACI. As for surface with no preparation (AC), the recorded results fall into the range provided by ACI requirements. Consequently, for the substrate's surface preparation with DH and SB, the results exceeded ACI's acceptable range. Even after cyclic exposure of UHPC-NC composite specimen, the sandblasted samples exceed the requirements. It is concluded that UHPC materials used as

an overlay to the normal concrete substrate (NC) shall be a suitable repair and fulfill the specified requirements by ACI even after degradation of wet-dry and heat-cool repeated cycles.

4.3 Bi-surface shear test results

From the bi-surface shear test, failure load was observed, and the bond strength under pure shear stress has been calculated using Eq. 3.3. In general, the typical failure modes can be divided into three distinct forms, namely adhesive failure (A), mixed failure of the interfacial zone and concrete substrate (B), and cohesive failure (C), as shown in Figure 4.3. The overall test results related to the bond strength, average shear stress, standard deviation (SD), coefficient of variation (COV), and the mode of failure corresponding to various specimen configurations are listed in Table 4.4. Figure 4.4 shows the bond's performance across various surface roughness, curing conditions, and after coupled cyclic exposure of wet-dry and heat-cool cycles.

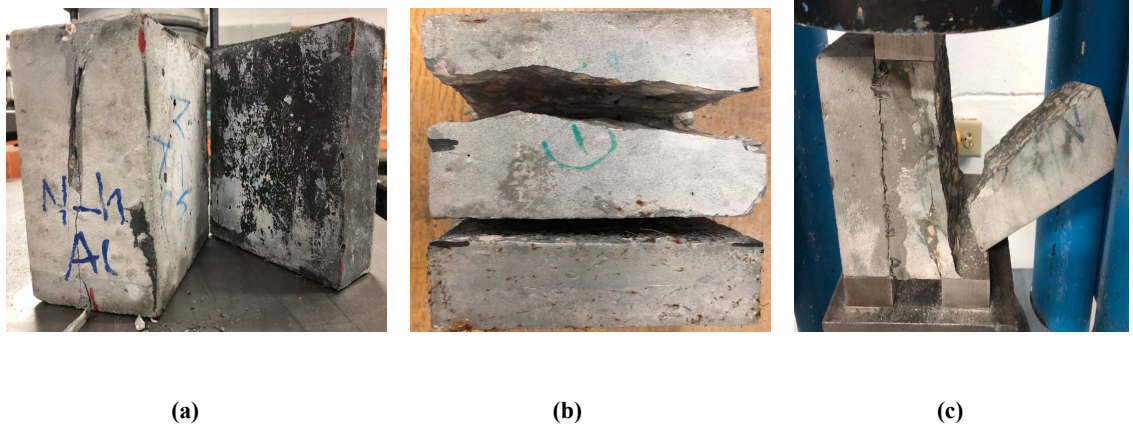


Figure 4.3 Failure mode under bi-surface shear test. a: interfacial zone and partially substrate failure (Adhesive failure: A), b: mixed failure of the precast and interfacial zone (Mixed failure: B), c: precast failure (Cohesive failure: C)

Table 4.4 Summary of bi-surface shear test results

Surface preparation	Specimen ID	v_{bs} (MPa)	SD (MPa)	COV (%)	Failure mode
As cast	W-N	4.13	0.16	4.0	C
	H-N	4.90	0.22	4.6	A
	W-R	3.47	0.17	5.0	A
Drill holes	W-N	6.86	0.20	2.9	C
	H-N	5.70	0.22	3.9	C
	W-R	5.22	0.18	3.4	C
Sandblast	W-N	5.63	0.07	1.2	B
	H-N	5.14	0.24	4.6	B
	W-R	4.45	0.33	7.3	B

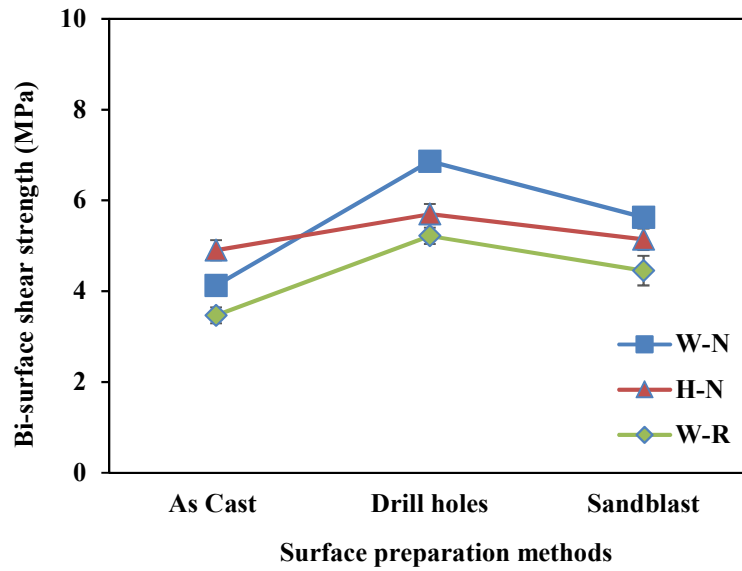


Figure 4.4 Evaluation of the average bond strength under bi-surface shear test

For the group (W-N) with no surface preparation, the specimen failed in precast concrete (C), with an average shear stress of 4.13 MPa, SD of 0.16 MPa, and COV of 4%, as shown

in (Figure 4.3c and Table 4.4). Similarly, in the UHPC-NC with drill hole surface preparation, the failure occurred in precast concrete (C). In contrast, the mixed failure of the interfacial zone and concrete substrate was displayed with sandblasting preparation shown in Figure 4.3b. The present study findings are generally in agreement, and even better bond strength with previous research Farzad et al. (2019) [14], i.e., the average failure stress with AC interface increased to 39% of the present study. Furthermore, Figure 4.4 presented that the surface roughened by sandblasting and drill hole exhibits good bond strength of almost 36% and 66% higher, respectively, relative to the as cast surface.

For the group (H-N) with as cast, the specimen failed in the interfacial zone and partially substrate cracks (A), with an average shear stress of 4.90 MPa, SD of 0.2 MPa, and COV of 4.55%, as shown in (Figure 4.3a and Table 4.4). As for UHPC-NC with substrate roughness, the failure occurred in the mixed failure of the interfacial zone and concrete substrate (B) handled by sandblasting treatment as shown in Figure 4.3b, while for drill hole composites, the failure occurred within the precast concrete (C) showed on Figure 4.3c. These results are consistent with the experimental findings from the previous study Semendary and Svecova (2020) [15], i.e., the bond strength of the sandblast (SB) composite (UHPC-NC) was 3.6 MPa, and the failure occurred in the mixed failure of the interfacial zone and concrete substrate. Figure 4.4 displayed that the surface roughened by sandblasting and drill hole exhibits good bond strength of approximately 5% and 16%, respectively, relative to the as cast surface.

For the group (W-R) with as cast, the specimen failed in the interfacial zone and partially substrate cracks (A), with an average shear stress of 3.47 MPa, SD of 0.2 MPa, and COV of 5.02%, as shown in (Figure 4.3a and Table 4.4). As for UHPC-NC with substrate

roughness, the failure occurred in the mixed failure of the interfacial zone and concrete substrate (B) handled by sandblasting treatment as shown in Figure 4.3b, while for drill hole composites, the failure occurred within the precast concrete (C) showed on Figure 4.3c. Despite the slight reduction of bond strength after coupled cyclic exposure, the failure mode is always the same as the (H-N) composite. Figure 4.4 displayed that the surface roughened by sandblasting and drill hole exhibits good bond strength of approximately 28% and 50%, respectively, relative to the as cast surface.

From the bi-surface shear test results, it can be observed that for the specimen with different curing conditions (W-N and H-N), the bond strength results under heat curing conditions were increased to 18.6% with no surface preparation (AC). However, by increasing the roughness to DH and SB, the bond strength underwater condition increased by 20.4% and 9.5%, respectively, compared to the composite heat curing condition (H-N) (Table 4.4). The maximum bond strength of the UHPC-NC composite was observed with substrate handled by drill hole preparation under bi-surface shear test, which is the opposite of the slant shear test method. The bi-surface shear with maximum bond strength by drill hole preparation thus, because of the compressive force act exactly parallel to the surface treatment and with the aid of mixed steel fibers and finer cementations materials of the overlay. As a result, an interfacial failure is predicted since the concrete substrate's strength is typically greater than the bond strength. The average bond strength of the UHPC-NC composite specimen falling under coupled cycles of wet-dry and heat-cool (W-R) went to decrease to 16%, 21%, and 24% of AC, DH, and SB surface preparation, respectively, of the normal condition (W-N) as seen in Figure 4.4. It is noted that the bond strength between the UHPC overlay and the normal concrete substrate is always good even after repeated

cyclic exposure. Thus the UHPC, with its superior properties and mechanical strength, is an outstanding repair material. At the drill hole treatment, the bond strength variability evaluated by COV was lower by 1.1%, 0.7%, and 1.6% of (W-N), (H-N), and (W-R) categories, respectively, compared to the as cast specimens.

According to the ACI concrete repair guide (ACI 546-06, [1]), repair materials used as an overlay intend to have a specified minimum acceptable bond strength of 2.8-4.1 MPa at 28 days for the direct shear test. Based on this standard, it's clear that almost all the bond strength results reported by the bi-surface shear test exceed the range displayed by ACI specifications. As for the as cast surface (AC), the measured results exceed the range specified by ACI standard, but the bond strength was very critical and close to the limit after repeated cyclic exposure. On the other hand, the UHPC-NC composites with drill hole and sandblast surface roughness of the substrate, including the composite with repeated cyclic exposure (W-R), exceeded the acceptable range specified by ACI. It is concluded that even after degradation of wet-dry and heat-cool repeated cycles, the UHPC material used as an overlay of the normal concrete substrate (NC) shall serve as excellent repairs materials and comply with the required ACI requirements.

4.4 Splitting tensile test results

From the split tensile test, failure load was observed, and the tensile stress has been calculated using Eq. 3.4. Three forms of failure, pure interface failure (A), interface and partial concrete substrate failure (B), and the interface failure and substrate fracture (C), have occurred in various tested specimens Figure 4.5. The average bond strength, standard

deviation (SD), coefficient of variation (COV) values, and failure mode corresponding to different specimen configurations presented in Table 4.5. Figure 4.6 shows the bond's performance across different surface preparation, curing conditions, and the effect of exposure conditions after wet-dry and heat-cool repeated cycles.

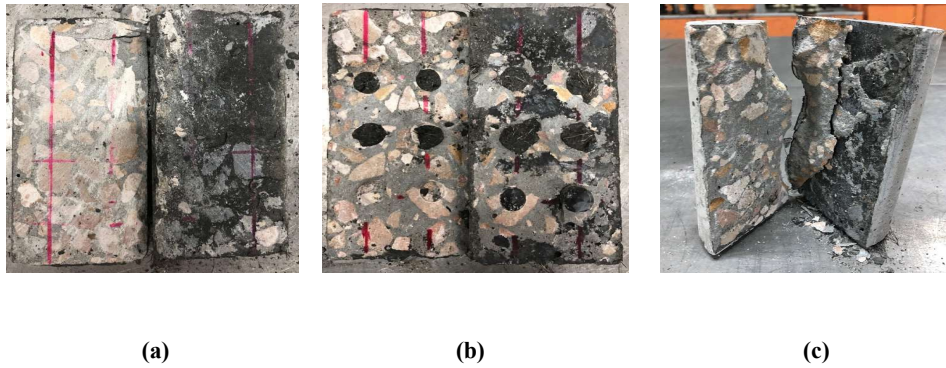


Figure 4.5 Failure modes under splitting tensile test. a: pure interface failure (A), b: interface and partial concrete substrate failure (B), c: interface failure and substrate fracture (C)

Table 4.5 Summary of splitting tensile test results

Surface preparation	Specimen ID	f_{sp} (MPa)	SD (MPa)	COV (%)	Failure mode (%)
As cast	W-N	1.85	0.19	10.3	A:100
	H-N	1.97	0.15	7.6	A:100
	W-R	1.26	0.15	11.9	A:66.7, B:33.3
Drill holes	W-N	4.2	0.32	7.5	C:66.7, B:33.3
	H-N	3.99	0.68	17.1	C:66.7, B:33.3
	W-R	2.59	0.45	17.3	B:100
Sandblast	W-N	4.62	0.43	9.3	C:100
	H-N	4.43	0.40	8.9	C:66.7, B:33.3
	W-R	3.95	0.63	15.9	C:100

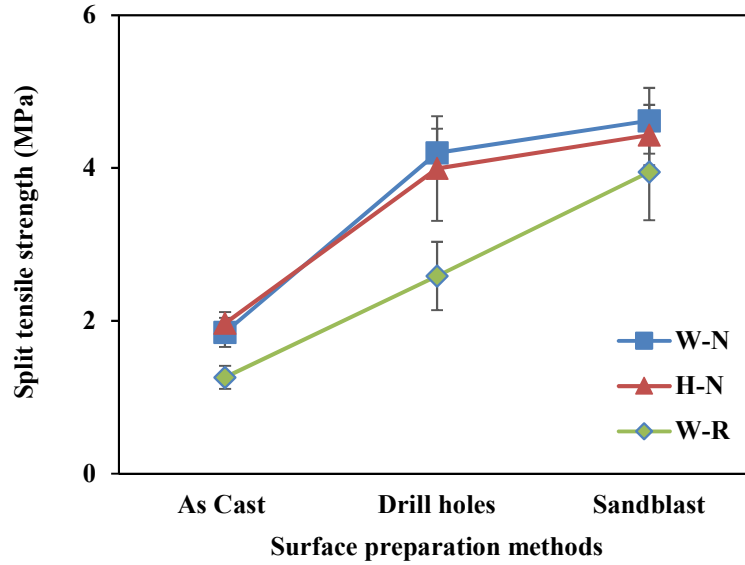


Figure 4.6 Evaluation of the average bond strength under splitting tensile test

For the group (W-N) with no surface preparation, the specimen failed in a pure interface (A), with average failure stress of 1.85 MPa, SD of 0.19 MPa, and COV of 10.3%, as shown in (Figure 4.5a and Table 4.5). As for UHPC-NC with substrate roughness, the failure occurred in the mixed interface plane and substrate fracture (C), which indicates a strong bond strength with the substrate that handling a surface roughness (Figure 4.5c). Furthermore, Figure 4.6 showed that the surface roughened by drill hole and sandblast exhibits excellent bond strength of almost 125% and 150% higher, respectively, relative to the as cast surface. Researchers [34], [36], [41] agreed that the failure occurred in the substrate fracture when the surface was roughened by the drill hole and sandblast between UHPC-NC composite specimens.

For the group (H-N) with as cast surface, the specimen failed in a pure interface (A), with average failure stress of 1.97 MPa, SD of 0.15 MPa, and COV of 7.6%, as shown in (Figure 4.5a and Table 4.5). As for UHPC-NC with substrate roughness, the failure occurred in the

mixed interface plane and substrate fracture (C), which similar to (W-N) group (Figure 4.5c). Figure 4.6 showed that the surface roughened by drill hole and sandblast exhibits excellent bond strength of approximately 100% and 125%, respectively, relative to the as cast surface. These results are consistent with the experimental findings from the previous study Al-Osta et al. (2017) [42], i.e., the bond strength of the sandblast (SB) composite (UHPC-NC) was 3.73 MPa, with the properties of the same materials of UHPC strength but less concrete substrate. It is concluding that increasing the strength of substrate normal concrete (NC) increases the bond strength to 24% and 19% for W-N and H-N composites, respectively.

For the group (W-R) with as cast surface, the specimen failed in a pure interface (A), with average failure stress of 1.26 MPa, SD of 0.15 MPa, and COV of 11.9%, as shown in (Figure 4.5a and Table 4.5). As for UHPC-NC with drill holes substrate preparation, the failure occurred in both interfacial zone and partially cracked of the substrate (B), which different from (W-N and H-N) groups (Figure 4.5b). However, the failure displayed in mixed interface plane substrate concrete fracture (C) in the treatment with the sandblast method (Figure 4.5c). Thus, indicate that even the bond strength decreased to 13% from normal exposure condition, the failure still strong enough between the (UHPC) overlay and concrete substrate (NC). Figure 4.6 showed that the surface roughened by drill hole and sandblast exhibits a strong bond strength of approximately 100% and 200%, respectively, relative to the as cast surface.

From the split tensile test results, it can be observed that for the specimen with different curing conditions (W-N and H-N), the bond strength results were very close, corresponding to various surface preparation methods with the maximum relative change of 6% (Table

4.5). Thus, as indicated on the slant shear test results, the curing condition does not seem to vary the bond strength compared to the surface roughness. As for the composite specimen undergoing wet-dry and heat-cool coupled cycles (W-R), the average bond strength (UHPC-NC) went to decrease to 32%, 38%, and 15% of AC, DH, and SB surfaces, respectively, of the normal condition (W-N) as seen in Figure 4.6. It is worth mentioning that, even after repeated cyclic exposure and with the treated surface, the COV only increased by 5.4% and 4% of the DH and SB, respectively, compared to the as cast surface. The error bars for the specimens with drill holes and sandblasted treatment were nearly higher than the smooth surface (AC) due to increased friction on the NC substrate. Thus, the UHPC materials sustain a significant bond strength to be used as an overlay to NC under various exposure conditions.

Comparing the recorded split tensile strength of the UHPC-NC composites with the quantitative bond strength quality suggested by Sprinkel and Ozyildirim [54], it's obvious that almost all the bond strength attained by drill hole and sandblast composites is classified as "Excellent" since the bond strength exceeds 2.1 MPa. Similarly, even after the degradation of roughened UHPC-NC composites under repeated cyclic exposure, the bond performance is labeled under an "Excellent" category. In addition, the as cast sample obtained a bond performance value in the range 1.7-2.1 MPa that could be categorized as "very good" for (W-N and H-N) composites. On the other hand, the results obtained from (W-R), the bond strength could be considered "fair" at the range of 0.7-1.4 MPa, which can be rejected. Thus the surface should be roughened to accommodate the predictable degradation. As a result, the splitting tensile test is reliable compared to the slant shear and bi-surface shear tests.

4.5 Third-point flexural test results

From the third-point flexural test, failure load was observed, and the modulus of the rupture has been calculated using Eq. 3.5. Three forms of failure interfacial zone failure (A), interface and partial concrete substrate failure (B), and interface failure and substrate fracture (C) have occurred in various tested specimens Figure 4.7. The average bond strength, standard deviation (SD), coefficient of variation (COV) values, and failure mode corresponding to different specimen configurations presented in Table 4.6. Figure 4.8 shows the performance of the bond across different surface preparation and curing conditions.

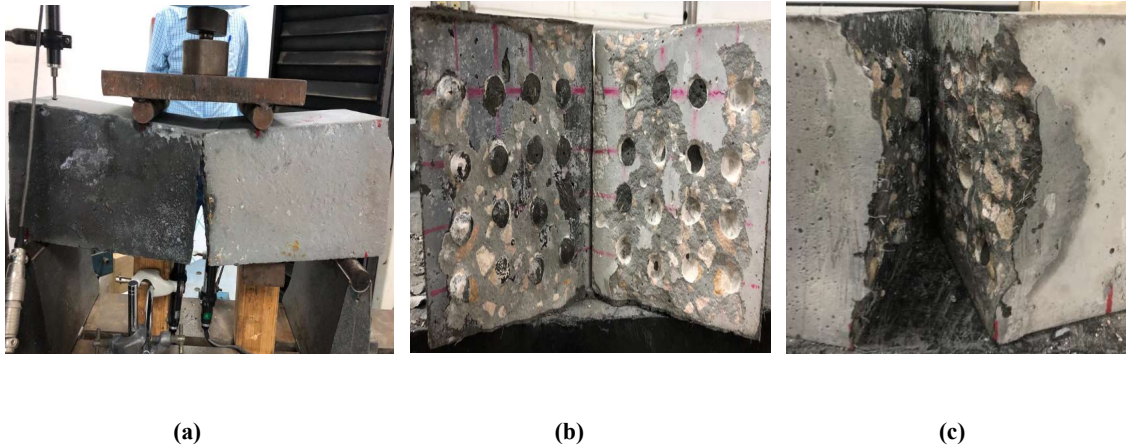
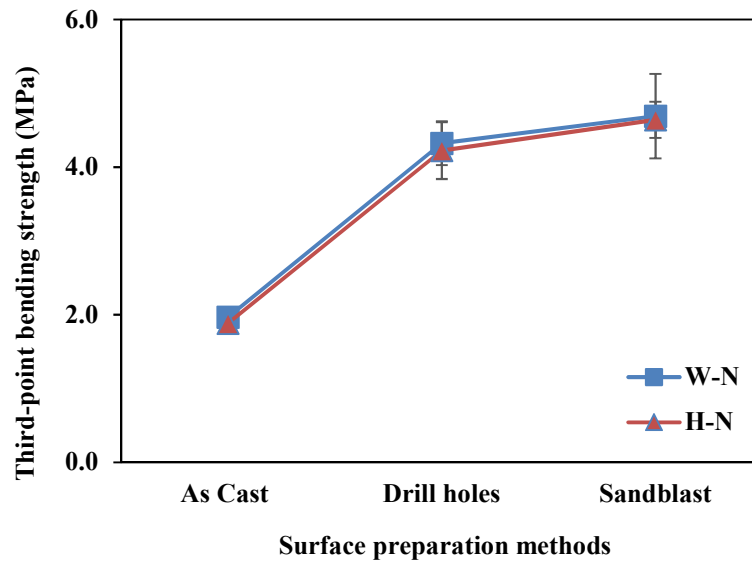


Figure 4.7 Failure mode under third-point flexural test. a: interfacial zone failure (A), b: interfacial zone and partially substrate crack (B), c: interfacial zone and partially substrate fracture (C)

Table 4.6 Summary of third-point flexural test results

Surface preparation	Specimen ID	f_R (MPa)	SD (MPa)	COV (%)	Failure mode
As cast	W-N	1.97	0.04	2.2	A
	H-N	1.89	0.09	4.6	A
Drill holes	W-N	4.32	0.30	6.9	C
	H-N	4.22	0.39	9.1	B
Sandblast	W-N	4.69	0.57	12.2	C
	H-N	4.64	0.25	5.3	B

**Figure 4.8 Evaluation of the average bond strength under third-point flexural test**

For the group (W-N) with no surface preparation, the specimen failed in the interfacial zone (A), with average failure stress of 1.97 MPa, SD of 0.04 MPa, and COV of 2.2%, as shown in (Figure 4.7a and Table 4.6). As for UHPC-NC with substrate roughness, the failure occurred in the mixed interfacial zone and substrate fracture (C), which indicates a strong bond strength with the substrate handling a drill hole and sandblasted treatment

(Figure 4.7c). The variability in the bond strength calculated by the COV was increased by 4.7% and 10% for DH and SB, respectively. Figure 4.8 showed that the surface roughened by drill hole and sandblast exhibits excellent bond strength of approximately 120% and 138% higher, respectively, relative to the as cast surface.

For the group (H-N) with as cast surface, the specimen failed in a pure interface (A), with average failure stress of 1.89 MPa, SD of 0.09 MPa, and COV of 4.6%, as shown in (Figure 4.7a and Table 4.6). As for UHPC-NC with substrate roughness, the failure occurred in the interface plane and partially substrate cracks (B), which similar to (W-N) group (Figure 4.7b). Figure 4.8 showed that the surface roughened by drill hole and sandblast exhibits excellent bond strength of almost 125% and 145%, respectively, relative to the as cast surface.

From the third-point flexural test results, it can be observed that for the specimen with different curing conditions (W-N and H-N), the bond strength results were very close for various surface preparation methods with the maximum relative change of 4.4%. Consequently, even with the SB surface, the error bars were very small, as represented in Figure 4.8. However, the UHPC-NC composites with the watering condition (W-N) indicated a strong bond compared to heat curing (H-N). The failure occurred in both the interfacial zone and partially substrate cracks. Regardless of the limited research studies of the UHPC-NC under the third-point flexural test, Farzad et al. (2019) [14] obtained that the average failure stress with as cast interface was 2.8 MPa and pure interface failure. It is worth noting that the substrate with sandblasting preparation showed the highest bond strength of the UHPC-NC composite, which is very close to the substrate's tensile strength.

The third-point flexural test's recorded bond strength could be classified in accordance with Sprinkel and Ozyildirim [54]. From the test results, it is clear that almost all the bond strength of UHPC-NC composite that was handled with roughened surface were labeled as "Excellent." Furthermore, the UHPC-NC composites with no surface treatment were obtained a bond performance value that could be classified as "very good" under watering and heating curing conditions, which were similar to the results reported by the split tensile test method.

4.6 Effect of wet-dry/heat-cool repeated cycles

The primary aim of this section is to discuss the effects of the treatment of the exposed concrete surface and the effect of wet-dry/heat-cool cyclic exposure of the UHPC-NC interface. The specific variations in the interfacial bond strength induced by the different types of bond tests performed in this study are summarized in Figure 4.9. It indicates that the bond strengths observed in the splitting tensile, slant shear, and bi-surface shear tests are highly sensitive to the NC substrate surface treatment method. The typical scenario is that the repeated and excessive curing temperature leads to a reduction in the interfacial bond properties related to the rapid expansion of the UHPC shrinkage.

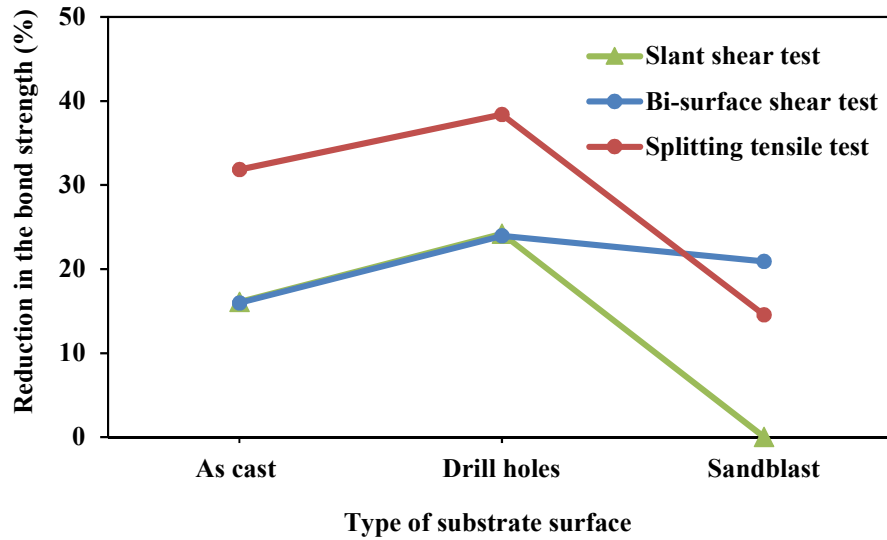


Figure 4.9 The reduction of the bond due to the effect of repeated cyclic exposure condition

Compared to the AC surface, the highest reduction in bond strength experienced in the splitting tensile test was roughly 32%. It is noteworthy to mention that the AC samples were still lower than those with surface treatment and decreased after repeated cyclic exposure. This proves that the AC samples cannot be used in the splitting tensile test. The findings of both slant shear and bi-surface shear tests have decreased bond strength by almost 16% for such AC samples. Compared to the DH surface, the highest decrease in bond strength resulted from a splitting tensile test of approximately 38%. The probable scenario is that this interface's presence in the holes resulted in a decrease in the rough surface area and reduced the indirect tensile strength of the UHPC-NC interface.

On the other hand, the findings of both slant shear and bi-surface shear tests have decreased bond strength by almost 24%. This may be due to further mechanical interlocking by the UHPC filling of the NC substrate holes. Compared to the SB surface, the bi-surface shear test showed the highest bond strength decrease of nearly 21%.

However, there is no reduction in bond strength experienced in the slant shear test with sandblasting surface preparation. This is due to the normal stress, which increases the friction between the contact layer in the slant shear test. It is noteworthy to address that the splitting tensile test results showed the highest decrease in bond under the repeated cyclic exposure of the UHPC-NC interface. This confirmed that the splitting tensile test was the most reliable test method to satisfy the minimum acceptable design specifications. In summary, SB, the most appropriate methods to enhance the interfacial bonding performance and the reliable consistency of repaired NC frameworks, are the necessary roughing preparations for the substrate surface.

4.7 Mechanisms of the bond

Adhesion and aggregate interlocking mechanisms may act as a function of surface roughness by increasing surface roughness, enhancing aggregate interlocking, and improving the chemical interaction between the NC aggregate and the UHPC that validates the concept cohesion term as a mechanism of surface roughness [55]. The bond strength mechanisms can be analyzed by determining cohesion and friction parameters via the interface properties of the UHPC-NC. The cohesion and shear friction are typically measured using Eq. 4.1.

$$\tau_n = c + \sigma_n \mu \quad 4.1$$

where τ_n and σ_n are the shear and normal bond strength of interface, respectively; c is the cohesion, and μ is the friction coefficient. AASHTO LRFD (2014) [56] provides bond

interface cohesion and friction values for surface roughened, i.e., 1.65 MPa and 1.0 for the raw surface, and 0.5 MPa and 0.6 for the smooth surface. To investigate the cohesion parameter, the splitting tensile test results were used to estimate this value. However, under indirect tensile strength, the cohesion between the surfaces is highly conservative to presume. The empiric equation specified in the ACI318 (2014) [57] can therefore be used to approximate the tensile strength from the result of the splitting tensile test, as stated in Eq. 4.2.

$$f_t = 0.62\sqrt{f'_c} \quad 4.2$$

In addition, the results from the slant shear test can be used as a combined shear and normal bond strength between UHPC-NC interfaces, and then by using Eq. 4.1, the friction coefficient is calculated. The calculated values were then compared with the values suggested in the design code. The results are listed in Table 4.7.

Table 4.7 Cohesion and friction coefficients collected from the slant shear test and estimated direct tensile strength from splitting test

Surface preparation	Specimen ID	σ_n (MPa)	τ_n (MPa)	c (MPa)	μ (MPa)
As cast	W-N	10.89	18.86	1.69	1.58
	H-N	11.71	20.29	1.74	1.58
	W-R	9.14	15.83	1.39	1.58
Drill holes	W-N	12.82	22.21	2.54	1.53
	H-N	12.47	21.60	2.48	1.53
	W-R	9.72	16.83	1.99	1.53
Sandblast	W-N	14.57	25.23	2.66	1.55
	H-N	14.88	25.77	2.61	1.56
	W-R	15.00	25.98	2.46	1.57

The findings in Table 4.7. show that for the UHPC-NC interface, the cohesion (c) and friction coefficient (μ) are significantly higher than the standard values defined in AASHTO LRFD [56]. It is noted that the results obtained from the as cast samples are higher than those estimated from the rough surface with an average increase of 1.28%. This may be due to the overestimated shear and normal stresses observed from the slant shear test compared to the cohesion value. In addition, the friction coefficient is higher than the cohesion value for the sample with the effect of repeated cyclic exposure. Nevertheless, the estimated average cohesion and friction coefficient values were 1.60 and 1.58 MPa, respectively, which increased by up to 200 percent relative to the AASHTO LRFD [56] specifications. As mentioned before from the splitting tensile test results, the composites with as cast surfaces were less than the minimum criteria , which interpret that the samples with as cast surface under this type of bond test should not be adopted for the design consideration.

On the other hand, the friction coefficient's average values for the specimen with the sandblasted surface were slightly higher than the drilled holes by 1.96%. The sample values with repeated cyclic exposure did not fit well since the friction coefficient's value did not decrease with the cohesion values' decrease. Therefore, the sample with repeated cyclic exposure with the sandblasted surface under the slant shear test did not affect. Overall, the average cohesion was between 2.34 and 2.58 MPa, while the friction coefficient was between 1.53 and 1.56 MPa, based on the results obtained from the rough surfaces. It is found that the friction coefficient values agreed with the specifications provided in the AASHTO LRFD [56] and very close to the values stated in the design code of the ACI318 [57]. In contacts, the values of cohesion were increased by approximately 55% compared

to the typical values specified in the AASHTO LRFD [56]. Therefore, this study's results indicate that the values given by the ACI318 [57] requirements are conserved, and further studies are expected to decide if they can be improved in the future in the design of UHPC contacts.

For further investigation, this study's findings may be compared with previous research [45], [58], as shown in Table 4.8. It can be noted that the results observed by Zhang et al. (2020) [45] for the rough surface sample were very similar to the parameters obtained from this study. Husam et al. (2016) [58], however, reported much higher cohesion values than the results found in this analysis and hence much higher than the results specified in the AASHTO LRFD [56] specification. However, the bonding performance of the UHPC-NC interfaces varies considerably for different factors, such as exposed aggregate interface, substrate surface preparation, curing state, exposure to repeated cycles, material strength, and interface stress. Therefore, the authors propose that comprehensive experimental studies for UHPC-NC interfaces with various parameters should be performed to validate the validity of cohesion (c) and friction coefficient (μ).

The results obtained from the bi-surface shear test can be compared with the maximum shear strength specified by ACI318 [57] for the normal-weight concrete placed against hardened concrete, as listed in Table 4.9. Therefore, the allowable shear strength for smooth and sandblasted samples was 5.5 MPa, while the maximum value for the surface with drilled holes was 8.2 MPa, as the amplitude was greater than 6 mm according to ACI318 [57].

Table 4.8 Comparison of the coefficient of friction and cohesion obtained from previous studies

Sources	Surface preparation	Slant shear results		Tensile results	
		τ_n (MPa)	σ_n (MPa)	c (MPa)	μ (MPa)
This study	AC	20.29	11.71	1.74	1.58
	DH	22.21	12.82	2.54	1.53
	SB	25.77	14.88	2.61	1.56
Zhang et al. (2020) [45]	AC	12.06	6.97	2.18	1.42
	SB	21.34	12.32	2.92	1.5
Husam et al. (2016) [58]	AC	4.1	2.3	3.02	0.47
	SB	33.1	19.1	5.63	1.44

Table 4.9 Maximum f_u across the assumed shear plane ACI318 (2014) [57]

Condition	Maximum f_u (MPa)		
Normal weight concrete placed monolithically or placed against hardened concrete intentionally roughened to a full amplitude of approximately 6 mm	Least of (a), (b), and (c)	$0.2 f'_c$	(a)
		$3.3+0.08 f'_c$	(b)
		11	(c)
Other cases	Lesser of (d) and (e)	$0.2 f'_c$	(d)
		5.5	(e)

Figure 4.10 illustrates the comparisons of the estimated shear bond strength from the bi-surface shear test in accordance with the maximum shear strength specified on the ACI318. It is noteworthy that the results obtained from this study were met the allowable shear strength values for the different types of the condition stated in the specification. However, the sandblasted sample results seem to have increased by roughly 2.4% of the requirements

of ACI318. This can be attributed to the higher degree of roughness, which consequently tends to increase the coefficient of friction and cohesion between the UHPC-NC interfaces. Results from the effect of repeated cyclic exposure tend to have decreased significantly by up to 37% from the shear strength specified in ACI318. Therefore, based on this observation, it can be suggested that the ACI equation has to be modified to take into account the effect of repeated cyclic exposure of the composite samples. To better interpret the UHPC-NC interface mechanism resulting from repeated cyclic exposure, further investigations must be carried out to use scanning electron micrographs (SEM) of the interfacial zones between the UHPC overlay and the concrete substrate.

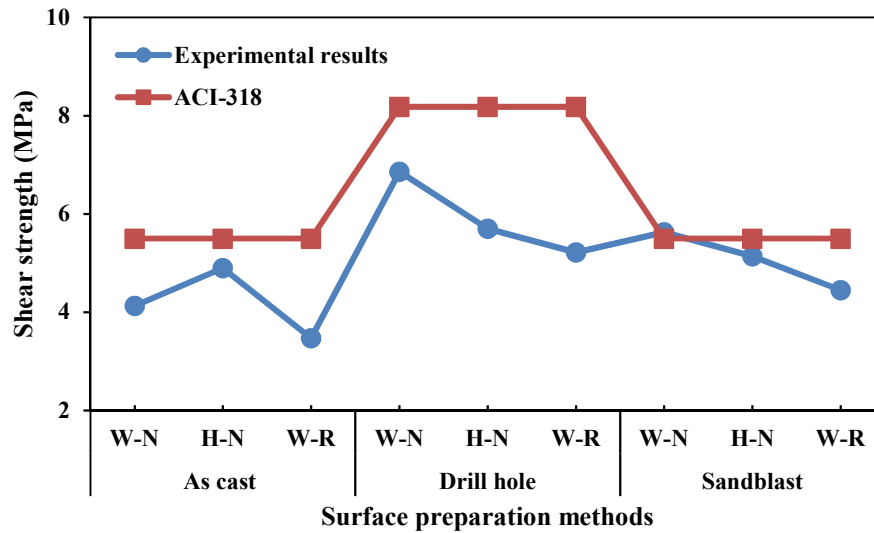


Figure 4.10 Comparison of bi-surface shear strength results with ACI318 allowable shear strength [57]

4.8 Comparison with Other Studies

The present results are compared with the relevant literature for the slant shear, bi-surface shear, splitting, and third-point flexural strength samples in Table 4.10. Only literature

studies using the same interface surface preparation and bond testing method were considered in the correlation. However, the variation in mixing design, fiber type, and content of UHPC, compressive, and tensile strength for both the substrate and the UHPC may also have influenced the correlation. No comparable observations in the literature reported the effect of the wet-dry/heat-cool cyclic exposure on the bond strength between UHPC and the NC interface.

Table 4.10 Comprehensive bond strength comparison of slant shear, bi-surface shear, split tensile, and third-point flexural test

Reference	Surface preparation	Slant shear (MPa)	Failure mode	Bi-surface (MPa)	Failure mode	Split tensile (MPa)	Failure mode	Third-point flexural (MPa)	Failure mode	Substrate, f'_c (MPa)	UHPC, f'_c (MPa)
This study (W-N)	AC	18.86	A	4.13	C	1.85	A	1.97	A	61	145
	DH	22.21	C	6.86	C	4.20	C	4.32	C		
	SB	25.23	D	5.63	B	4.62	C	4.69	C		
This study (H-N)	AC	20.29	A	4.90	A	1.97	A	1.89	A		
	DH	21.60	A	5.70	C	3.99	C	4.22	B		
	SB	25.77	D	5.14	B	4.43	C	4.64	B		
This study (W-R)	AC	15.83	A	3.47	A	1.26	A	-	-		
	DH	16.83	A	5.22	C	2.59	B	-	-		
	SB	25.98	A	4.45	B	3.95	C	-	-		
Semendary and Svecova (2020) [15]	SB	17.60	D	3.6	B	-	-	-	-	68	160
Valikhani et al. (2020) [46]	AC	-	-	2.8	B	-	-	-	-	48	124
	SB	-	-	6.3	C	-	-	-	-		

Zhang et al. (2020) [45]	AC	12.06	A/B	-	-	2.77	B/C	-	-	53	126
Ganesh and Murthy (2020) [48]	DH	11.87	A	-	-	1.46	B	-	-	35	118
Bahraq et al. (2019) [59]	SB	22.91	B	-	-	3.41	B	-	-	65	151
Farzad et al. (2019) [14]	AC	21.80	A	2.97	A	-	-	2.80	A	48	174
Jafarinejad et al. (2019) [44]	AC	11.50	A	-	-	-	-	-	-	53	150
	SB	29.40	C/D	7.81	C	-	-	-	-		
Aaleti and Sritharan (2019) [43]	SB	25.53	D	-	-	-	-	-	-	47	145
Haber and Graybeal (2018) [60]	SB	34.23	D	-	-	-	-	-	-	46	157
Al-Osta et al. (2017) [42]	AC	21.56	A	-	-	2.58	A	-	-	54	128
	SB	27.01	D	-	-	3.73	B	-	-		

AL Hallaq et al. (2017) [41]	AC	5.23	A	-	-	3	A	-	-	33	112
	SB	18.40	D	-	-	4.6	C	-	-		
Baharuddin et al. (2016) [39]	AC	2.45	A/B	-	-	2.25	B/C	-	-	40	150
Li and Rangaraju (2016) [38]	SB	25.46	D	-	-	-	-	4.40	D	49	158
Carbonell Muñoz et al. (2014) [34]	AC	-	-	-	-	3.82	A/B	-	-	56	127
	SB	21.70	D	-	-	4.05	C	-	-		
Tayeh et al. (2013) [36]	AC	8.47	A/B	-	-	1.82	A	-	-	38	170
	DH	11.10	B/C	-	-	2.28	B	-	-		
	SB	17.17	D	-	-	3.53	C	-	-		
Tayeh et al. (2012) [20]	AC	8.68	A/B	-	-	1.85	A/B	-	-	45	170
	DH	12.27	C	-	-	2.60	C	-	-		
	SB	17.81	D	-	-	3.79	C	-	-		
Harris et al. (2011) [19]	AC	11	A	-	-	5	A/B	-	-	38	103
	DH	14	C/D	-	-	-	-	-	-		

CHAPTER 5

RESULTS AND DISCUSSIONS FOR UHPC-SC

COMPOSITE SPECIMENS

5.1 Failure patterns

For all test specimens' configurations, the stresses corresponding to the failure load were reported, and the identifying failure pattern has been defined. As seen in Figure 5.1 and based on the properties and position of the failure plane, the typical failure modes of the composite specimens observed in the slant shear testing can generally be divided into three distinct types, namely, a pure interface failure (A), interface failure and substrate failure (B), and substratum failure (C). As for the UHPC-SC composites under bi-surface shear tests, three typical failure modes were observed, namely, adhesive failure (A), mixed failure of the interfacial zone and concrete substrate (B), and cohesive failure (C), as shown in Figure 5.2. On the other hand, as can be seen in Figure 5.3 and 5.4, three forms of interfacial failure zone can obtain in various tested specimens: pure interface failure (A), interface and partial concrete substrate failure (B), and interface failure and substrate fracture (C).

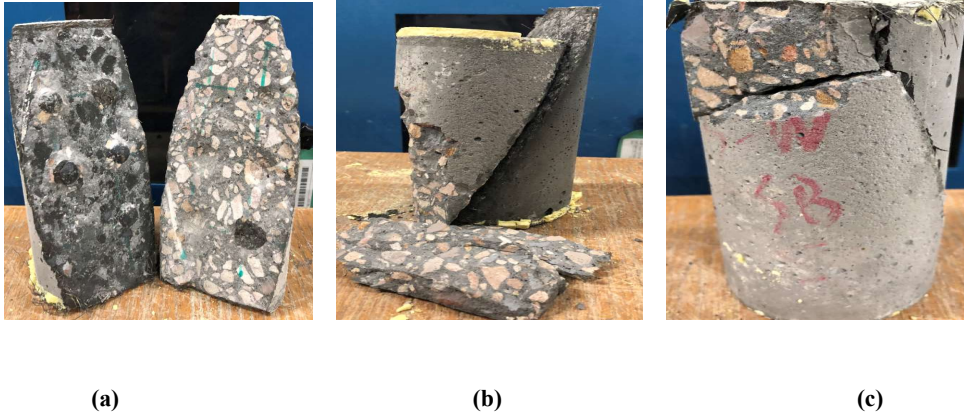


Figure 5.1 Failure mode under slant shear test. a: pure interface failure (A), b: interface failure and substrate failure (B), c: concrete substrate fracture (C)

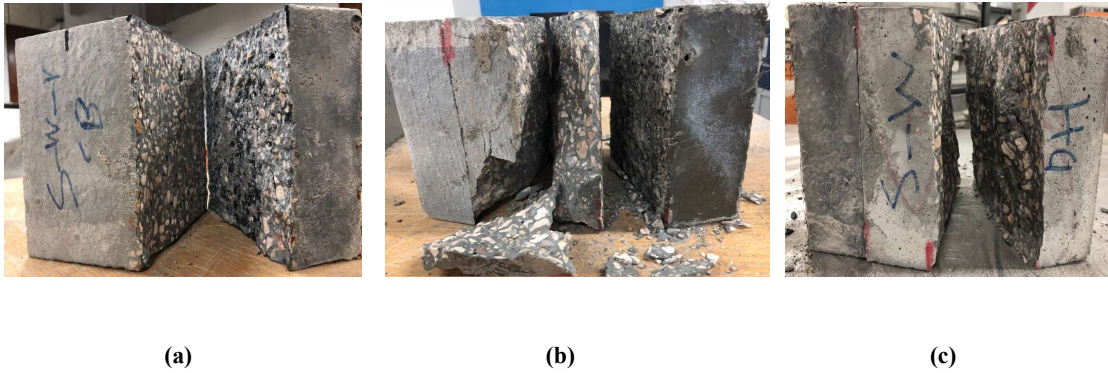


Figure 5.2 Failure mode under bi-surface shear test. a: interfacial zone and partially substrate failure (Adhesive failure: A), b: mixed failure of the precast and interfacial zone (Mixed failure: B), c: precast failure (Cohesive failure: C)

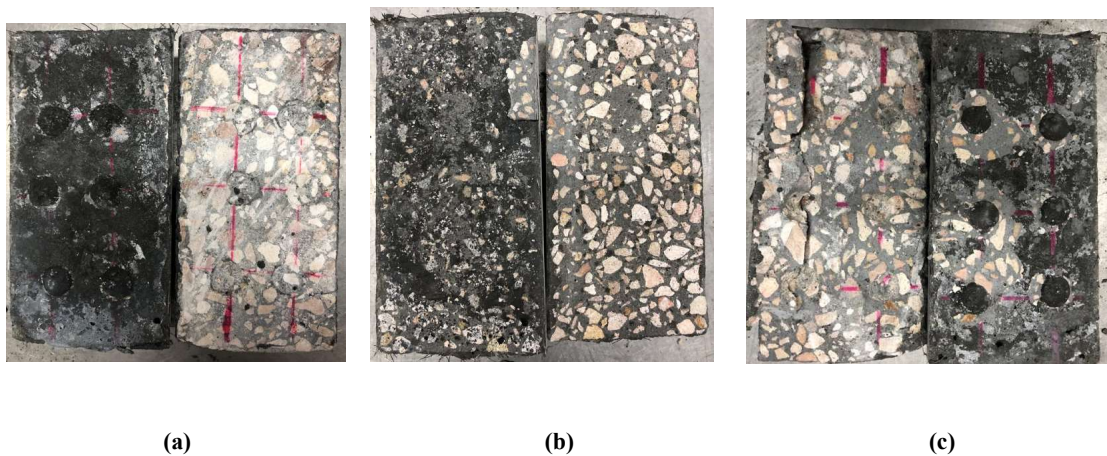


Figure 5.3 Failure modes under splitting tensile test. a: pure interface failure (A), b: interface and partial concrete substrate failure (B), c: interface failure and substrate fracture (C)

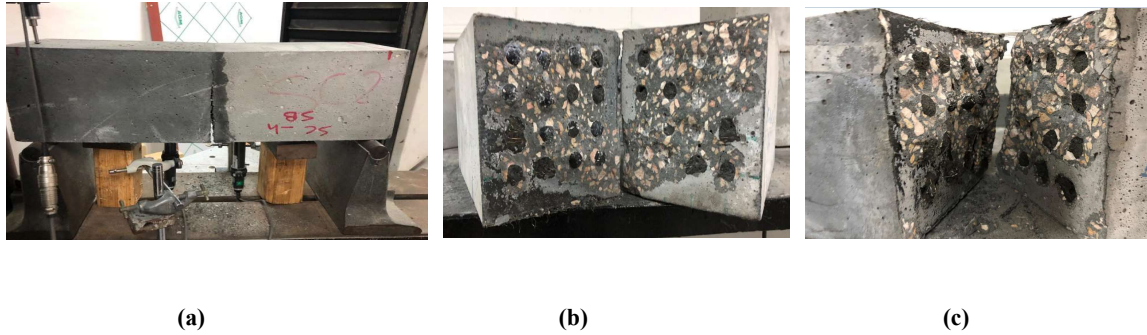


Figure 5.4 Failure mode under third-point flexural test. a: interfacial zone failure (A), b: interfacial zone and partially substrate crack (B), c: interfacial zone and partially substrate fracture (C)

The observed failure modes under normal water curing condition (W-N) indicated that the UHPC-SC composites with the failure modes of A, B, and C (refer to Figure 5.1- 5.4) accounted for 38.9%, 13.9%, and 47.2% of the total specimens on average, respectively. On the other hand, the typical failure under heat curing (H-N) was regarded as 41.7%, 25%, and 33.3% of A, B, and C, respectively. Thus, the typical failure modes underwater curing condition was significantly stronger than those of heat cured. In comparison, the higher ratio of the pure interface failure was obtained from the AC specimens. However, the composites' failure modes exposed to wet-dry/heat cool cycles (W-R) were 51.9%, 25.9%, and 22.2% of A, B, and C, respectively. Thus, a pure interface failure occurred mainly under repeated cyclic exposure, two times weaker than the W-N specimens' failure mode.

On the other hand, the failure mode that occurred in the concrete substratum (C) was obtained of 0.8%, 39.4%, and 57.6% of the UHPC-SC substrate of AC, SB, and DH, respectively (Figure 5.1c and 5.2c). It is noteworthy that the DH specimens observed a stronger failure mode relative to the SB specimens due to the higher contribution of the bi-surface shear resulting in precast failure due to the higher mechanical material interlocking of the UHPC-SC interface. Despite the failure modes obtained from the bi-surface shear

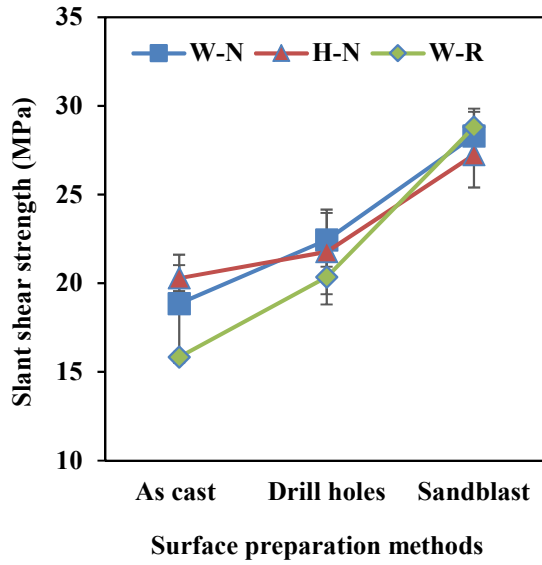
test, the SB specimens observed the strongest typical failure mode in the various bond tests. In sum, the quality of the bond has been accessed. Since the failure seems to occur in the interfacial bonding field, the failure's strength is assumed to be the composite specimen's bond strength. Likewise, where the failure occurs in the concrete substrate, the bond strength is assumed to be greater than the substrate specimen's strength.

5.2 Bond strength

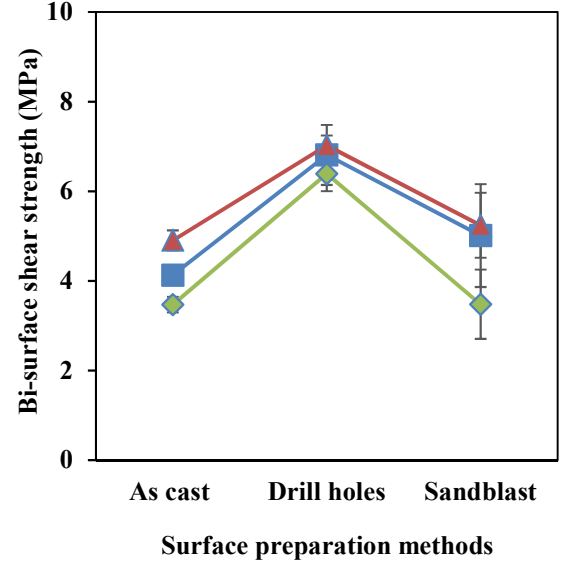
Table 5.1 summarizes the results of the slant shear, bi-surface shear, splitting tensile, and third-point flexural tests, including the average bond strength, standard deviation (SD), coefficient of variation (COV) values, and failure mode corresponding to different specimen configurations of each test group. For a better interpretation of the effect of the studied parameters on the interfacial bonding strength of a UHPC-SC interface, the evaluation of the bond strength under different roughness preparation of SC, curing condition of the composites, and effect of repeated cyclic exposure (wet-dry/heat-cool) were observed and displayed in Figure 5.5.

Table 5.1 Summary of slant shear, bi-surface shear, splitting tensile, and third-point flexural test results

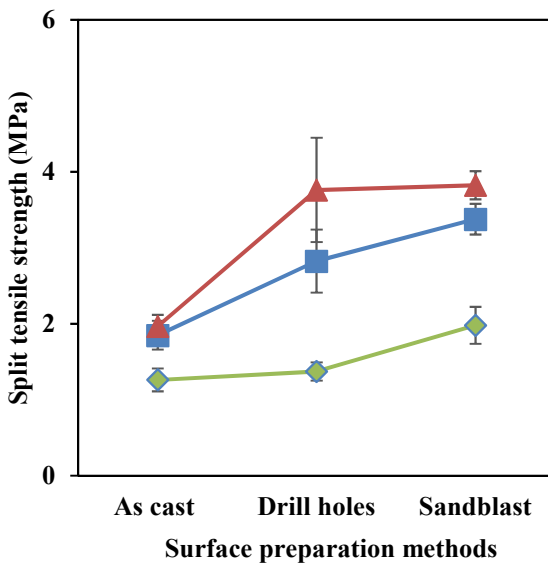
Surface preparation	Specimen ID	Slant shear test						Bi-surface shear test				Splitting tensile test				Third-point flexural test			
		σ_n (MPa)	SD (MPa)	τ_n (MPa)	SD (MPa)	COV (%)	Failure mode (%)	ν_{bs} (MPa)	SD (MPa)	COV (%)	Failure mode	f_{sp} (MPa)	SD (MPa)	COV (%)	Failure mode (%)	f_f (MPa)	SD (MPa)	COV (%)	Failure mode
As cast (AC)	W-N	10.89	1.59	18.86	2.75	14.6	A:100	4.13	0.16	4.0	C	1.85	0.19	10.3	A:100	1.97	0.04	2.2	A
	H-N	11.71	0.42	20.29	0.73	3.6	A:100	4.90	0.22	4.6	A	1.97	0.15	7.6	A:100	1.89	0.09	4.6	A
	W-R	9.14	0.18	15.83	0.31	2.0	A:100	3.47	0.17	5.0	A	1.26	0.15	11.9	A:66.7, B:33.3	-	-	-	-
Drill holes (DH)	W-N	12.96	0.88	22.45	1.52	6.8	A:66.7, C:33.3	6.81	0.67	9.8	C	2.82	0.41	14.7	C:100	3.10	0.43	13.9	B
	H-N	12.57	1.38	21.77	2.39	11.0	B:100	7.02	0.22	3.1	C	3.76	0.69	18.2	C:100	3.77	0.11	2.95	C
	W-R	11.75	0.89	20.35	1.55	7.6	B:100	6.39	0.39	6.1	C	1.37	0.12	8.6	A:100	-	-	-	-
Sandblast (SB)	W-N	16.34	0.89	28.31	1.54	5.4	C:66.7, B:33.3	5.01	1.15	22.9	C	3.38	0.20	6.0	C:66.7, B:33.3	4.48	0.41	9.1	A
	H-N	15.73	1.06	27.24	1.84	6.8	B:100	5.24	0.73	13.8	B	3.82	0.19	4.9	C:100	4.14	0.27	6.5	A
	W-R	16.64	0.49	28.81	0.85	3.0	B:100	3.48	0.77	22.2	A	1.98	0.24	12.3	C:100	-	-	-	-



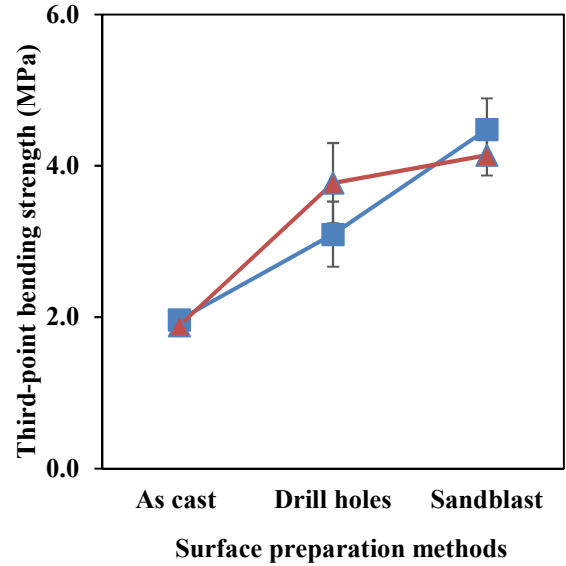
(a)



(b)



(c)



(d)

Figure 5.5 Relative increase of the average bond strength under different parametric studies: (a) slant shear; (b) bi-surface shear; (c) splitting tensile; (d) third-point flexural test

For the group (W-N), composite specimens with DH and SB substrate surfaces had a bond strength increase of almost 20% and 50%, respectively, relative to the AC surface under slant shear test, as seen in Figure 5.5a. However, the bond's performance under the bi-

surface shear test showed the highest increase by DH preparation of 65% compared to 21% by SB treatment of AC surface, as seen in Figure 5.5b. On the other hand, the DH and SB substrate's bond performance improved to approximately 50% and 80%, respectively, relative to the AC surface under splitting tensile test, as shown in Figure 5.5c. In addition, the bond strength under the third-point flexural test, the bond performance acquired a significance increase by DH and SB surface roughened of almost 60% and 130% of the AC surface, respectively, as shown in Figure 5.5d.

For the group (W-H), composite specimens with DH and SB substrate surfaces improved bond strength of almost 7% and 35%, respectively, compared to the AC surface under slant shear test, as shown in Figure 5.5a. However, the bond's performance under the bi-surface shear test showed the highest increase by DH preparation of 43% compared to 7% by SB treatment of AC surface, as shown in Figure 5.5b. On the other hand, the DH and SB substrate's bond performance improved to approximately 90% and 95%, respectively, relative to the AC surface under splitting tensile test, as seen in Figure 5.5c. In addition, the bond strength under the third-point flexural test, the bond performance was considerably improved by DH and SB surface roughened by almost 100% and 120% of the AC surface, respectively, as shown in Figure 5.5d.

For the group (W-R), composite specimens with DH and SB substrate surfaces increased bond strength of almost 30% and 80%, respectively, compared to the as cast (AC) surface under slant shear test as shown in Figure 5.5a. However, the bond's performance under the bi-surface shear test exhibited the highest increase by DH preparation of 84% compared to 0.3% by SB treatment of AC surface, as shown in Figure 5.5b. On the other hand, DH and SB substrate's bond performance increased to nearly 10% and 55%, respectively, compared

to the AC surface under splitting tensile test, as shown in Figure 5.5c. In sum, the interfacial bond strengths of the specimens under wet-dry/ heat cool cycles decreased significantly under the splitting tensile test. In contrast, the bond strength slightly decreases under slant shear and bi-surface shear tests. It is worth noting that the results obtained by splitting tensile test were significantly more reliable to assess the bond strength under different exposure conditions.

It is obvious, according to Table 5.1 and Figure 5.5 that, the curing condition does not seem to have a significant change in the bond behavior. It was observed that the heat-curing AC specimens were slightly higher than those with a watering condition of almost 8% and 19% of the slant shear and bi-surface shear tests, respectively (Figure 5.5a and b). However, from splitting tensile and third-point flexural tests, the heat-curing DH specimens were markedly higher than those with a watering condition of almost 33% and 22%, respectively (Figure 5.5c and d). In sum, the substrate's surface preparation is a major factor in the interfacial bond strength between the SC substrate and UHPC repair material. However, the composites' curing conditions comparatively less substantial for the interfacial bonding strength [45]. Notably, the sandblasting method provided the highest strength performance under different bond tests, except for the bi-surface shear test, which was the highest due to the drill holes' preparation. Thus, it may be that the sandblasting did not fill with UHPC overlay, which the air voids resulted in lower interaction of the UHPC-SC interface.

A comprehensive study of the test results obtained by slant shear, bi-surface shear, splitting tensile, and third-point flexural tests shows that the slant shear tests have the highest bond strengths among all specimens due to the strong interlocking and friction forces caused by compression [26]. In the bi-surface shear tests, the bond strength was decreased

considerably since the stress was under pure shear only. In addition, the third-point flexural test displayed slightly higher interfacial bond performance or the same as those with the splitting tensile test. However, slightly lower than the bi-surface shear test and significantly lower than the slant shear test. Thus, the bond strengths obtained by the slant shear tests should not be adopted when the UHPC-SC interface is in a tension state without providing suitable correction factors. However, the implementation of the third-point bending and splitting tensile bond strengths for a UHPC-SC interface subjected to pure shear or combined shear and compression loading would underestimate the actual bond strengths.

In addition, the coefficient of variations (COV) of the bond strengths of UHPC-SC composites for the various test results varied from 2% to 22.9%, with relatively small error bars. Consequently, the COV results are consistent with the previous study's experimental findings [22], [34], and less than 23.9%, indicating consistent results across different tests. Low COV's in the present tests can be assumed within an acceptable range, which confirms the test's validity.

5.3 Effect of wet-dry/heat-cool repeated cycles

Figure 5.6 indicates the particular differences in interfacial bond behavior caused by the different forms of bond testing carried out in this study. Compared to the AC surface, the highest reduction in bond strength experienced in the splitting tensile test was roughly 32%. It is noteworthy to mention that the AC samples were still lower than those with surface treatment and decreased after repeated cyclic exposure. This proves that the AC samples cannot be used in the splitting tensile test. The findings of both slant shear and bi-surface

shear tests have decreased bond strength by almost 16% for such AC samples. Compared to the DH surface, the highest decrease in bond strength resulted from a splitting tensile test of approximately 51%. The probable scenario is that this interface's presence in the holes resulted in a decrease in the rough surface area and reduced the indirect tensile strength of the UHPC-SC interface.

On the other hand, the bi-surface shear test showed the lowest bond strength decrease of approximately 6%. This may be due to further mechanical interlocking by the UHPC filling of the SC substrate holes. Compared to the SB surface, the splitting tensile test showed the highest bond strength decrease of nearly 41%. However, there is no reduction in bond strength experienced in the slant shear test with sandblasting surface preparation.

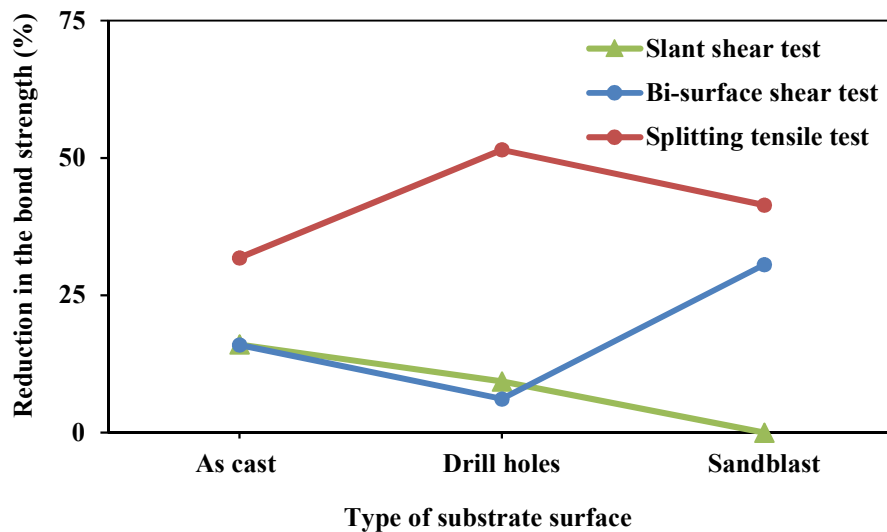


Figure 5.6 The reduction of the bond due to the effect of repeated cyclic exposure condition

5.4 Comparison with the minimum requirement specified by the ACI and evaluation criteria of the interfacial bond

The slant shear test results of the UHPC-SC composite interface bond strengths meet the minimum acceptable requirements defined by ACI 546–06 [1]. It is noteworthy that the composite specimens with DH and SB substrate surface exceeded the specified requirements by ACI and even after wet-dry and heat-cool cyclic exposure. Compared to the bi-surface shear test, the AC and SB specimens were near to the ACI limit. Therefore, SC substrate's required surface preparation under a different state of stress is needed to ensure minimum acceptable ACI specifications of the UHPC-SC interfacial bond strength.

Comparing the recorded splitting tensile strength of the UHPC-SC composites under degradation to wet-dry/heat-cool exposure with the quantitative bond strength assessment suggested by Sprinkel and Ozyildirim [54], it's obvious that the strength rating obtained by the sandblasting composites falls within the "Very Good" bonding range as the values recorded are between 1.7-2.1 MPa. On the other hand, the AC and DH specimens reported a bond strength of less than 1.4 MPa that could be labeled as "Fair" and could be ignored in the case of repeated cyclic exposure. Thus, the UHPC-SC composite can only be prepared using the SB technique. It's worth noting that the splitting tensile test is reliable relative to the slant shear and bi-surface shear tests.

5.5 Cohesion and friction parameters of the interfacial surfaces

The load is transmitted by adhesion at the interface until a certain value is reached and then transferred through friction. Adhesion and aggregate interlocking mechanisms can act as a function of mechanical properties by increasing surface roughness, enhancing aggregate interlocking, and enhancing the chemical interaction between the SC aggregate and the UHPC that validates the cohesion concept of a surface roughness mechanism [61].

To investigate the c parameter, the splitting tensile and bi-surface shear test results were used to estimate these values. Then, the results from the slant shear test can be used as τ_n and σ_n between UHPC-SC interfaces, and then by using Eq. 4.1, the μ is calculated.

Results of c and μ in tension and shear of the UHPC-SC interface AC, DH, and SB substrate surfaces in this study are listed in Table 5.2 and the previous corresponding research [15], [45], [58], [34], [20] which was proposed for further investigation.

The findings from Table 5.2 demonstrated that the cohesion (c) and friction coefficient (μ) in tension and shear for the UHPC-SC interface were significantly higher than the defined values proposed by AASHTO (2014) [56]. The results show that the coefficient of friction estimated from the splitting tensile test was higher than that estimated using the bi-shear test results, comparable to Semendary and Svecova (2020) [15] but with different forms of an exposed aggregate surface. The friction coefficient was between 1.43 and 1.62 based on the splitting tensile data, while it was between 1.17 and 1.52 based on the bi-surface shear data. The shear friction (μ) highest values were 1.52 MPa using the sandblast interfacial surface. In the case of DH, the friction (μ) value was slightly higher than that of SB; it was

1.62 and 1.61 MPa, respectively, from splitting tensile data. This may be attributed to the high consistency of the UHPC-SC interface in the case of indirect tension.

Table 5.2 Cohesion and friction coefficients collected from the different types of bond testing

Sources	Surface preparation	Specimen ID	Slant shear test		Direct tensile or splitting tensile test		Bi-surface shear test	
			τ_n (MPa)	σ_n (MPa)	c (MPa)	μ (MPa)	c (MPa)	μ (MPa)
This study	AC	W-N	18.86	10.89	1.85	1.56	4.13	1.35
		H-N	20.29	11.71	1.97	1.56	4.9	1.31
		W-R	15.83	9.14	1.26	1.59	3.47	1.35
	DH	W-N	22.45	12.96	2.82	1.51	6.81	1.21
		H-N	21.77	12.57	3.76	1.43	7.02	1.17
		W-R	20.35	11.75	1.37	1.62	6.39	1.19
	SB	W-N	28.31	16.34	3.38	1.53	5.01	1.43
		H-N	27.24	15.73	3.82	1.49	5.24	1.40
		W-R	28.81	16.64	1.98	1.61	3.48	1.52
Semendary and Svecova (2020) [15]	SB	UHPC-NC	17.6	10.2	3.6	1.37	3.6	1.37
Zhang et al. (2020) [45]	AC		12.06	6.97	2.18	1.42	-	-
	SB		21.34	12.32	2.92	1.5	-	-
Husam et al. (2016) [58]	AC		4.1	2.3	3.02	0.47	-	-
	SB		33.1	19.1	5.63	1.44	-	-
Carbonell et al. (2014) [34]	SB		21.7	12.3	2.3	1.58	-	-
Tayeh et al. (2012) [20]	AC		7.51	4.34	2.3	1.2	-	-
	SB		15.42	8.9	2.34	1.47	-	-

On the other hand, the tension and shear parameters obtained from the water curing were higher than the heat curing of the UHPC-SC interface. This may be attributed to the rapid hardening of the UHPC with the exposed SC interface, contributing to decreased cohesion and friction parameters. Compared to the cohesion and friction coefficient obtained from the bi-surface shear test, the composite under repeated cyclic exposure was higher than the normal condition. The exceptions are the results obtained for samples of DH surface. This may differ from slant shear in UHPC-SC surface preparation due to the bond performance obtained from bi-surface shear. The tension friction parameters obtained from repeated cyclic exposure of the UHPC-SC using splitting tensile test were lower than the cohesion values, except for the composite subjected to a sandblasting preparation. This irrelevant estimation may be due to the failure to meet the acceptable criterion defined [54], as mentioned above, with the specimens subject to repeated cyclical exposure. It can be noted that the results observed by (Zhang et al. [45]; Carbonell et al. [34]; Tayeh et al. [20]) for the smooth surface sample but with the different exposed aggregate interface (NC) were considerably higher than the results obtained in this research (SC). However, the cohesion parameters obtained in this study were higher than in the previous research relative to the rough surface sample [45], [34], [20]. Husam et al. [58], in addition, the cohesion values were much higher than the results found in this analysis and hence much higher than the results specified in the AASHTO (2014) [56].

CHAPTER 6

RESULTS AND DISCUSSIONS FOR UHPC-SCC

COMPOSITE SPECIMENS

6.1 Failure patterns

For all test specimens' configurations, the stresses corresponding to the failure load were reported, and the identifying failure pattern has been defined. As seen in Figure 6.1 and based on the properties and position of the failure plane, the typical failure modes of the composite specimens observed in the slant shear testing can generally be divided into three distinct types, namely, a pure interface failure (A), interface failure and partially substrate crack (B), and interface failure and substrate fracture (C). As for the UHPC-SCC composites under bi-surface shear tests, three typical failure modes were observed, namely, adhesive failure (A), mixed failure of the interfacial zone and concrete substrate (B), and cohesive failure (C), as shown in Figure 6.2. On the other hand, as can be seen in Figure 6.3 and 6.4, three forms of interfacial failure zone can obtain in splitting tensile and third-point flexural test specimens: pure interface failure (A), interface and partial concrete substrate failure (B), and interface failure and substrate fracture (C).



(a)

(b)

(c)

Figure 6.1 Failure mode under slant shear test. a: pure interface failure (A), b: interface failure and partially substrate crack (B), c: interface failure and substrate fracture (C)



(a)

(b)

(c)

Figure 6.2 Failure mode under bi-surface shear test. a: interfacial zone and partially substrate failure (Adhesive failure: A), b: mixed failure of the precast and interfacial zone (Mixed failure: B), c: precast failure (Cohesive failure: C)



(a)

(b)

(c)

Figure 6.3 Failure modes under splitting tensile test. a: pure interface failure (A), b: interface and partial concrete substrate crack (B), c: interface failure and substrate fracture (C)

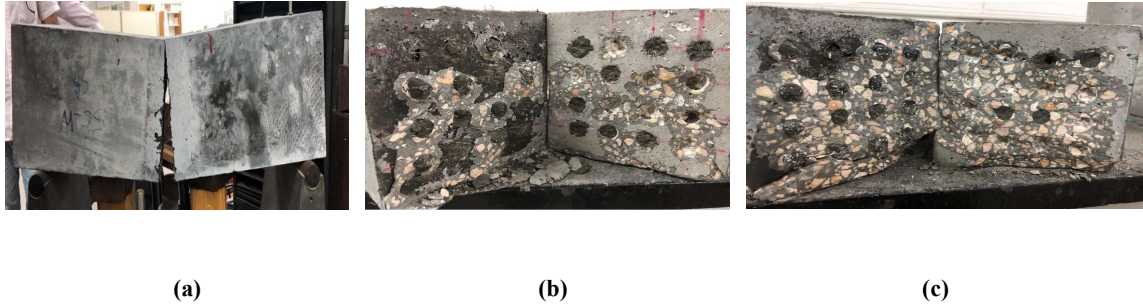


Figure 6.4 Failure mode under third-point flexural test. a: interfacial zone failure (A), b: interfacial zone and partially substrate crack (B), c: interfacial zone and partially substrate fracture (C)

The observed failure modes of slant shear and bi-surface shear test specimens under normal laboratory environment condition (W-N and H-N) for the UHPC-SCC interface sandblasting and drilling hole preparation indicated that the failure modes of A, B, and C (refer to Figure 6.1, and 6.2) accounted for 8.3%, 16.7%, and 75% of the total specimens on average, respectively. However, the composites' failure modes exposed to wet-dry/heat cool cycles (W-R) were 41.7%, 33.3%, and 25% of A, B, and C, respectively. Thus, a pure interface failure occurred mainly under repeated cyclic exposure.

On the other hand, the observed failure modes of splitting tensile and third-point flexural test specimens under normal laboratory environment condition (W-N and H-N) for the UHPC-SCC interface sandblasting and drilling hole preparation indicated that the failure modes of A and B/C (refer to Figure 6.3 and 6.4) accounted for 37.5%, and 62.5% of the total specimens on average, respectively. However, the composites' failure modes exposed to wet-dry/heat cool cycles (W-R) were 66.7% and 33.3% of B and C, respectively. In sum, the typical failure mode was mostly a pure interface of the composites with as cast interface.

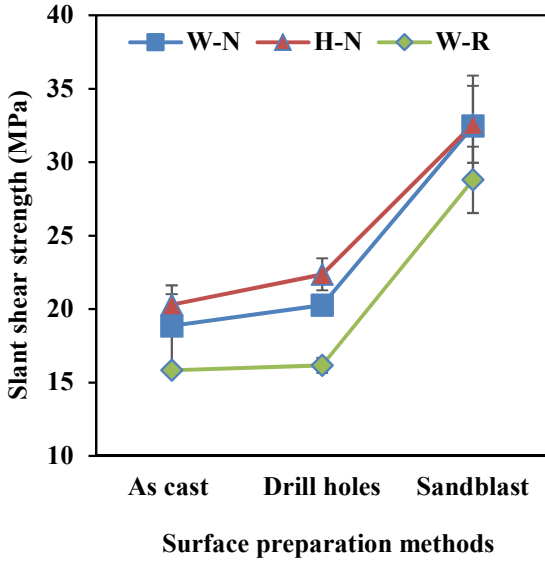
6.2 Bond strength

Table 6.1 summarizes the results of the slant shear, bi-surface shear, splitting tensile, and third-point flexural tests, including the average bond strength, standard deviation (SD), coefficient of variation (COV) values, and failure mode corresponding to different specimen configurations of each test group. For a better interpretation of the effect of the studied parameters on the interfacial bonding strength of a UHPC-SCC interface, the evaluation of the bond strength under different roughness preparation of SCC, curing condition of the composites, and effect of repeated cyclic exposure (wet-dry/heat-cool) were observed and displayed in Figure 6.5.

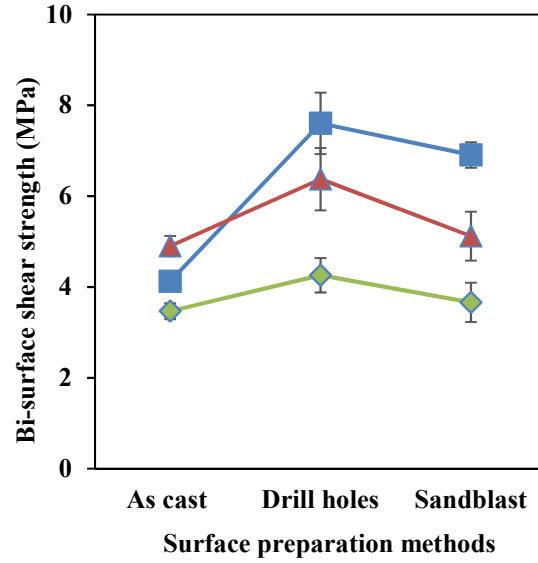
From the slant shear test, W-N composite specimens with DH and SB substrate surfaces had a bond strength increase of almost 7% and 72%, respectively, compared to the AC surface, as seen in Figure 6.5a. In addition, H-N composite specimens with DH and SB substrate surfaces improved bond strength of almost 10% and 60%, respectively, compared to the AC surface. Furthermore, W-R composite specimens with DH and SB substrate surfaces increased bond strength of almost 2% and 82%, respectively, compared to the as cast AC.

Table 6.1 Summary of slant shear, bi-surface shear, splitting tensile, and third-point flexural test results

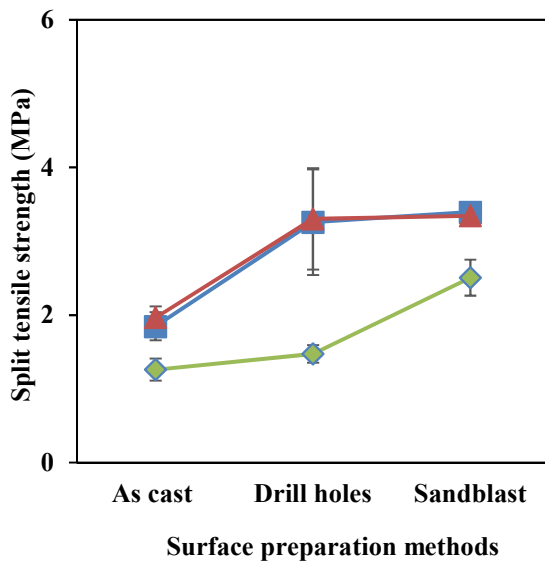
Surface preparation	Specimen ID	Slant shear test						Bi-surface shear test				Splitting tensile test				Third-point flexural test			
		σ_n (MPa)	SD (MPa)	τ_n (MPa)	SD (MPa)	COV (%)	Failure mode (%)	v_{bs} (MPa)	SD (MPa)	COV (%)	Failure mode	f_{sp} (MPa)	SD (MPa)	COV (%)	Failure mode (%)	f_f (MPa)	SD (MPa)	COV (%)	Failure mode
As cast (AC)	W-N	10.89	1.59	18.86	2.75	14.6	A:100	4.13	0.16	4.0	C	1.85	0.19	10.3	A:100	1.97	0.04	2.2	A
	H-N	11.71	0.42	20.29	0.73	3.6	A:100	4.90	0.22	4.6	A	1.97	0.15	7.6	A:100	1.89	0.09	4.6	A
	W-R	9.14	0.18	15.83	0.31	2.0	A:100	3.47	0.17	5.0	A	1.26	0.15	11.9	A:66.7, B:33.3	-	-	-	-
Drill hole (DH)	W-N	11.70	0.38	20.26	0.66	3.2	C:100	7.61	0.68	8.9	C	3.26	0.72	22.0	C:100	3.43	0.64	18.5	C
	H-N	12.91	0.63	22.36	1.09	4.9	A:66.7, B:33.3	6.38	0.69	10.8	C	3.30	0.69	20.8	C:100	3.37	0.58	17.2	B
	W-R	9.34	0.29	16.17	0.51	3.1	A:100	4.26	0.38	8.9	C	1.47	0.04	2.7	B:66.7, C:33.3	-	-	-	-
Sandblast (SB)	W-N	18.74	1.98	32.46	3.42	10.6	C:100	6.91	0.28	4.1	C	3.40	0.02	0.7	B:100	5.67	0.36	6.3	A
	H-N	18.81	1.51	32.57	2.62	8.0	C:100	5.12	0.54	10.5	B	3.35	0.05	1.4	A:100	4.43	0.40	9.1	A
	W-R	16.63	1.30	28.80	2.26	7.9	A:66.7, B:33.3	3.66	0.43	11.9	B	2.51	0.39	15.7	B:66.7, C:33.3	-	-	-	-



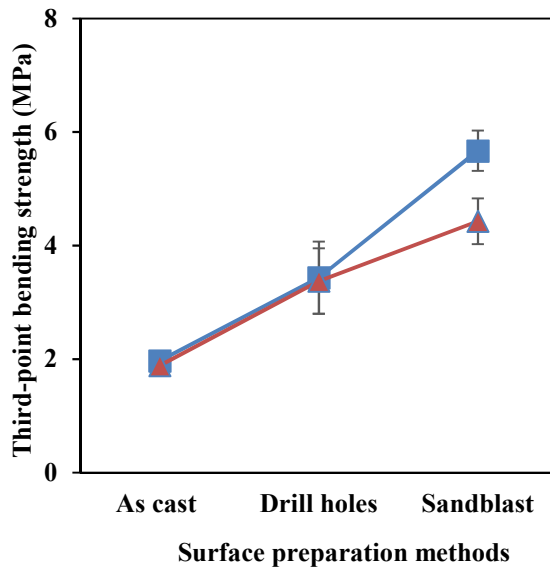
(a)



(b)



(c)



(d)

Figure 6.5 Relative increase of the average bond strength under different parametric studies: (a) slant shear test; (b) bi-surface shear test; (c) splitting tensile test; (d) third-point flexural test

From the bi-surface shear test, bond's performance of the W-N composite specimens showed the highest increase by DH preparation of 84% compared to 67% by SB treatment of AC surface as seen in Figure 6.5b. In addition, H-N composite specimens showed the

highest increase by DH preparation of 30% compared to 4% by SB treatment of AC surface. Furthermore, bond's performance of the W-R composite specimens exhibited the highest increase by DH preparation of 23% compared to 6% by SB treatment of AC surface.

From splitting tensile test, W-N composite specimens with DH and SB substrate's bond performance improved to approximately 76% and 84%, respectively, relative to the AC surface, as shown in Figure 6.5c. In addition, H-N composite specimens with the DH and SB substrate's bond performance improved to approximately 68% and 70%, respectively, relative to the AC surface. Furthermore, W-R composite specimens with DH and SB substrate's bond performance increased to nearly 17% and 99%, respectively, compared to the AC surface.

W-N composite specimens with DH and SB substrate's acquired a significant increase of almost 74% and 188% of the AC surface from the third-point flexural test, respectively, as shown in Figure 6.5d. The H-N composite specimens' bond strength was considerably improved by DH and SB surface preparation by almost 79% and 135% of the AC surface, respectively.

It is obvious, according to Table 6.1 and Figure 6.5 that, the curing condition does not seem to have a significant change in the bond behavior. It was observed that the largest increase attributable to water curing was almost 19% and 35 % of DH and SB, respectively, as compared to the bi-surface shear test's heat curing (Figure 6.5b).

The reliability of the test results is accomplished by comparing the collected COV differing in the range from 0.7% to 22% and with an average of 6.4%, 7.6%, 9.65%, and 10.3% in

slant shear, bi-surface shear, third-point flexural, and splitting tensile tests, respectively. Based on the previous study by Carbonell et al. (2014) [34] and by Momayez et al. (2005) [22] where the COV values had been limited to 2.4%–23.9%. Therefore, Low COV's in the present tests can be assumed within an acceptable range, which confirms the tests' validity.

6.3 Effect of wet-dry/heat-cool repeated cycles

The particular differences in the interfacial bond strength caused by the various types of bond tests conducted in this research are summarized in Figure 6.6. It shows that the bond strengths found in splitting tensile, slanting shear, and bi-surface shear tests are extremely sensitive to the SCC substrate surface treatment process. The typical situation is that the repeated and extreme curing temperature contributes to decreased interfacial bonding properties and accelerated UHPC shrinkage expansion. It is noteworthy to address that the splitting tensile test results demonstrated the highest decrease in the bond of almost 32%, 55%, and 26%, respectively, as casting, drilling hole, and sandblasting surface preparation under the repeated cyclic exposure of the UHPC-SCC interface. The probable scenario is that this interface's presence in the holes resulted in a decrease in the rough surface area and reduced the indirect tensile strength of the UHPC-SCC interface. The drilling hole technique obtained the highest reduction strength of approximately 55%, 44%, and 20% under splitting tensile, bi-surface shear, and slant shear tests, respectively. This may be due to the degradation of mechanical interlocking between the UHPC filling of the SCC substrate holes caused by repeated wet-dry/heat-cool cycles. Compared to the AC surface,

the lowest reduction in bond strength experienced in the slant shear and bi-surface shear tests was almost 16%. It is noteworthy to mention that the AC samples were still lower than those with surface treatment and decreased after repeated cyclic exposure. This proves that the AC samples cannot be used in the splitting tensile test. Compared to the SB surface, the slant shear test showed the lowest bond strength decrease of nearly 11%.

On the other hand, the findings of bi-surface shear tests have increased the reduction of the bond strength by almost 47%. This is due to the normal stress, which increases the friction between the contact layer in the slant shear test. In sum, SB, the most effective methods for improving the efficiency of interfacial bonding and the repaired SCC structures' stable consistency, required roughing preparations for the substrate surface.

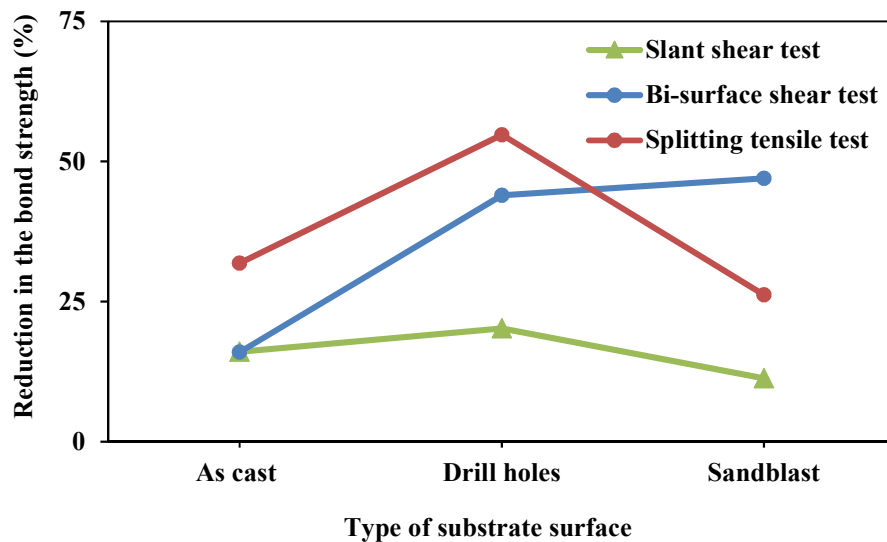


Figure 6.6 The reduction of the bond due to the effect of repeated cyclic exposure condition

6.4 Comparison with the minimum requirement specified by the ACI and evaluation criteria of the interfacial bond

The slant shear test results of the UHPC-SCC composite interface bond strengths meet the minimum acceptable requirements defined by ACI 546–06 [1]. It is noteworthy that the composite specimens with SB substrate surface exceeded the specified requirements by ACI and even after wet-dry and heat-cool cyclic exposure. Compared to the bi-surface shear test, the AC and SB specimens were near to the ACI limit. Therefore, the SCC substrate's required surface roughness under a different state of stress is needed to ensure minimum acceptable ACI specifications of the UHPC-SCC interfacial bond strength.

Comparing the recorded splitting tensile strength of the UHPC-SCC composites under degradation to wet-dry/heat-cool exposure with the quantitative bond strength assessment suggested by Sprinkel and Ozyildirim [54], it's obvious that the strength rating obtained by the sandblasting composites falls within the "Excellent" bonding range as the values recorded are over 2.1 MPa. On the other hand, the AC and DH specimens reported a bond strength of less than 1.4 and 1.5 MPa that could be labeled as "Fair" and "good" that could be ignored in the case of repeated cyclic exposure. Thus, the UHPC-SCC composite can only be prepared using the SB technique. It's worth noting that the splitting tensile test is reliable relative to the slant shear and bi-surface shear tests.

6.5 Cohesion and friction parameters of the interfacial surfaces

Results of cohesion (c) and friction coefficient (μ) in tension and shear of the UHPC-SCC interface AC, DH, and SB substrate surfaces in this study are listed in Table 6.2. The friction coefficient was between 1.45 and 1.59 based on the splitting tensile data, while it was between 1.08 and 1.51 based on the bi-surface shear data. In the case of AC, the friction (μ) value was slightly higher than that of SB and DH; it was 1.59, 1.58, and 1.57 MPa, respectively, from splitting tensile data. This may be attributed to the high consistency of the UHPC-SCC interface in the indirect tension. On the other hand, the shear friction (μ) highest values were 1.51 MPa using the sandblast interfacial surface. In sum, the results show that the coefficient of friction estimated from the splitting tensile test was higher than that estimated using the bi-shear test results. This is attributable to the indirect tension that overestimates the strength by splitting tensile test. The findings showed that the cohesion (c) and friction coefficient (μ) in tension and shear for the UHPC-SCC interface were significantly higher than the defined values proposed by AASHTO LRFD (2014) [56].

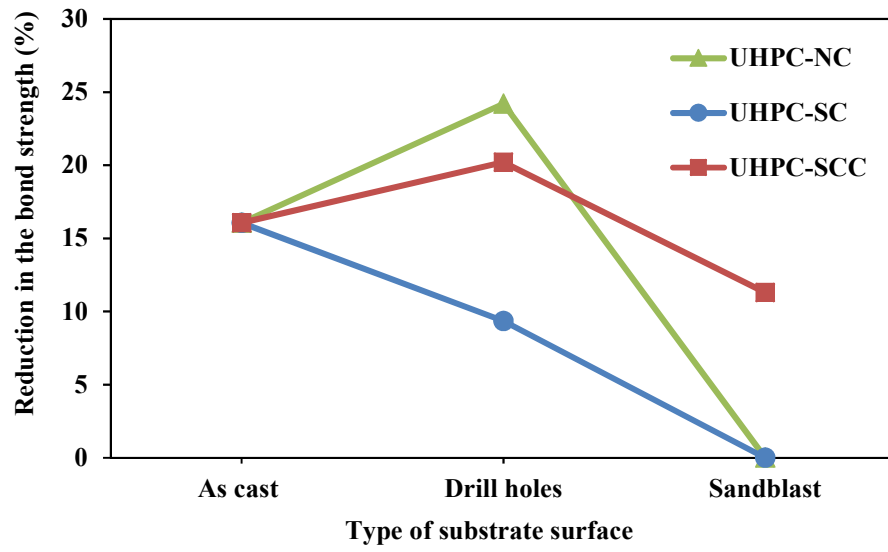
In sum, low bond strength and high relative deformation give rise to the more potential cracking of the bond interface. Cracks significantly reduce the interlocking point and therefore deteriorate the bond strength, which is the primary factor for the interface's degradation after heat-cooling cycles. In wet-dry cycles, water plays a significant role in reducing adhesion. In sum, reducing the interlocking point and the chemical bonding forces are due to the interface's degradation during coupled processes and further reducing the tensile and shear stress resistance of the bonding interface.

Table 6.2 Cohesion and friction coefficients collected from the different types of bond testing

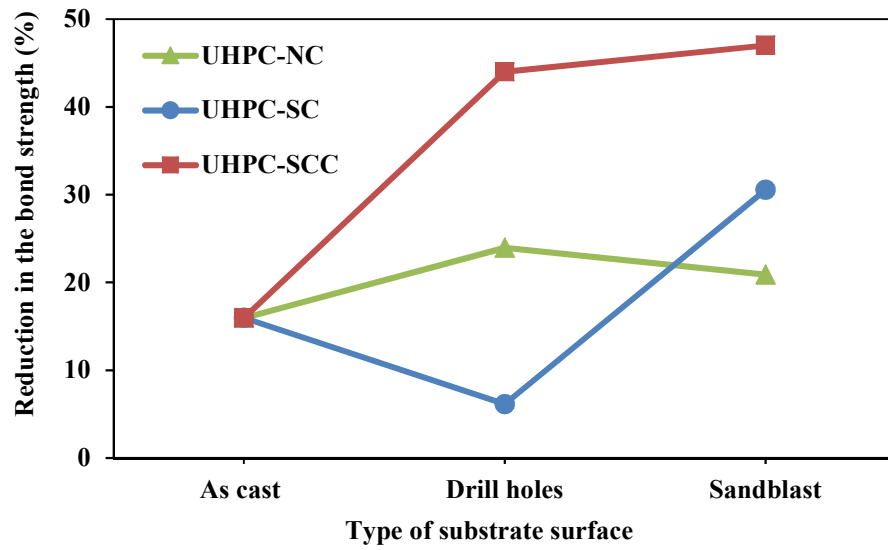
Surface preparation	Specimen ID	Slant shear test		Direct tensile or splitting tensile test		Bi-surface shear test	
		τ_n (MPa)	σ_n (MPa)	c (MPa)	μ (MPa)	c (MPa)	μ (MPa)
AC	W-N	18.86	10.89	1.85	1.56	4.13	1.35
	H-N	20.29	11.71	1.97	1.56	4.9	1.31
	W-R	15.83	9.14	1.26	1.59	3.47	1.35
DH	W-N	20.26	11.7	3.26	1.45	7.61	1.08
	H-N	22.36	12.91	3.3	1.48	6.38	1.24
	W-R	16.17	9.34	1.47	1.57	4.26	1.28
SB	W-N	32.46	18.74	3.4	1.55	6.91	1.36
	H-N	32.57	18.81	3.35	1.55	5.12	1.46
	W-R	28.8	16.63	2.51	1.58	3.66	1.51

6.6 Observations

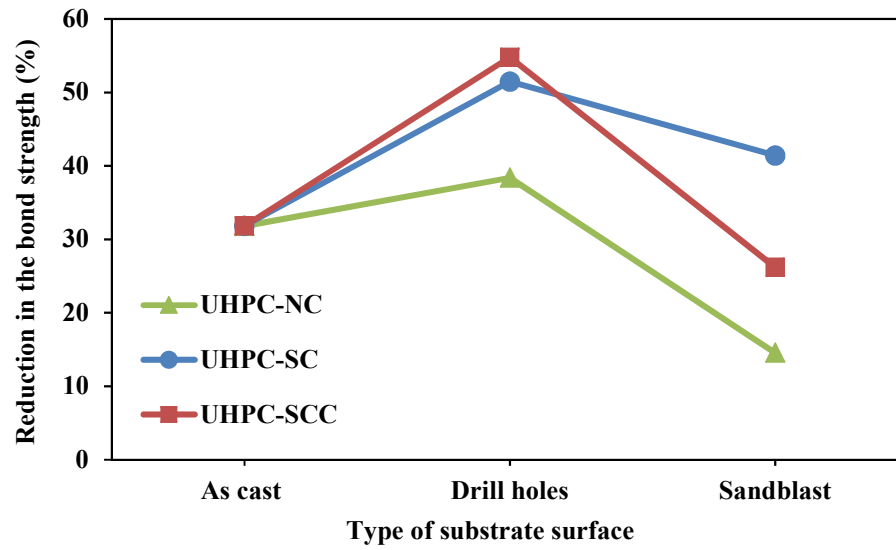
The observations can be summarized in Figure 6.7. The bond reduction due to wet-dry/heat-cool cyclic exposure conditions between UHPC and different exposed aggregate concrete interfaces (NC, SC, and SCC).



(a)



(b)



(c)

Figure 6.7 The reduction of the bond due to the effect of repeated cyclic exposure condition: (a) slant shear; (b) bi-surface shear; (c) splitting tensile tests

CHAPTER 7

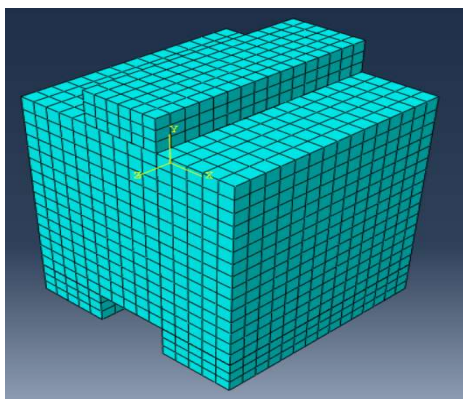
NUMERICAL MODELING

7.1 General

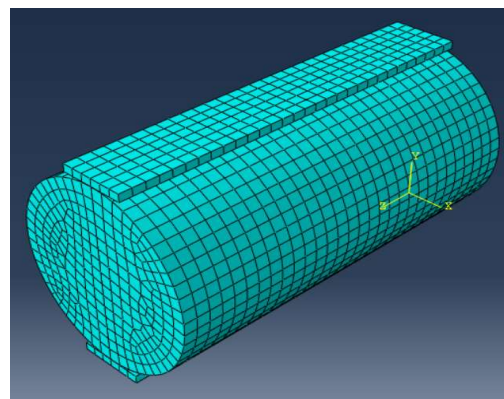
Numerical modeling of the bond behavior between UHPC overlay and NC substrate lack in the literature [20]. Complexity can increase overwhelmingly if the surface consists of various interface surface treatments and distinct composite exposure conditions. The complexity of the various parameter studies obtained from UHPC-NC composites. In this study, the FE model's ideal bonding assumptions are made between composites incorporating various substrate preparations and composite exposure conditions. For UHPC-NC composites, each part's FE model as a single element would be convenient and computationally effective to encounter the preparation methods. The interaction between the two surfaces was simulated first using a prefect bond contact approach (tied). Consequently, the surface-based cohesive behavior model was utilized to simulate the UHPC-NC interface to relate the different parametric studies stated earlier.

7.2 Modeling of the UHPC-NC composites

Non-linear static analysis was carried out to study the bond between the two surfaces of the composite UHPC-NC having different preparations and exposure conditions under different tests, bi-surface shear and splitting tensile tests a commercial FE tool (ABAQUS). Dynamic Explicit analysis is used to simulate the failure mode as described earlier. However, it must be noted that using dynamic analysis for static problems where inertial effects should be minimized by slow loading rates or by increasing the density to minimize the oscillation of the results [62]. Three-dimensional eight-noded solid elements (C3D8R) are utilized for modeling of UHPC-NC composites. The boundary conditions of bi-surface shear and splitting tensile test configurations are modeled, as shown in Figure 3.13 and 3.14. The steel plates were considered a perfect bond (Tie) with concrete. However, the bond between NC and UHPC was modeled, as mentioned above, and represented, as shown in Figure 7.1.



(a)



(b)

Figure 7.1 3D FE model in ABAQUS: (a) bi-surface shear test model; (b) splitting tensile test model

The non-linear behavior of the concrete is defined by a concrete damaged plasticity model (CDP) [63], [64]. The material parameters needed for the CDP are the values of Poisson's ratio, modulus of elasticity, the characterization of compressive and tensile stress-strain plastic behavior, and plastic damage parameters, as represented in Table 7.1.

Table 7.1 Parameters used for CDP model

Material properties	Dilation angle ψ	Flow potential eccentricity ε	Initial biaxial compressive stress to initial compressive stress f_{b0}/f_{c0}	Ratio of second stress invariant on the tensile meridian K_c	Viscosity parameter λ
NC	30.5	0.1	1.16	0.667	0
UHPC	39	0.1	1.16	0.667	0

K_c is the tensile proportion to the compressive meridian and determines the form of the deviatoric plane's yield layer (Figure 7.2) [65]. According to (ABAQUS manual 6.10) [66], the default value for eccentricity (ε) is close to 0.1. The dilation angle indicates the direction of the iteration vector of the plastic strain (Figure 7.3) [65]. Dilatation angles of NC and UHPC were used as 30.5° and 39°, respectively, reported by many researchers [67]. In addition, the other plastic damage properties were used as default, as suggested by ABAQUS (Table 7.1).

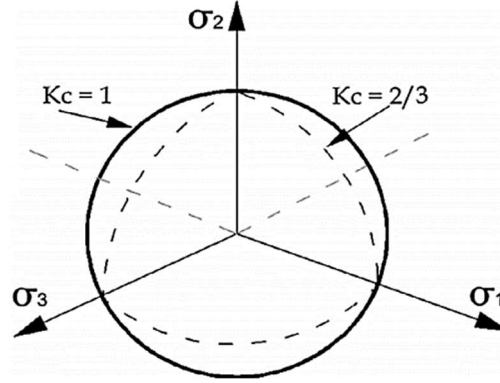


Figure 7.2 Yield surfaces in the deviatoric plane ($K_c = 0.667$ and $K_c = 1$ corresponds to the Rankine formulation and Drucker-Prager criterion, respectively) [65]

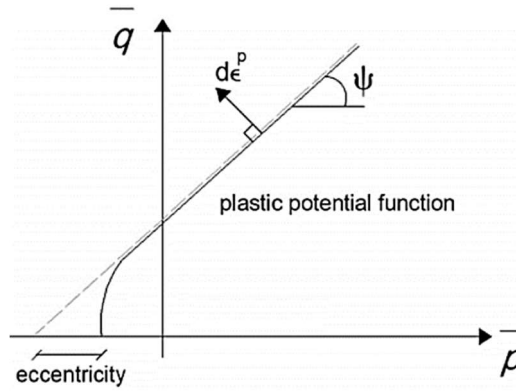


Figure 7.3 Dilation angle (ψ) and eccentricity (ϵ) in the meridian plane [65]

The concrete hardening and softening were applied in ABAQUS based on CEB-FIP Model Code [68], as seen in Figure 7.4, and expressed in the Eq. 7.1. Figure 7.4 indicates that an approximate of $0.4 f_c'$ was assumed for the compression curve's linear part. Consequently, this data is required in the form of a stress-inelastic strain in the CDP model.

$$\frac{\sigma_c}{f_{cm}} = \frac{k\eta - \eta^2}{1 + \eta(k - 2)} \quad 7.1$$

where σ_c is concrete stress, f_{cm} the average compressive strength of the concrete cylinder, k and η are two factors specified in accordance with Eqs. 7.2 and 7.3.

$$\eta = \frac{\varepsilon_c}{\varepsilon_{c1}} \quad 7.2$$

$$k = \frac{E}{E_{c1}} \quad 7.3$$

where ε_c is the concrete strain, ε_{c1} the compressive strain at the corresponding f_{cm} and E_{c1} is the secant elasticity modulus of the concrete from origin to the peak point of compressive stress.

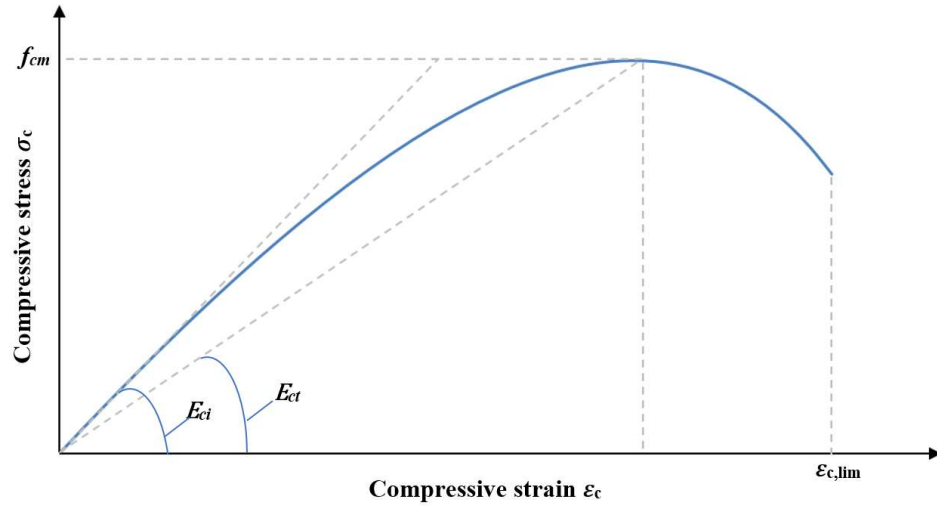


Figure 7.4 Schematic representation of the uniaxial compression stress-strain relation of NC [68]

The stress concrete behavior is assumed to be linear elastic before concrete cracking starts at a concrete rupture modulus, f_t and can be measured by Eq. 7.4 specified in ACI-318-14 [57]. The linear softening part after cracking shall be used as seen in Figure 7.5 with $W_c = 2G_f/f_t$ after the translation of the cracking opening to strain values divided by a

characteristic length, l_c , (this is calculated to be three times the maximum aggregate size of the concrete) [69]. The fracture energy G_F is determined using Eq. 7.5.

$$f_r = 0.62 \sqrt{f'_c} \quad 7.4$$

$$G_F = 73 (f'_t)^{0.18} \quad 7.5$$

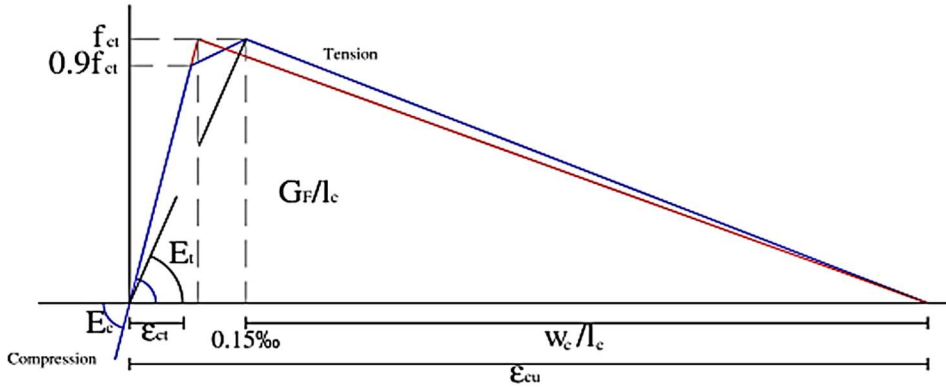


Figure 7.5 Bilinear concrete tension model [69]

The CDP model needed the data for the compression and tension damage parameters (d_c and d_t). These parameters can be calculated from the Eqs. 7.6 and 7.7, with b_c and b_t value limits between 0 and 1 [70].

$$d_c = 1 - \frac{\sigma_c E^{-1}}{\varepsilon_c^{pl} (1/b_c - 1) + \sigma_c E^{-1}} \quad 7.6$$

$$d_t = 1 - \frac{\sigma_t E^{-1}}{\varepsilon_t^{pl} (1/b_t - 1) + \sigma_t E^{-1}} \quad 7.7$$

The modeling of UHPC material was estimated in a similar way to NC [71]. The properties of NC and UHPC in compression and tension estimated and observed from the concrete behavior model are presented in Figure 7.6 and 7.7, respectively.

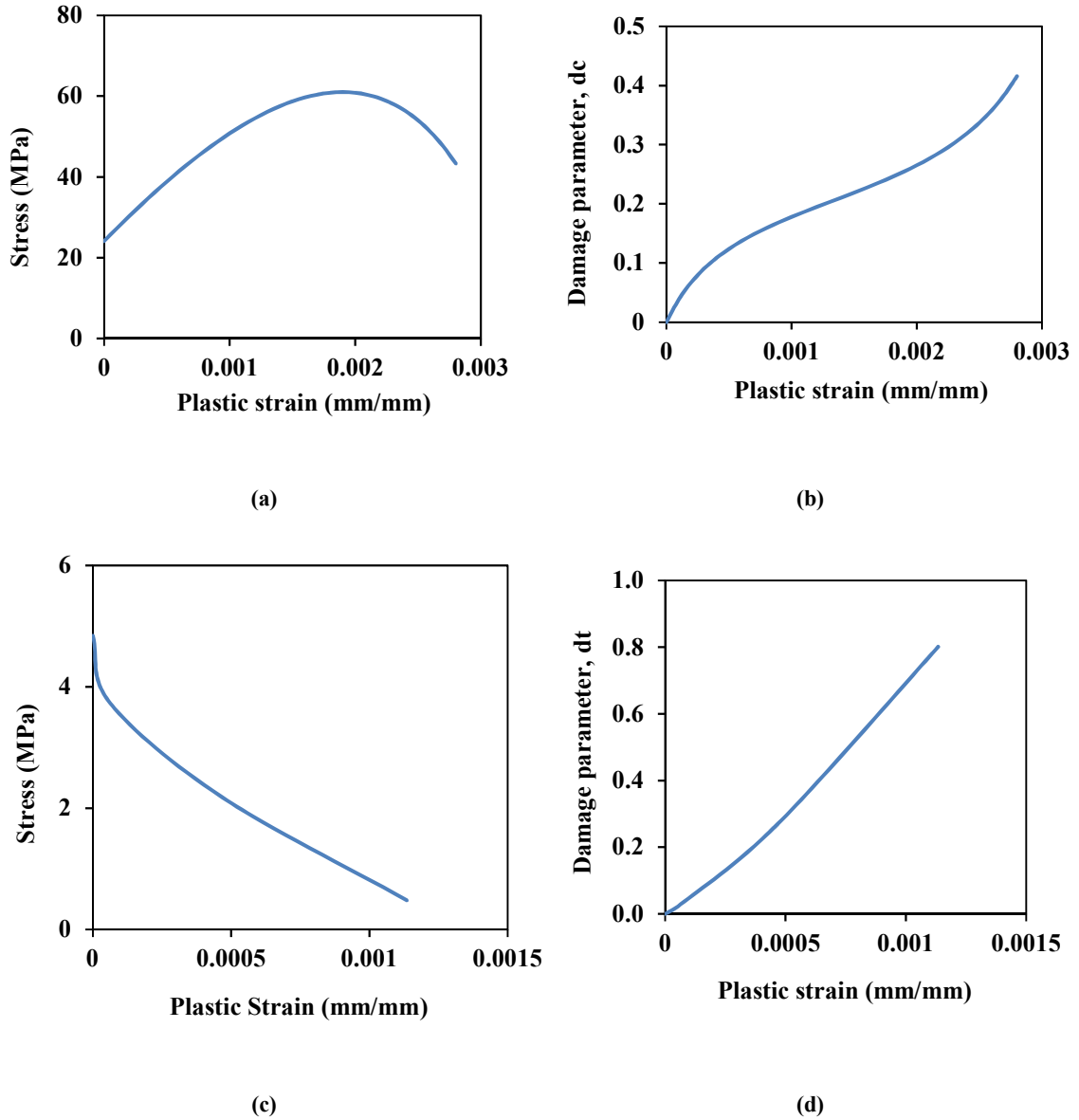


Figure 7.6 Properties of NC in compression and Tension: (a) Compression stress-plastic strain; (b) Compression damage-plastic strain; (c) Tension stress-plastic strain; (d) Tension damage-plastic strain

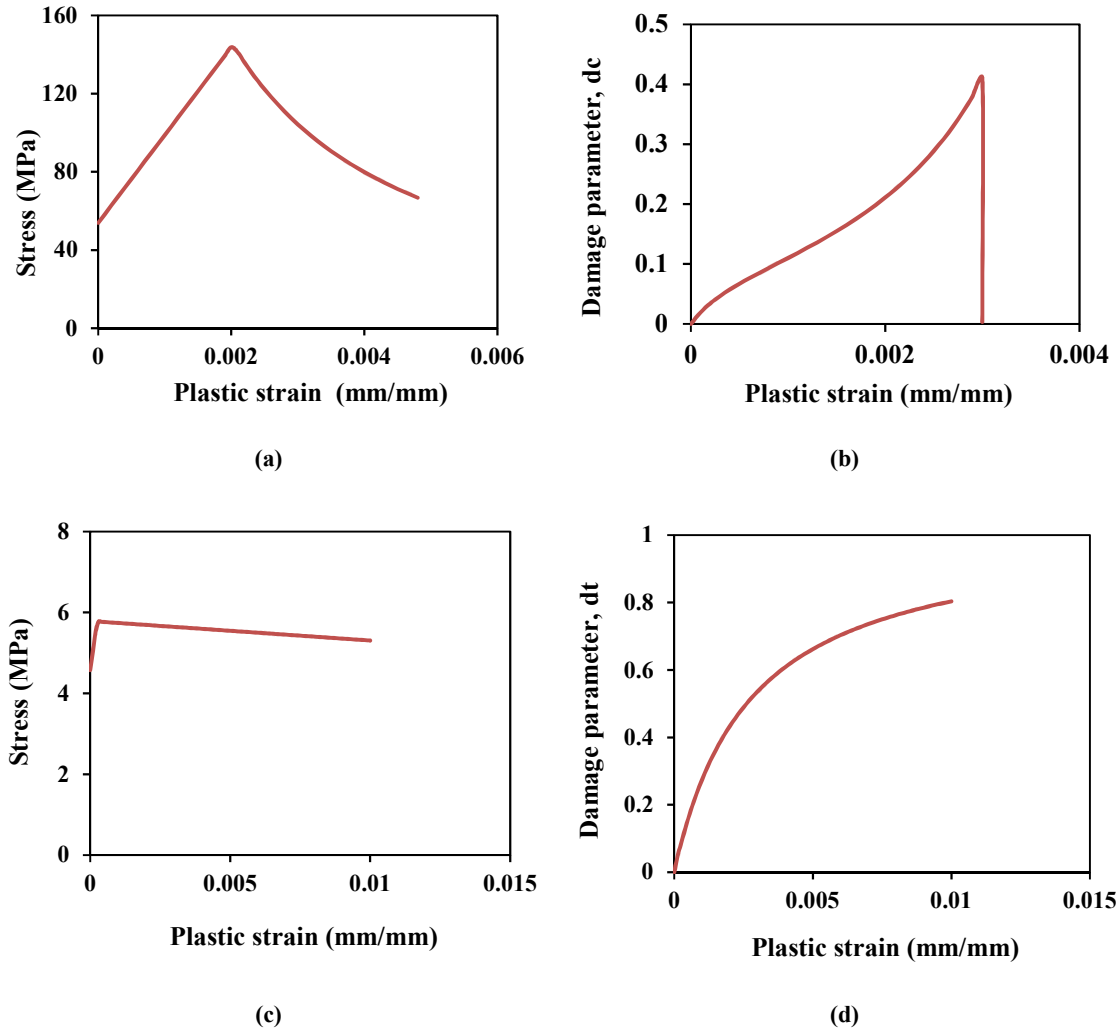


Figure 7.7 Properties of UHPC in compression and Tension: (a) Compression stress-plastic strain; (b) Compression damage-plastic strain; (c) Tension stress-plastic strain; (d) Tension damage-plastic strain

7.3 Surface-based cohesive behavior model

ABAQUS has two approaches to model bonded interface behavior utilizing traction-separation behavior, namely, cohesive elements and surface-based cohesive behavior. In this analysis, the interface thickness is negligible. Thus, due to its convenience and effectiveness, a surface-based cohesive approach is used [72]. This model based on the

concept of strain and displacement reinterpreted as contact separations. The respective displacements between the nodes on the slave layer and their associated projection points on the master surface along the normal contact and shear directions are redefined. Stresses are characterized for surface-based cohesion behavior as cohesive forces acting along normal contact and shear directions separated by the current area at each point of contact. The formulae and laws that govern surface-based cohesive behavior consist of two parts in ABAQUS, namely, the initial linear elastic and the post-elastic behavior established by the initiation and evolution of bond damage.

7.3.1 Linear elastic traction-separation behavior

In this model, the bond behavior between the two surfaces is represented as a linear elastic relationship between traction ($\mathbf{t}$) and separation (δ), which refer to the bond stress and slip, respectively. The elastic behavior is represented in terms of an elastic constituent matrix that compares the shear and normal stresses to the shear and normal separations through the interface [73]. The elastic behavior of the cohesive layer in the initial elastic range with uncoupled behavior is expressed in Eq. 7.8.

$$\mathbf{t} = \begin{pmatrix} t_{nn} \\ t_{ss} \\ t_{tt} \end{pmatrix} = \begin{bmatrix} K_{nn} & 0 & 0 \\ 0 & K_{ss} & 0 \\ 0 & 0 & K_{tt} \end{bmatrix} \begin{pmatrix} \delta_n \\ \delta_s \\ \delta_t \end{pmatrix} = \mathbf{K} \delta \quad 7.8$$

The traction (bond stress) vector $\mathbf{t}$, consists of three traction t_{nn} , t_{ss} and t_{tt} , which represent the normal and the local 1 and 2 directions related to the two shear tractions, respectively. The associated separations are referred by δ_n , δ_s and δ_t . In the present

investigation, the uncoupled traction-separation behavior (K_{nn} , K_{ss} and K_{tt}) is defined to avoid the default contact estimated by ABAQUS, indicated by several research studies. The unit [Force/Length²/Length] stiffness elements describe interaction in normal and two tangential directions, estimated based on exponential regression.

7.3.2 Damage initiation and evolution behavior

Post-elastic behavior is defined by the initiation and evolution of bond damage. Damage initiation corresponds to the start of a cohesive reaction deterioration at the interaction point. The deterioration process occurs when interaction stress and/or separation meets such damage initiation conditions, which depends on the relationship between the bond stress and slip, i.e., the UHPC-NC interaction surface behavior's bond performance. The traction-separation (bond stress-slip) reaction with initiation and evolution failure mechanism is described in Figure 7.8. Several damage initiation criteria are available in ABAQUS, namely, maximum stress, maximum separation, quadratic stress, and quadratic separation criteria (ABAQUS Manual, [66]). Each criterion for inducing damage also has an outcome variable. For an instant, a value of 1 or higher shows that the criterion has been accomplished. Criteria for the initiation of damages that do not have a related evolution law; thus, the criteria could be used, without determining the evolution of damage, to determine the material's tendency to endure a particular degradation.

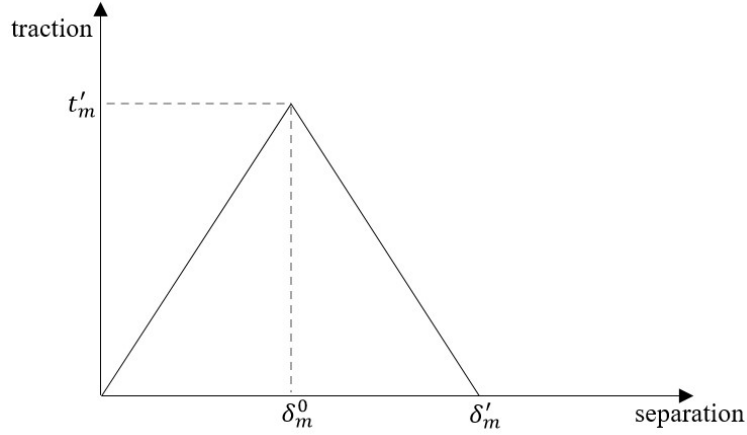


Figure 7.8 Typical bond traction separation response with linear damage development

In this study, the maximum stress criterion of the separation (slip) was used and related to the bond damage stress. The relationship of these criteria is estimated in Eq. 7.9. The symbol used in the normal stress (t_n) below represents within the Macaulay bracket with the typical interpretation, to imply that a purely compressive displacement and/or stress ($t_n < 0$) does not initiate damage.

$$\text{Max} \left\{ \frac{\langle t_n \rangle}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0} \right\} = 1 \quad 7.9$$

The Damage evolution rule defines how cohesive stiffness is degraded until the relating initiation criterion has been met. Thus, by using ABAQUS, the linear response was defined by maximum separation in which the bond fully degraded. The maximum effective separation (δ_m) determined from Eq. 7.10.

$$\delta_m = \sqrt{\langle \delta_n^2 \rangle + \delta_s^2 + \delta_t^2} \quad 7.10$$

7.4 FEM Validation

To validate the proposed FE model, a mesh sensitivity analysis was carried out for bi-surface shear and splitting tensile models. Four different mesh sizes (5 mm, 25 mm, 50 mm, and 100 mm) were used to examine the mesh sensitivity of the bi-surface shear model (Figure 7.9a). On the other hand, the splitting tensile model (2.5 mm, 5 mm, and 7.5 mm) was assumed (Figure 7.9b).

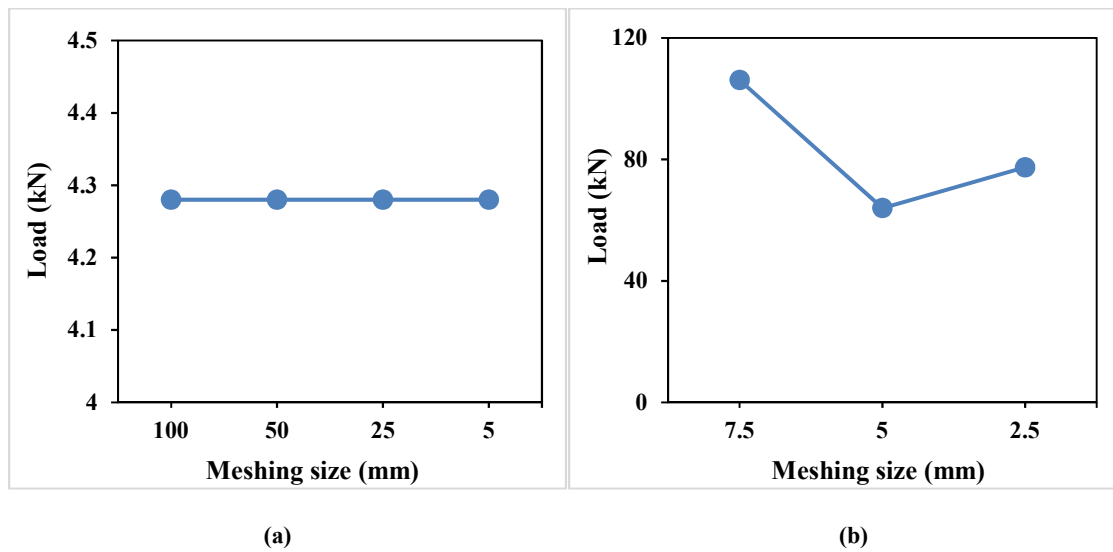
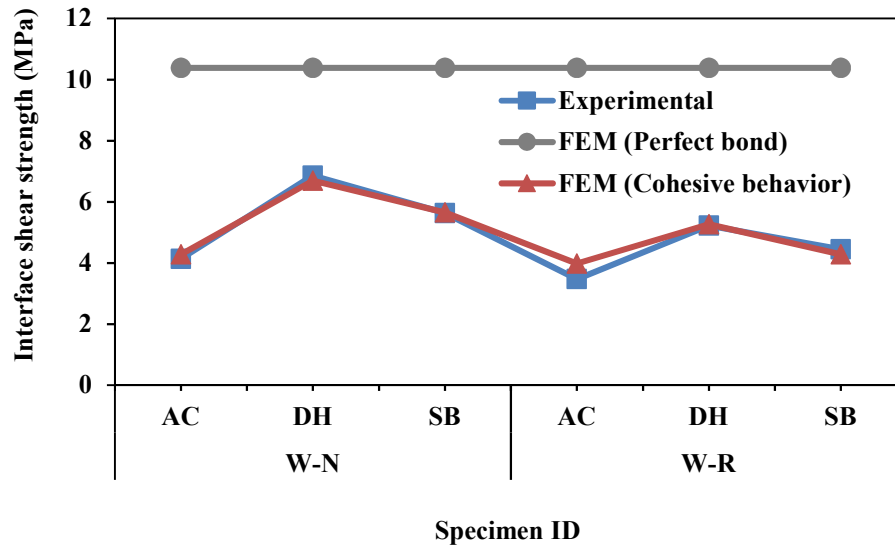


Figure 7.9 Mesh sensitivity analysis: (a) bi-surface shear; (b) splitting tensile

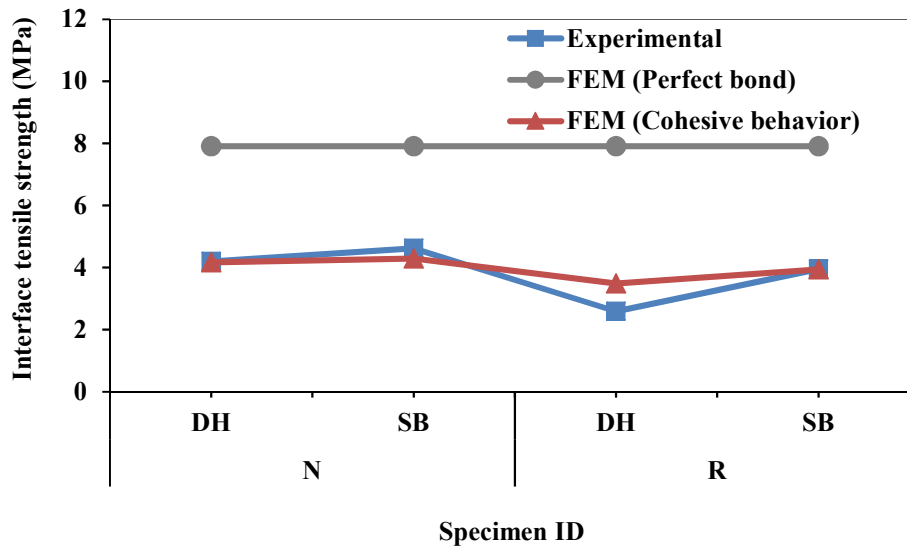
It can be noted that the bi-surface shear model exhibits no change in the results even with the finest mesh size of 5 mm, as shown in Figure 7.9a. However, there was a significant change in the results for splitting tensile model of up to 40% of 7.5 mm mesh compared to 5 mm, as shown in Figure 7.9b, thus large convergence due to the coarser size of the mesh. Therefore, for bi-surface shear and splitting tensile models, a meshing size of 50 mm and 5 mm was considered, which provided a constant and reasonable estimate of the model simulation results.

Different values of the stiffness, damage initiation, and evolution parameters have been used to validate the proposed numerical model. The results of the cohesive model with experimental findings and the model with a perfect bond contact of the UHPC-NC interfaces are compared in Figure 7.10 and Table 7.2.

Figure 7.10 describes the findings obtained from the perfect contact and the surface-based cohesion model compared to the experimental results. Compared to the AC surface, the highest error dropped from approximately 200% of the tie model to 15% of the cohesive contact simulation compared to the experimental findings (Figure 7.10a). Similarly, the overall error margin decreased from almost 205% to 35% estimated from DH interfaces (Figure 7.10b). In addition, relative to the UHPC-NC sandblasting surface roughness, there was a substantial reduction in the error from nearly 135% to 4% utilizing a bi-surface shear model, as shown in Figure 7.10a.



(a)



(b)

Figure 7.10 Experimental and numerical validation results modeled with different surface preparation and exposure condition of the UHPC-NC composites: (a) bi-surface shear; (b) splitting tensile test methods

Table 7.2 Numerical validation results of bi-surface shear and splitting tensile models

Model	Spec. ID	Surface prep.	Cohesive Stiffness Parameters (N/mm ² /mm)			Damage Initiation (mm)	Damage Evolution	Exp. results (MPa)	FEM results (MPa)
			K_{nn}	K_{ss}	K_{tt}	δ_t	$Total/U_{pl}$		
Bi-surface shear	W-N	AC	2.4	20	20	5	0.1	4.13	4.28
		DH	2.4	20	20	9	0.1	6.86	6.69
		SB	2.4	20	20	5	0.5	5.63	5.65
	W-R	AC	2.4	12	12	3	0.1	3.47	3.98
		DH	2.4	14	14	5	0.1	5.22	5.26
		SB	2.4	20	20	5	0.1	4.45	4.28
Splitting tensile	W-N	DH	2.4	16	16	5	0.1	4.2	4.17
		SB	2.4	20	20	7	0.1	4.62	4.29
	W-R	DH	2.4	30	30	5	0.1	2.59	3.49
		SB	2.4	11	11	5	0.1	3.95	3.94

Based on the adopted parameters of the stiffness, damage initiation, and evolution for the different UHPC-NC composites (Table 7.2), a typical failure mode has been observed utilizing ABAQUS software, as shown in Figure 7.11 and 7.12.

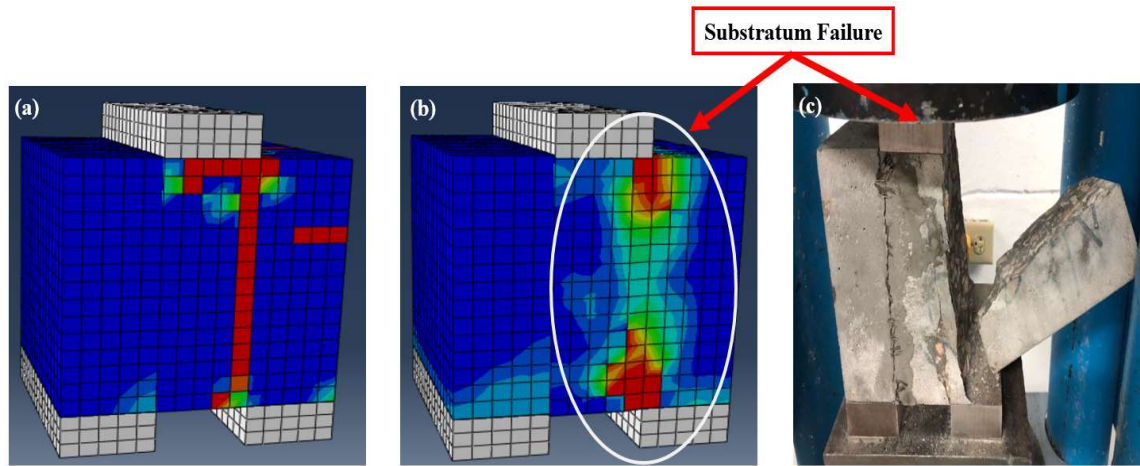


Figure 7.11 FE typical failure mode for cubic model: (a) tension damage; (b) compression damage; (c) specimen failure

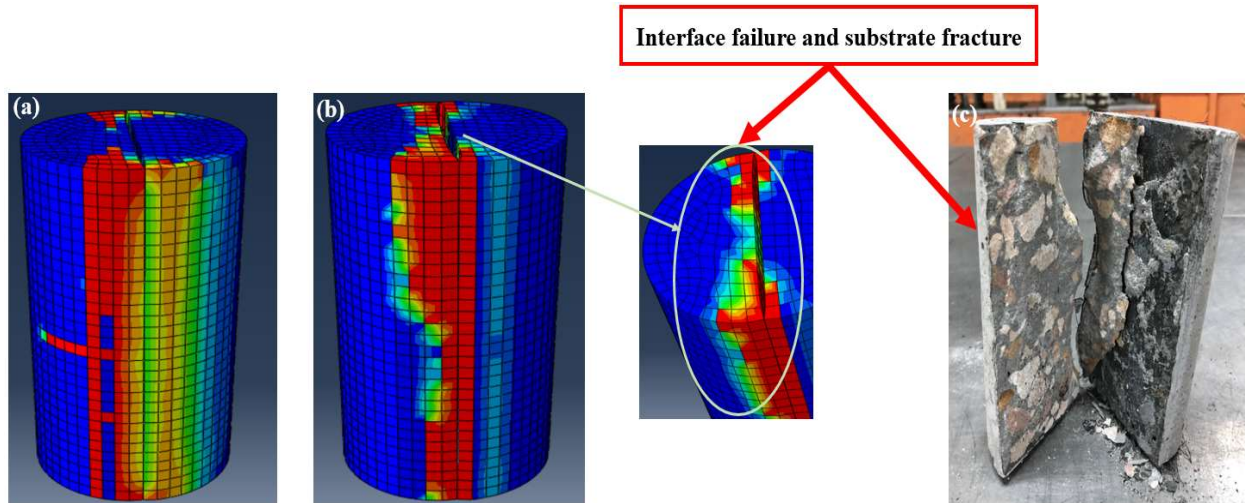


Figure 7.12 FE typical failure mode for cylindrical model: (a) tension damage; (b) compression damage; (c) specimen failure

The bi-surface shear and splitting tensile failure obtained from the ABAQUS FE model by damage pattern represented by tension damage (d_t) and compression damage (d_c). Figure 7.11 indicates that experimental findings have verified the cubic model's cohesive failure mode. In addition, the FE simulation, as shown in Figure 7.12, also confirmed the failure of the interface and the fracturing of the substrate resulting from the tensile splitting test methods.

In conclusion, by comparing the tie model and surface-based cohesive model with experimental results, it noted that using a surface-based cohesive behavior approach to encounter different surface roughness and prevent load capacity erroneous that overestimated from perfect bond (tie). To sum up, based on the FEM validation, a parametric analysis was then carried out as outlined in the following section.

7.5 FEM Parametric studies

A parametric study was conducted to study the effects of key parameters, such as cohesive stiffness (k_{ss}, k_{nn}, k_{tt}), damage initiation ($\delta_s, \delta_n, \delta_t$) and evolution ($Total/U_{pl}$). Based on several iterations for these parameters, it is found that the value of the normal stiffness (k_{nn}) is kept fixed while the shear and tangential stiffnesses are varying based on the different surface preparations and exposure conditions (Figure 7.13 and 7.14). On the other hand, varying the value of the slip in a tangential direction (δ_t) and keeping the other two deflection as zero since are very small in other directions (Figure 7.15 and 7.16). Moreover, the value of the total per plastic displacement ($Total/U_{pl}$) is also varies from 0.1 to 1

(Figure 7.17 and 7.18). In the end, reasonable range values were obtained on the basis of this parametric analysis, as detailed in Table 7.3.

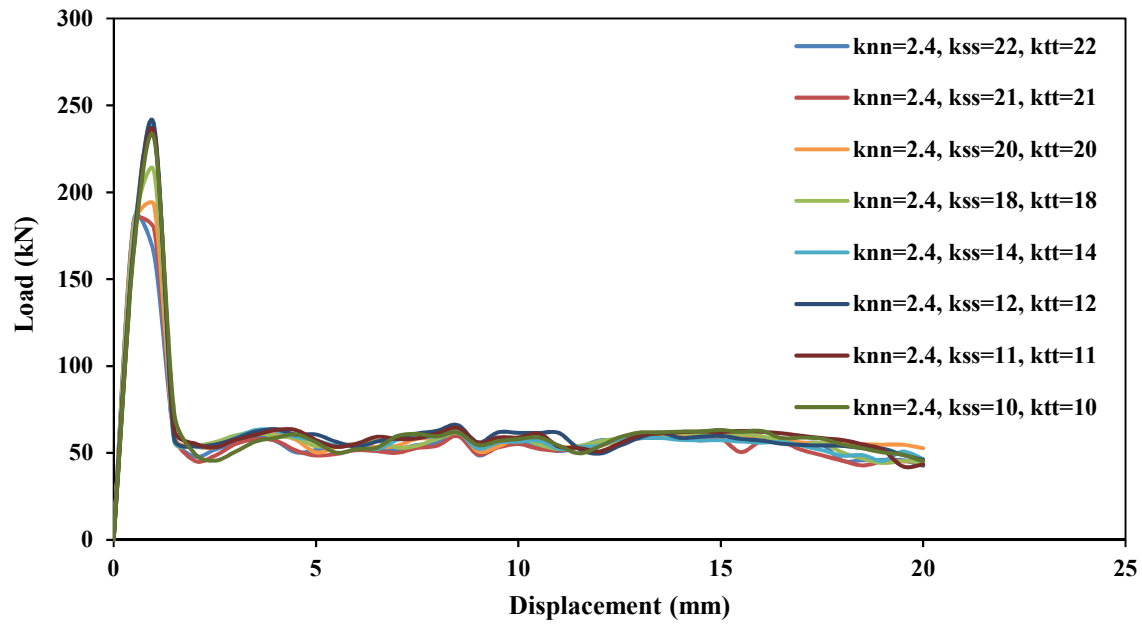


Figure 7.13 Cohesive stiffness parameters analysis of the bi-surface shear model (Load-displacement curve)

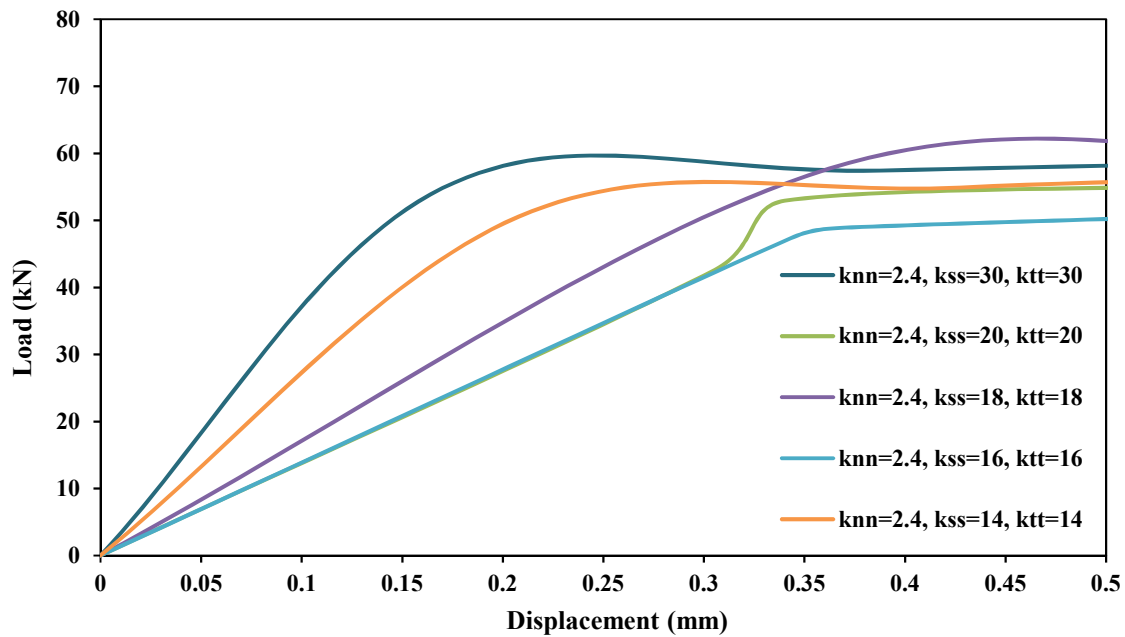


Figure 7.14 Cohesive stiffness parameters analysis of splitting tensile model (Load-displacement curve)

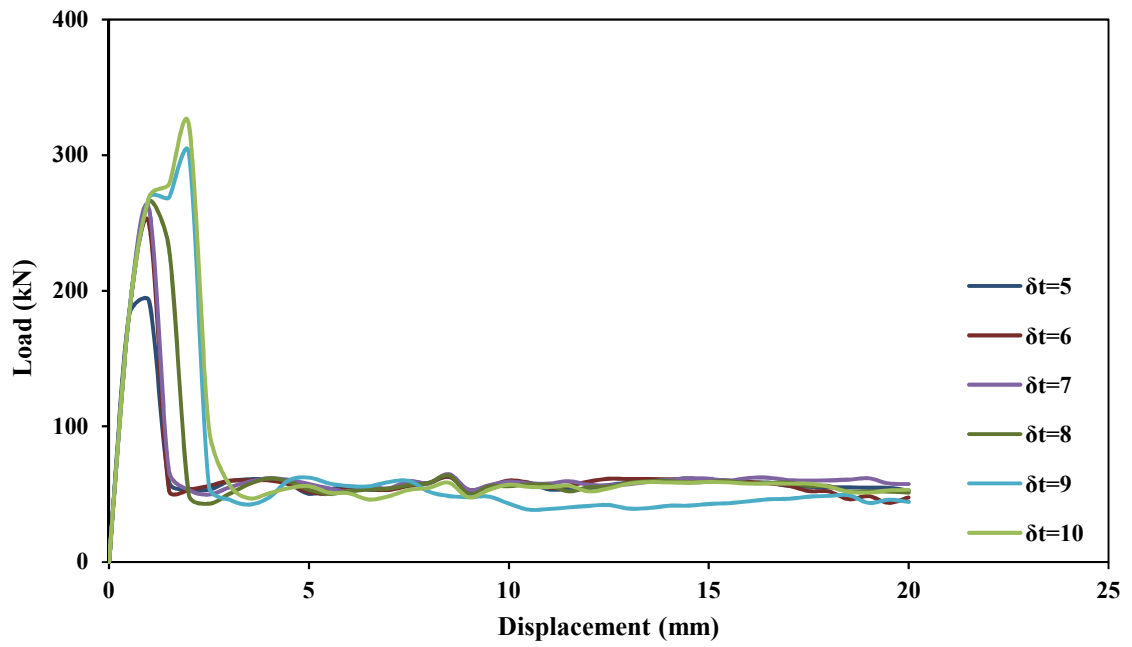


Figure 7.15 Damage initiation analysis of the bi-surface shear model (Load-displacement curve)

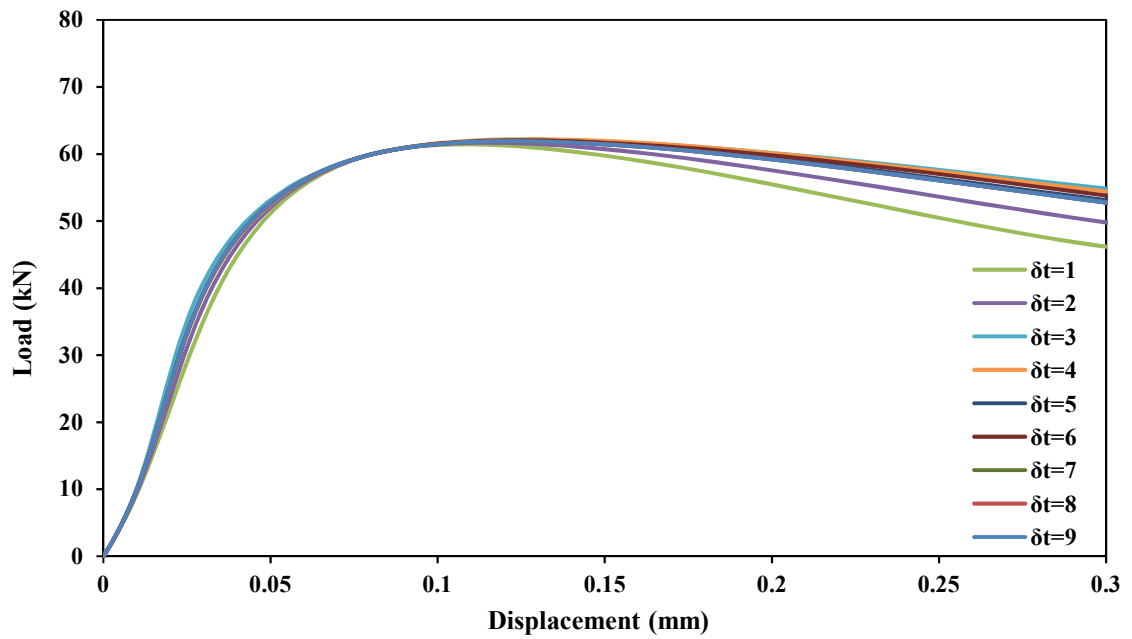


Figure 7.16 Damage initiation analysis of splitting tensile model (Load-displacement curve)

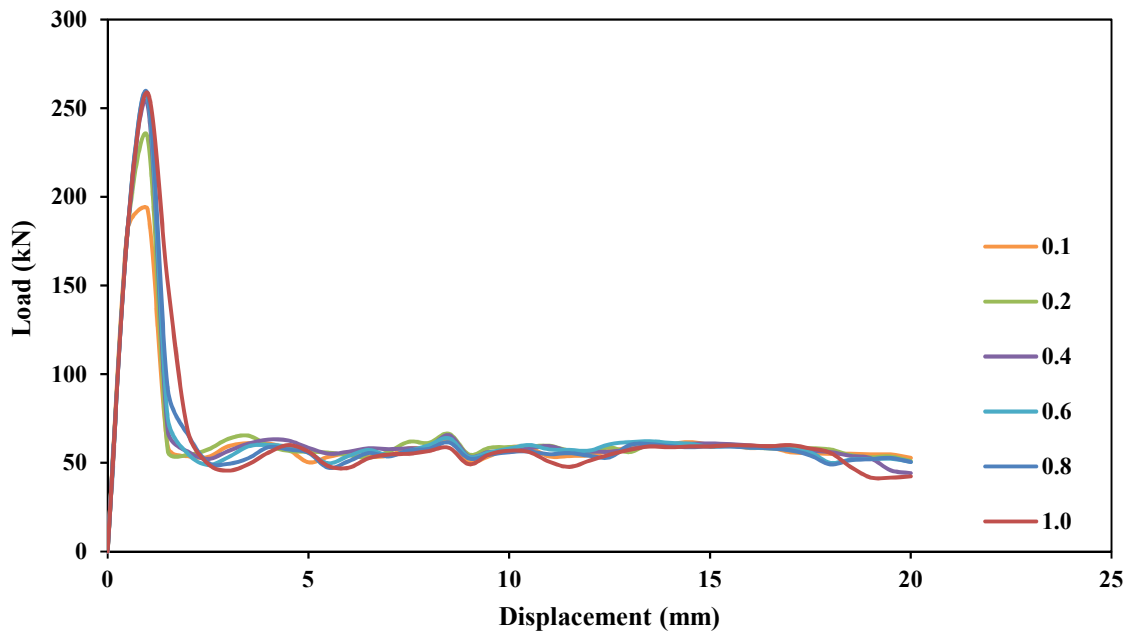


Figure 7.17 Damage evolution analysis of the bi-surface shear model (Load-displacement curve)

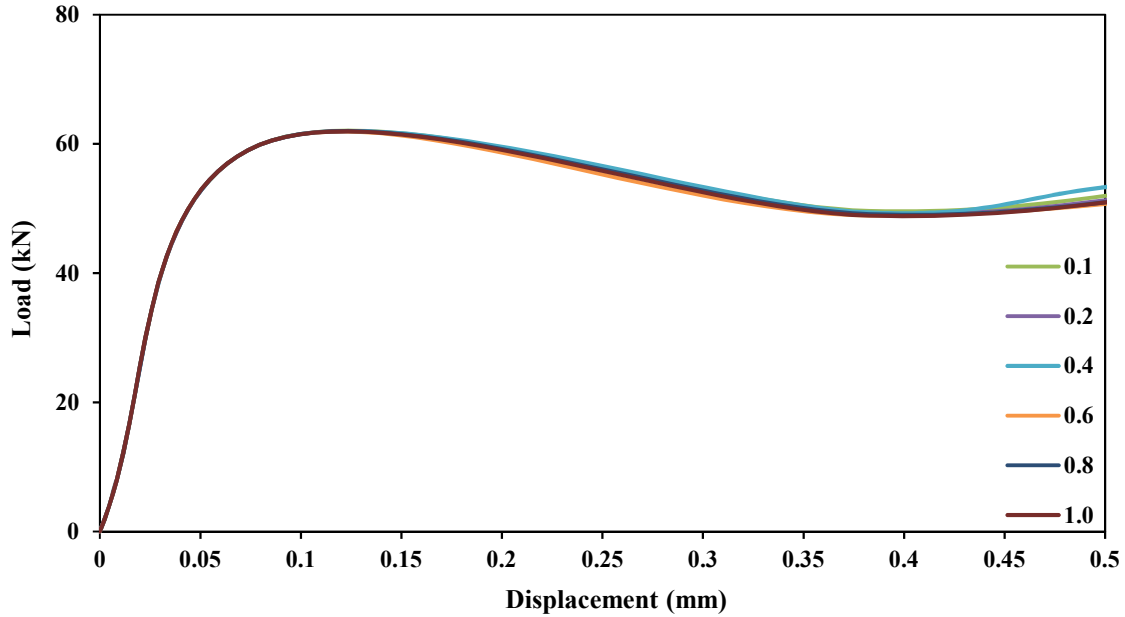


Figure 7.18 Damage evolution analysis of splitting tensile model (Load-displacement curve)

Table 7.3 The acceptable range of parameters of the interface model for different surface preparation validated from bi-surface shear and splitting tensile tests

Bond tests	Surface preparation	Cohesive stiffness parameters (N/mm ² /mm)				Damage initiation (mm)		Damage evolution	
		k_{ss} (min)	k_{ss} (max)	k_{tt} (min)	k_{tt} (max)	δ_t (min)	δ_t (max)	$Total/U_{pl}$ (min)	$Total/U_{pl}$ (max)
Bi-surface Shear	SB	12	20	12	20	5	8	0.1	0.9
	DH	11	20	11	20	5	9	0.1	0.9
	AC	12	22	12	22	3	5	0.1	0.1
Splitting tensile	SB	11	20	11	20	5	7	0.1	0.9
	DH	11	30	11	30	5	7	0.1	0.8

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 General

In this study, firstly, the bond behavior between various exposed concrete substrate interfaces (NC, SC, and SCC) and UHPC (used as repairing/strengthening overlay) was investigated utilizing the test results obtained through different tests. Secondly, modeling of the UHPC-NC composites was carried out using nonlinear FE analysis in ABAQUS software for bi-surface shearing and splitting tensile test methods. The load-displacement curve and the typical failure mode were predicted and simulated. Finally, a parametric study was conducted using the validated model.

The following conclusions can be drawn based on the results of the experimental and numerical studies.

8.2 Conclusions

8.2.1 General

- The curing condition does not significantly change the bond behavior compared to the substrate's surface preparation.

- The sandblasting technique provided the highest strength under different types of bond tests, except for the bi-surface shear test, which the highest due to the preparation of the drill holes. Thus, it could be that the sandblast did not fill with UHPC overlay in which the air voids resulted in lower surface contact between the UHPC and substrate.
- The slant shear test results can be used to investigate the bond behavior between the UHPC and concrete substrate interface by defining the cohesion parameter to estimate the coefficient friction and better understand the bond mechanisms under various contact conditions.
- Based on the results obtained from different types of bond tests, it can be observed that the need to utilize bond behavior under the various state of stress applied is necessary. To satisfy the minimum requirement and acceptance criteria, the mechanisms of the bond behavior in various parametric studies, i.e., surface preparation, curing condition, and the effect of repeated cyclic exposure is essential to interpret the purpose for such bond testing properly.
- Based on the results obtained from the bi-surface shear test, it can be noted that the samples with drilled holes preparation tend to have a slightly greater improvement in bond strength relative to sandblasted roughness. This interprets that the sample with the drill holes' surface must be prepared if direct shear stress is applied.
- By comparing the results obtained from different types of bond tests, it is found that the splitting tensile test is reliable since the results obtained from as cast samples were very critical and even did not meet the acceptable criteria for repeated cyclic exposure samples.

- The results obtained from splitting tensile and third-point flexural tests were very similar. However, the third-point flexural test provided more conservative bond strength than the splitting tensile test as flexural strength leads to higher tensile strength due to bending in extreme fiber that could be free from defects.
- The bond strength in the slant shear was higher than the bi-surface shear due to the normal stress, which increases the friction between the contact layers in the slant shear test.
- The lowest reduction in bond strength experienced in the slant shear test was exactly 0% with the sandblast's surface preparation, except for the UHPC-SCC with a 10% decrease relative to the normal condition.
- In the splitting tensile test, the composites (UHPC-SC and UHPC-SCC) with the as cast and drilled holes surfaces did not meet the minimum ACI546-06 specifications, while the composite (UHPC-NC) only failed under the as cast surface.
- Knowing the minimum bond strength values and then compared them to the values specified by the design codes and the relevant research studies would give engineers the confidence they require while using this new material in various field applications.
- The values of the cohesion and friction coefficient for UHPC-NC, UHPC-SC, and UHPC-SCC composites achieved the acceptable limits specified by the AASHTO LRFD (2014).

8.2.2 UHPC-NC composite specimens

- The highest bond strength change occurred in drilled holes samples ranging from 2.3% to 20.4% of third-point flexural and bi-surface shear, respectively.
- The highest reduction in bond strength experienced in the splitting tensile test was roughly 38% with the drill holes' surface preparation.
- It could be suggested that the shear strength equations for normal-weight concrete defined in ACI318 take into account the effect of repeated cyclic exposure of the composite samples.

8.2.3 UHPC-SC composite specimens

- The highest increase in bond strength that occurred to heat curing was almost 33% compared to the splitting tensile test's water curing.
- The highest reduction in bond strength experienced in the splitting tensile test was approximately 51% with the drill holes' surface preparation.

8.2.4 UHPC-SCC composite specimens

- The highest increase in bond strength that occurred to water curing was almost 35% compared to the bi-surface shear test's heat curing.
- The highest reduction in bond strength experienced in the splitting tensile test was approximately 55% with the drill holes' surface preparation.

8.2.5 Finite element modeling

- The results of FEM showed good agreement with the experimental test results.
- The Surface-based cohesive behavior model could predict the bond with good accuracy.

8.3 Recommendations for Future Research

The following suggestions for future work in this area:

- The behaviors of the bond should be researched under long term exposure condition.
- The strengthening technique should be investigated under various cyclic reversal loads.
- More numerical research is required to investigate the performance of the FE model.

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