

**EFFECT OF FIBER TYPE AND CURING REGIME ON
THE MECHANICAL PROPERTIES OF ULTRA-HIGH
PERFORMANCE CONCRETE**

BY

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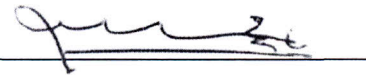
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To

My Beloved Parents

My Lovely Wife and Son

My Brothers and Sister

For Their Support, Patience, and Love

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In the Name of Allah, Most Gracious Most Merciful. All perfect praise be to Allah, the Lord of the worlds, for guiding me and granting me patience, knowledge, courage, and health, to complete this research successfully. May the peace and blessings be upon our Prophet Mohammad, his household, his companions, and upon those following them in goodness until the Day of Judgment.

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LIST OF ABBREVIATIONS

UHPC	: Ultra-High Performance Concrete
SC	: Steam Curing
WC	: Water Curing
HSS	: High Strength Steel
RS	: Regular Steel
ASTM	: American Society for Testing and Materials
RILEM	: Réunion Internationale des Laboratoires et Experts des Matériaux
LVDT	: Linear Variable Differential Transformer
MOT	: Modulus of Toughness
PVC	: Polyvinyl chloride
UTM	: Universal Testing Machine
CDP	: Concrete Damage Plasticity

ABSTRACT

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Thesis Title : Effect of fiber type and curing regime on the mechanical properties of UHPC

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Ultra-high performance concrete (UHPC) is a newly developed concrete material that has excellent mechanical and durability characteristics along with its special features that include high ductility and fracture toughness. Although, research works pertaining to UHPC are widely reported in the literature, still efforts are being made to understand the behavior of UHPC to explore possibilities of using it for different applications. There is a wide coverage of mechanical characteristics of UHPC in terms of strength, ductility, and fracture toughness, by researchers around the globe. However, a very limited information is available in the literature on the characteristics of the bond between UHPC and embedded steel rebars. The present research work was conducted with the main objective of investigating the effect of two key factors (hybridization of two types of fibers and two curing methods) on the mechanical properties (compressive strength, flexural strength, modulus of elasticity and modulus of toughness) of UHPC including the bond strength considering two different types of steel rebars.

The experimental program consisted of preparation of several sets of specimens used to conduct different tests. UHPC specimens were cast using the same proportions of ingredients. However, the constitution of the steel fiber component of the UHPC mixtures was varied to produce five different combinations of straight and hooked steel fibers. The

five combinations of steel fibers considered were obtained by replacing straight fibers with hooked fibers at: 0%, 30%, 50%, 70%, and 100%. UHPC specimens prepared by embedding steel bars of two different strength grades (G60 and G230) were utilized for the evaluation of steel-UHPC bond characteristics. All test specimens were subjected to two curing regimes: water curing and steam curing. The data generated through this experimental investigation helped to understand the effects of the studied key factors on the mechanical properties of UHPC, including steel-UHPC bond characteristics. The test results exhibited significant effect of the hybridization of straight and hooked fibers on the studied properties of UHPC. The performance of steam curing was found better than that of water curing in all aspects. Finite element model (FEM) and empirical models were developed to model the behavior of the bond between UHPC and embedded rebar for each of the fibers combinations, curing methods and grades of embedded steel bars.

|

ملخص الرسالة

الاسم الكامل: عبدالرحمن محمد شريف

عنوان الرسالة: تأثير نوعية الألياف الفولاذية ونظام المعالجة على الخصائص الميكانيكية لمادة ال UHPC

التخصص: هندسة مدنية

تاريخ الدرجة العلمية: أبريل 2020

الخرسانة عالية الأداء (UHPC) هي مادة خرسانية تم تطويرها حديثاً وتتميز بخصائص ميكانيكية ومثانة ممتازة إلى جانب ميزات الخاصة التي تتضمن الليونة العالية وصلابة الكسر. على الرغم من أن الأعمال البحثية المتعلقة بال UHPC تم مناقشتها في نطاق واسع من الأوراق البحثية والمنشورات ، إلا أن مادة ال UHPC لا تزال قيد الدراسة لفهم سلوكياتها واستكشاف إمكانيات استخدامها للتطبيقات المختلفة. معظم البحوث المتعلقة بـ UHPC تناقش خصائص القوة والليونة وصعوبة الكسر للمادة. بالمقابل، فإن الأعمال البحثية المتوفرة التي تتناول سلوك العلاقات الترابطية بين UHPC وقضبان حديد التسليح محدودة جداً. الهدف الرئيسي من هذا البحث هو التحقق من تأثير عاملين رئيسيين هما (خلط نوعين من الألياف الفولاذية، واتباع طريقتين مختلفتين لمعالجة الخرسانة) على الخواص الميكانيكية لل UHPC وتشمل (مقاومة الانضغاط، وقوة الانثناء، ومعامل المرونة، ومعامل الصلابة)، بما في ذلك قوة الربط بين ال UHPC وحديد التسليح مع الأخذ بعين الاعتبار نوعين مختلفين من حديد التسليح.

يتألف البرنامج التجريبي من إعداد عدة مجموعات من العينات بغرض استخدامها في إجراء اختبارات مختلفة. تم صب عينات ال UHPC باستخدام نفس نسب المكونات، ولكن تم استخدام خمس تركيبات مختلفة من الألياف الفولاذية حيث تم استبدال الألياف المستقيمة بألياف مثنية على النحو التالي: 0٪، 30٪، 50٪، 70٪ و 100٪. تم زرع قضبان فولاذية بدرجتين مختلفتين من الفولاذ هما (G230 و G60) في عينات ال UHPC المستخدمة لاختبار قوة الترابط بين ال UHPC وقضبان التسليح. في هذه الدراسة تم استخدام طريقتين لمعالجة الخرسانة وهما المعالجة بالمياه والمعالجة البخار. ساعدت البيانات التي تم الحصول عليها من خلال هذه الدراسة التجريبية على إدراك تأثير العوامل الرئيسية المدروسة على الخواص الميكانيكية لل UHPC بما في ذلك قوة الترابط. أظهرت نتائج الاختبار تأثيراً كبيراً لاختلاف

نسب كميات الألياف المستقيمة والمثنية على خصائص UHPC. كما كان للمعالجة بالبخار أداء أفضل من المعالجة بالماء في جميع الجوانب. تم تطوير نموذج العناصر المحدودة (FEM) والنماذج التجريبية لمحاكاة سلوك الرابطة بين UHPC وحديد التسليح لكل مجموعة من الألياف وطرق المعالجة ودرجات قضبان التسليح المستخدمة.

|

CHAPTER 1

INTRODUCTION

1.1. General

Ultra-high performance concrete (UHPC) is an advanced cement-based material that has a compressive strength above 150 MPa with excellent durability, tensile strength, ductility, and fracture toughness. Fibers are essentially used as an ingredient of the UHPC mixture to achieve the specified requirements. UHPC is typically made by combining Portland cement, supplementary cementitious materials (i.e., silica fume alone or in combination of the other mineral admixture), quartz powder, fine sand, superplasticizer, and water without using the coarse aggregates. The types of fibers used in UHPC include high carbon steel, PVA, glass, carbon, or a combination of these types. The fibers used in UHPC may be straight or hooked or mixture of straight and hooked.

The flowability of UHPC mixture makes it self-compacting. The high compressive and tensile properties of UHPC also facilitate a high bond strength allowing the shorter length of rebar embedment. The ductile behavior of UHPC gives it the ability to deform and withstand flexural and tensile loads, even after initial cracking. The use of UHPC in construction can eliminate the need for reinforcing steel in some applications. The use of UHPC can reduce the concrete member thickness and changing concrete structural shapes. The weakness of any cementitious material is in its low tensile strength when compared with the compressive strength, and this explains why steel reinforcement is added in areas

with tensile stresses. The stronger bond between the reinforcement and concrete makes the reinforced concrete member stronger in resisting the tensile loads [1]. Many parameters, like the properties of concrete, curing method, temperature, and surface condition, have a significant influence on the bond strength between concrete and rebar. The major factors that affect the bond strength of UHPC include compressive strength of UHPC, fiber content, fiber type, embedment length of the bar, bar type, bar diameter and curing regime [2-6]. Recently, investigations have shown that the use of different shaped steel fibers has a different effect on the bond strength of UHPC and reinforcement [7, 8].

1.2. Research significance

The advent of UHPC has led to considerable research efforts aiming to utilize the material in structural applications. This research tries to identify the effect of fiber hybridization and curing method on the compressive strength, modulus of elasticity, flexural strength, flexural toughness, and bond strength of UHPC besides the reinforcing steel grade. It is of an interest that this study would help to find the optimum proportioning of straight and hooked steel fibers based on the performance of UHPC at each combination of the straight and hooked fibers. The literature lacks the availability of explicit studies that address the mentioned factors on the mechanical properties of UHPC, especially the bond interaction between UHPC and the reinforcement.

Furthermore, this study would provide some upgraded empirical models that could be utilized to predict the mechanical properties of UHPC to an acceptable accuracy. The numerical modeling utilizing the experimental data developed under this study with the help of finite element method (FEM) was used to simulate the mechanical properties of

UHPC. The agreement between the numerical and experimental results proved the notable capabilities of FEM to provide accurate predictions.

1.3. Research objectives

The main objective of the this research work was to study the effects of three key factors (i.e., the hybridization of two types of steel fibers at different ratios, curing methods, and types of steel bars) on the compressive strength, modulus of elasticity, flexural strength, flexural toughness, and bond strength of UHPC. The specific objectives are:

1. To investigate the effect of different types and combinations of steel fibers (hooked and straight fibers) and curing regimes on the mechanical properties of UHPC.
2. To investigate the effect of different grades of steel bars on the bond strength of UHPC besides the effect of fiber combinations and curing regimes.
3. To conduct numerical and empirical modeling of the bond between UHPC and steel rebar.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

This chapter presents a collection of reviews of the literature pertaining to mechanical properties of UHPC including the compressive strength, flexural strength and the bond strength. The literature review presented in this chapter also include the information regarding the effect of fiber hybridization and curing methods on the characteristics of UHPC, mainly the compressive strength and how it relates to bond strength. Finally, the review of studies on numerical and empirical modelling of the bond between concrete and steel bars, conducted by previous researchers, study are also presented.

2.2. Compressive Strength and Flexural Strength

One of the most significant properties of UHPC is its high compressive strength, which could reach 150 MPa or even greater (Abbas et al. [9], Abbas et al. [10] and Ahmad et al. [11]). The high strength is achieved by using low water/binder ratio (less than 0.2), elimination of coarse aggregates, the use of superplasticizers, and the high dosage of cementitious materials. Another important property of UHPC is the flexural strength. In the studies of Abbas et al. [10] and Ahmad et al. [11] the flexural strength reached up to 35 MPa and greater. The high flexural strength is achieved due to the presence of the steel fibers in the UHPC mixture.

The existence of steel fibers in UHPC is very influential. An investigation that was carried out on the use of steel fibers found that UHPC with no fibers resulted in compressive and

flexural strengths of 107 and 9 MPa, respectively. However, by adding 2% fiber dosage, the compressive and flexural strengths increased to 161 and 27 MPa, with an increase of 33% and 66%, respectively (Ibrahim et al. [12], Wu et al. [13]).

From past studies, it was observed that the larger the fibers content used, the higher the compressive and flexural strengths recorded for UHPC [13-18]. While that might be true to some extent, another study by Wu et al. [17] concluded that the optimum fiber content is 2%, and any further increase has limited effect on strength and toughness. The work reported by Wang et al. [14] states that using 1% fiber dosage can cause small increase in compressive and flexural strengths, while increasing fiber content to 2% and 3% can cause a remarkable increase in the compressive and flexural strength.

Steel fibers are made out from different materials such as steel, glass, polypropylene and polyvinyl alcohol. They are available in different shapes such as straight (long, medium and short) or deformed (hooked, twisted and corrugated). The variety of fibers shapes imposes different effects on the mechanical properties of UHPC.

Some research works reported that deformed fibers (hooked, twisted or corrugated) can result in a higher compressive strength of UHPC compared to UHPC with the same dosage of straight fibers. This is due to the fact that the deformed ends of the fibers can restrain the initiation and propagation of cracks during loading (Wu et al. [13], Wu et al. [17], Larsen et al. [19]). However, this fact was not fully agreed by Gesoglu et al. [20] study, who attained almost negligible advantage from using deformed fibers rather than straight fibers. Wu et al. [17] and Larsen et al. [19] found that deformed fibers might cause

insignificant change to the compressive strength. However, their effect on flexural strength is much greater.

In addition to the fiber deformation, their length (long, medium or short) could affect the mechanical properties of UHPC. It was shown in Abbas et al. [9] study that the mixtures incorporating short fibers enhanced the flexural performance more than long fibers. This result was contradicted by Park et al. [21] which suggested that the flexural performance can be improved by increasing the length of the fibers. This result was confirmed by another study conducted by Yoo et al. [22] which concluded that long and medium length fibers are more efficient in improving flexural performance compared to the short straight fibers due to their higher aspect ratio. According to Gesoglu et al. [20] and Yoo et al. [22], the optimum fiber type to produce the best flexural strength depends on the amount of fibers in the mixture. Abbas et al. [9] stated that at low fibers content, deformed fibers are most effective in improving flexural strength; and at high fibers content, straight fibers are most effective in improving flexural strength. Fiber length was found to have insignificant effect on compressive strength.

The results reported in Ahmad et al. [11] showed that the compressive strength of UHPC increases with the increase of the duration of exposure to elevated temperatures. The compressive strength of UHPC increased by 50% when exposed to 300°C for 240 minutes. On the other hand, the flexural strength and modulus of elasticity of UHPC decreases with the increase of the duration of exposure to elevated temperatures. The flexural strength of UHPC decreased by 10% when exposed to 300°C for 240 minutes.

2.3. Effect of Fiber Hybridization

The use of a combination of two different types of fibers in the same mixture (hybrid mixtures) and their effect on the mechanical properties of UHPC were addressed in a group of articles. Zhao et al. [23] and Meng et al. [24] succeeded in producing high tensile and flexural strengths of UHPC when using straight fibers of different materials (steel and polyvinyl alcohol). This material combination outperformed the use of straight steel fibers only. However, the use of hybrid mixture of straight steel and polypropylene fibers provided less tensile strengths than using hybrid mixture as proved by Smarzewski et al. [25]. Some experimental works tried two different shapes of fibers in the same mixture. For example, the use of straight and hooked steel fibers together produced higher flexural strength compared to the use of a single shape of fibers [18, 24, 26, 27].

The work of Gesoglu et al. [20] considered adding hybrid long and short steel fibers up to 2% of the mixture. The highest compressive and flexural strengths were achieved at a proportion of 1.5% long fibers with 0.5% short fibers. The compressive strength was found to decrease with the increase of short fibers content. The use of hybrid fiber combinations had the potential to increase the tensile strength of UHPC. Some hybrid combinations were noticed to improve the flexural and tensile strengths, while others had negligible effects.

2.4. Factors affecting bond strength

2.4.1. Effect of steel fiber

Park et al. [7] studied the bond behavior of different types of steel macro-fibers (LS, HA, HB, and T steel fibers) embedded in UHPC by conducting pullout tests. They also studied

the influence of adding shrinkage-reducing admixtures to UHPC on the pullout strength. The use of T fibers led to the maximum bond capacity; and the effects of adding shrinkage-reducing admixtures were inconsistently varying according to the type of steel fibers as can be seen in Figure 1.

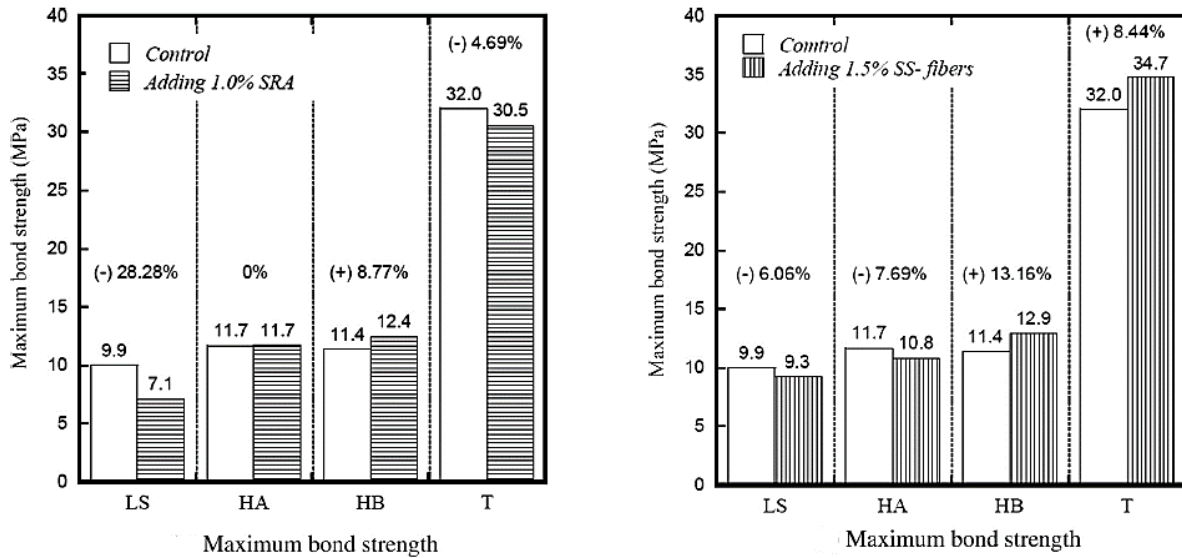
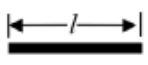
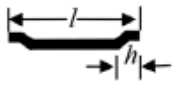
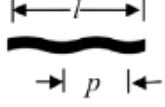


Figure 1: Influence of adding SRA and SS micro-fibers on the bond strength [1]

Wu et al. [8] examined the bond strength when using different types of steel fibers (straight, hooked, and corrugated fibers) (Table 1). They also studied how bond strength is affected by different portions of silica fume (15% or 20% by mass), at different curing ages. It was found that hooked and corrugated fibers significantly increase the bond strength by 3-7 times more than the straight fibers, as shown in Figure 2.

Table 1: Geometry of three selected fibers [8]

Shape	Geometry	Section	Details
Straight			$l = 13 \text{ mm}, d = 0.2 \text{ mm}$
Hooked			$l = 13 \text{ mm}, d = 0.2 \text{ mm}, h = 0.2 \text{ mm}$
Corrugated			$l = 13 \text{ mm}, d = 0.2 \text{ mm}, p = 6 \text{ mm}$

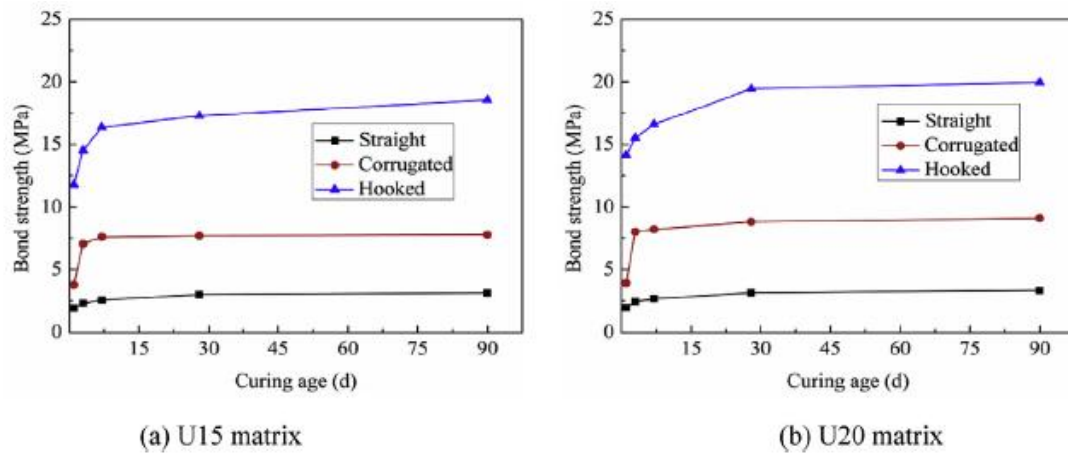


Figure 2: Effect of fiber shape on bond strength between fibers and U15 and U20 matrices [8]

Yoo et al. [2] studied the influence of fiber content in UHPFRC on the bond strength. They carried out a pullout test (Test setup is shown in Figure 3) to examine four different ratios of steel fibers ($V_f = 1\%$, 2% , 3% , and 4%). The results showed that by increasing the fiber content, the bond strength increases up to the degree where fiber content exceeds 3% . Beyond this percentage the bond strength starts to decrease. This indicates that the optimum steel fiber content is 3% , which produces the highest best bond strength.

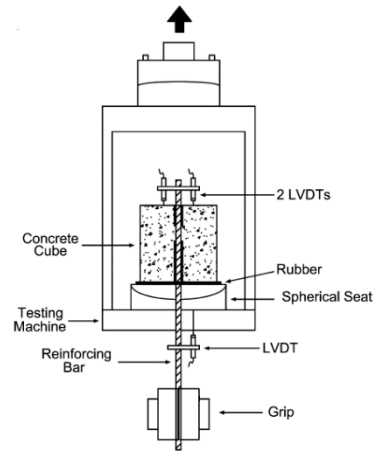


Figure 3: Pullout test setup implemented by [2]

2.4.2 Effect of rebar

Alkaysi et al. [3] studied the interaction between UHPC and steel bars. A series of pull out tests were carried out using grade 60 epoxy-coated and plain bars with differing sizes (13 mm, 16 mm, and 19 mm). Other studied factors included various development lengths (50 mm, 75 mm, and 100 mm). Test outcomes showed that bond stress achieved higher values at low embedded lengths, and the change of steel fibers changed the bond strength by 21% and 36%, as shown in Figure 4.

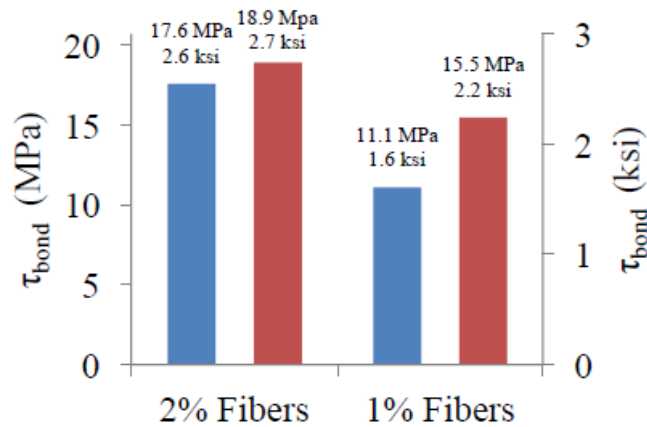


Figure 4: Bond Stress 1% and 2% Fibers: Embedded 4.0 d_b (Blue) and Embedded 6.0 d_b (Red) [3]

Yuan et al. [4] studied the bond strength of deformed rebars in UHPC by conducting direct tension pullout tests. They tested the influence of several parameters such as concrete cover, bar spacing, embedment length, concrete strength, rebar size and type, and yielding strength on the capacity of bond. It was found out that UHPC has similarities with traditional concrete and concluded that bond capacity decreases as rebar diameter becomes larger. On the other hand, bond strength increases with increasing the embedment length and the side cover. The compressive strength of UHPC was found directly proportional to bond strength.

Kim et al. [5] studied the bond behavior of steel bars embedded inside UHPC using direct pull-out tests. They investigated the effect of different compressive strengths (120, 150, and 180MPa), bar diameters (13, 16, 19, 22 and 25mm), cover to rebar diameter ratios and embedment lengths on the bond behavior. They found that using larger bar diameters leads to lower bond stresses, and the bond strength increases at larger embedment lengths.

Ronanki et al. [28] investigated the bond behavior of deformed reinforcing bar under varying bar sizes and types (rebars tested were #4, #5 grade 60 bars and #6, #7 grade 80 bars), embedment lengths (varied from $6d_b$ to $8d_b$) and side covers (varied from $1d_b$ to $3.5d_b$). They concluded that the bond strength increases with the increase in the embedment length and concrete cover (as shown in Figures 5 and 6, respectively).

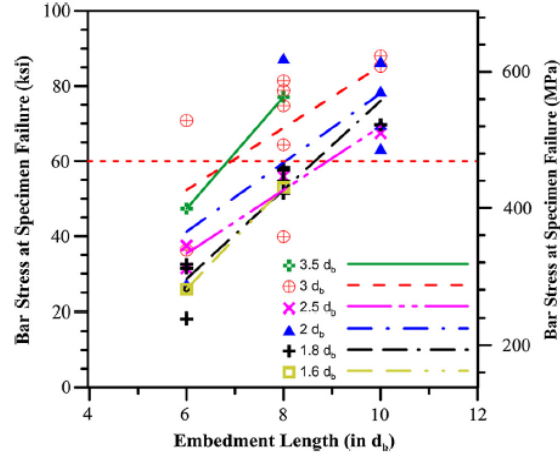


Figure 5: Measured bar stress at specimen failure vs. embedment length [28]

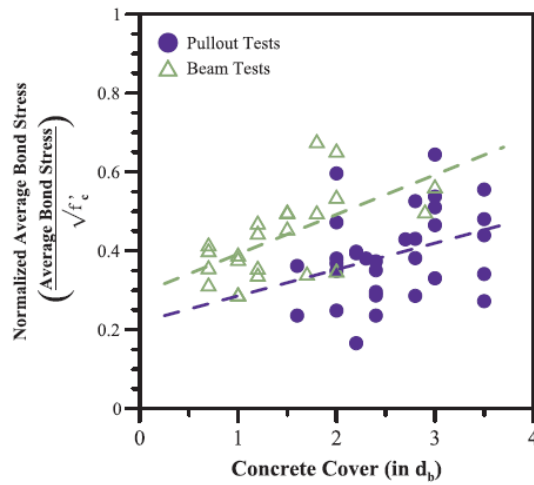


Figure 6: Bond strength vs. clear cover [28]

Alkaysi et al. [29] conducted a number of bar pull out tests in order to test the effect of varying factors on the bond strength of UHPC. These factors included bar diameter (13 mm, 16 mm, and 19 mm), development length (50 mm, 75 mm and 100 mm), casting orientations (longitudinal and transverse), steel fiber contents (1% and 2%) and age (1, 3 and 7 days curing). The main findings revealed a number of conclusions: increasing

embedment length reduces the bond strength, casting orientation of UHPC had negligible effects on bond strength, increasing steel fiber content increases the bond strength (by 21% and 36%) and finally, bond strength increases over time, (75% of UHPC bond strength developed within seven days of curing) as shown in Figure 7.

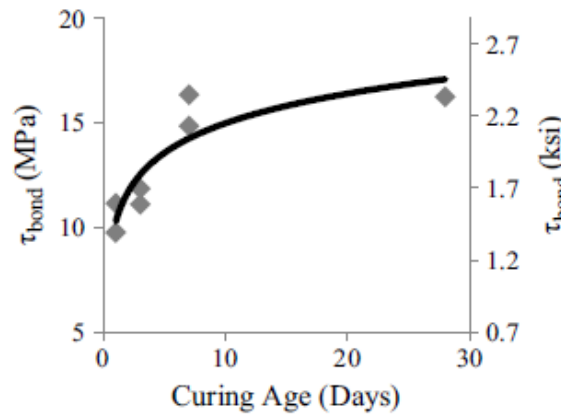


Figure 7: τ_{bond} as a Function of Curing Time [29]

2.4.3. Effect of temperature

Li et al. [6] studied the bond performance of rebars embedded in HPFRCC under the effect of different heat treatments (200, 400, 600, or 800 °C in a furnace for 2 hours), bar shapes, diameters, and embedment lengths. The bond strength between HPFRCC and embedment was found to decrease with higher temperature. Furthermore, they found that temperature is indirectly proportional to bond strength (temperature from 22 to 800 °C reduces bond strength by 82-92%), as shown in Figure 8. Water cooling was observed reducing the bond

strength (by 8%–18% for the specimens heated at 200 °C, 20%–30% at 400 °C, 15%–25% at 600 °C, and 37%– 55% at 800 °C) as shown in Figure 9.

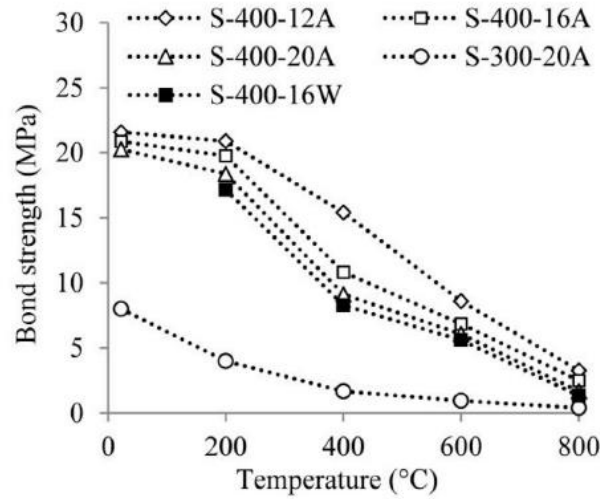


Figure 8: Effects of heating temperature on bond strength [6]

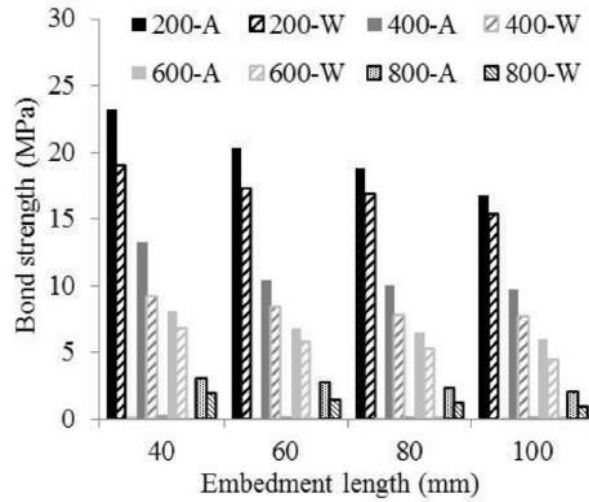


Figure 9: Effects of cooling method on the bond strength [6]

2.5. Effect of curing methods on the compressive strength of UHPC

UHPC performance under tension and compression has been well understood. However, studies on the interaction between UHPC and steel bar reinforcement remained limited, and data available for non-proprietary UHPCs are sparse. For instance, the effect of different curing methods on the bond strength of UHPC and steel reinforcement is limited, but there is a direct relationship between the compressive strength and the bond strength. Therefore, if a certain factor is known to increase the compressive strength, then it must also increase the bond strength and vice versa.

Prem et al. [30] examined the influence of curing cycles on the compressive strength of UHPC. It was found that when the specimens were thermally cured with hot air from 24 to 72 hours followed by water curing, they produced an average compressive strength between 153 and 213 MPa. They recommended a thermal curing time of 48 hours.

Park et al. [31] examined the influence of curing conditions on the compressive strength and concluded that the compressive strength is directly proportional to the curing temperature and curing period.

Ibrahim et al. [32] explored the effect of curing temperature on the mechanical properties of UHPC and concluded that increasing the temperature of curing results in increasing the compressive strength as shown in Figure 10.

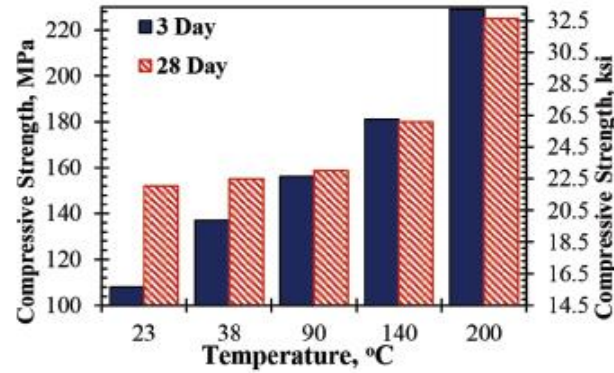


Figure 10: Effect of Curing Temperature on Compressive Strength [32]

2.6. FEM models used to simulate bond

To simulate the bond between concrete and rebars, various models have been created and analyzed.

The Cohesive Zone Damage (CZD) Model was used by Rolland et al. [33] in order to replicate a model of the pull-out tests, and a complementary model calibration was proposed to account for the non-uniform stress distribution along with the interface.

Gooranorimi et al. [34] used a smeared crack model to model the concrete behavior, where it combines the concepts of isotropic damage elasticity with isotropic tensile and compressive plasticity to represent the inelastic behavior of the concrete.

Gao et al. [35] used the fictitious crack model of fracture mechanics to consider the softening behavior of concrete under tension and the thick-walled cylinder model as an additional constraint for the stirrups.

Rezazadeh et al. [36] assessed the bond damage evolution by two damage-based approaches: the secant modulus-based model and the exponential damage model. The

exponential damage approach was developed to predict the bond stress-slip relationship. Afterwards, a 3D FEM model was developed which implemented both proposed damage-based approaches in order to simulate the GFRP bond behavior.

A new concrete damage plasticity model (based on Lubliner et al.'s [37] damage model) was implemented by Tao et al. [38] to capture the concrete -rebar bond behavior. The results were close to the test data, thereby validating the model. Besides accuracy, the model has two other advantages: it only requires the fundamental material parameters, and it can be directly applied in a Finite Element software.

In conclusion, for accurate modeling that represents the bond strength and bond-slip between UHPC and steel bars, it is necessary to adopt suitable models capable of simulating the actual behavior with high reliability. In addition, the nature of interaction between steel and concrete is an important factor for determining the bond strength.

2.7. Empirical models used to simulate bond

Empirical modeling is an acceptable method and can be of high reliability when it is based on a considerable amount of test data. The average bond strength at the interface of steel rebar embedded in unconfined specimens can be expressed by an equation proposed by Orangun et al. [39] as follows:

$$\tau_u = \left(0.10 + 0.25 \frac{C_{min}}{d_b} + 4.15 \frac{d_b}{l_d} \right) f_c'^{1/2} \quad (1)$$

Where the bond strength of the specimen is defined as a function of $(f_c'/2)$. Darwin et al. [40] found that using $(f_c'/2)$ is not appropriate in the case of high strength concrete. They

suggested that the quantity $(f'_{c1}/4)$ is more accurate in giving the contribution of compressive strength to the bond strength between rebar and concrete.

Cosenza et al. [41] provided a commonly known bond-slip relationship at the ascending stage, expressed as:

$$\frac{\tau}{\tau_u} = \left(\frac{S}{S_u} \right)^\alpha \quad (2)$$

Where the variable α is a constant calculated through regression analysis. The above relationship was further upgraded to suit concrete specimens affected by corrosion levels or temperature exposure as shown in the study of Zhang, et al. [42].

Another method for the determination of the bond stress is addressed in Hu et al. [43] where the bond stress-slip curves can be divided into five sections by four characteristic points: the micro-slip stage, slip stage, splitting stage, declining stage, and residual stage. The equation of each segment is expressed as follows:

$$\tau = \begin{cases} K_1 S & S \leq S_s \\ \tau_s + K_2 (S - S_s) & S_s < S \leq S_{cr} \\ \tau_{cr} + K_3 (S - S_{cr}) & S_{cr} < S \leq S_u \\ \tau_u + K_4 (S - S_u) & S_u < S \leq S_r \\ \tau_r & S > S_r \end{cases} \quad (3)$$

Numerous other equations have been introduced to approximate the bond strength between steel and concrete taking into account the influence of main parameters (i.e. compressive strength, concrete cover, bar diameter and embedment length) as shown in Alhawati et al. [44], Mousavi et al. [45] and Huang et al. [46] investigations.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1. Introduction

In this chapter, the experimental work, conducted to achieve the objectives of the present study, is described. The details of the UHPC mixtures prepared with different combinations of steel fiber are first presented. Thereafter, the details of the ingredients, mixture proportions, preparation of the mixture, and details of the tests on the fresh and hardened mixtures of UHPC are given.

3.2. UHPC mixtures with different fiber compositions

An optimum UHPC mixture, developed by Ahmed et al. [47] at the KFUPM labs using local fine dune sand and a water/binder ratio of 0.145, was adopted in the present study to investigate the effect of hybridization of fibers and curing regimes. The contents of the adopted UHPC mixture are as follows:

- Portland cement: 900 kg/m³
- Silica fume: 220 kg/m³
- Water: 163 kg/m³
- Fine dune sand: 1005 kg/m³
- Glenium® 51 superplasticizer: 40 kg/m³
- Steel fiber: 157 kg/m³

To investigate the effect of types of the different types of steel fiber composition on the bond between UHPC and steel rebar, different mixtures of UHPC were prepared. A total of five mixtures were produced using different proportions of straight and hooked steel fibers. The details of the steel fibers proportions in each mixture are presented in Table 2.

Table 2: Steel fiber proportions in UHPC mixtures

Mixture	Straight fibers (%)	Hooked fibers (%)
U0H ⁽¹⁾	100	0
U30H	70	30
U50H	50	50
U70H	30	70
U100H	0	100
⁽¹⁾ U: UHPC xxH: xx% hooked fiber content		

3.3. Material

3.3.1. Cement

Type I Ordinary Portland Cement (conforming to ASTM C150) with a specific gravity of 3.15 was used in all UHPC mixtures. The chemical composition of the used cement is provided in Table 3.

3.3.2. Silica Fume

The silica fume was sourced from a local supplier in Saudi Arabia with a specific gravity of 2.25, and the chemical composition is shown in Table 4.

Table 3: Chemical composition of Type 1 Portland cement [47]

Component	Weight (%)
CaO	64.35
SiO ₂	22
Al ₂ O ₃	5.64
Fe ₂ O ₃	3.8
K ₂ O	0.36
MgO	2.11
Na ₂ O	0.19
Equivalent Alkalis (Na ₂ O + 0.658 K ₂ O)	0.33
SO ₃	2.1
Loss on Ignition	0.7

Table 4: Chemical composition of Silica Fume [47]

Component	Weight (%)
CaO	0.48
SiO ₂	92.5
Al ₂ O ₃	0.72
Fe ₂ O ₃	0.96
K ₂ O	0.84
MgO	1.78
Na ₂ O	0.5
Loss on Ignition	1.55

3.3.3. Fine aggregates

Fine dune sand with a specific gravity of 2.65 and water absorption of 0.45% was used as a natural mixture replacing quartz powder and quartz sand. This type of sand is available in the eastern province of Saudi Arabia. The particle size distribution of the fine aggregates is shown in Table 5.

Table 5: Fine aggregate grading

Seive #	Size	% Passing
4	4.75 mm	100
8	2.36 mm	100
16	1.18 mm	100
30	600 μ m	76
50	300 μ m	10
100	150 μ m	4

3.3.4. Superplasticizer

The superplasticizer Glenium 51® (a polycarboxylic-based ether hyperplasticiser) was used in all the mixtures to provide adequate viscosity and workability. It was sourced from a local supplier in Saudi Arabia. The characteristics of the used superplasticizer are shown in Table 6.

Table 6: Glenium 51® characteristics [47]

Appearance	Brown liquid
Specific gravity @ 20°C	1.08 $\pm$ 0.02 g/cm ³
pH value @ 20°C	7.0 $\pm$ 1.0
Alkali content	$\leq$ 5.0
Chloride content	$\leq$ 0.1%

3.3.5. Steel fibers

Two types of steel fibers were used in the mixtures - straight and hooked steel fibers, which are plain smooth copper coated steel microfibers that were imported from China. These fibers were incorporated to the mixture with a dosage of 2% of the volume of concrete. The

properties of both types of fibers are listed in Table 7, and the geometry is shown in Figure 11.

Table 7: Properties of steel fibers

	Diameter (mm)	Length (mm)	Aspect ratio (L/d)	Density (g/cm ³)	Tensile strength (MPa)	Elastic modulus (GPa)
Straight fiber	0.2	13	65	7.8	2500	200
Hooked fiber	0.2	25	125	7.8	2500	200



Figure 11: Steel fiber geometry

3.3.6. Mixing water

Normal water was used for mixing and curing of the specimens.

3.4. Proportioning of UHPC mixtures

All UHPC mixtures considered in this study were designed using the absolute volume method (based on the physical properties of the ingredients). The quantities of each

material required to produce one cubic meter of each mixture of UHPC are shown in Table 8.

Table 8: Quantities of ingredients for producing 1 m³ of UHPC mixtures

	U0H	U30H	U50H	U70H	U100H
Cement (kg)	900	900	900	900	900
Silica fume (kg)	220	220	220	220	220
Sand (kg)	1005	1005	1005	1005	1005
Water (kg)	162	162	162	162	162
Superplasticizer (kg)	40.32	40.32	40.32	40.32	40.32
Straight steel fibers (kg)	157 (100%)	109.9 (70%)	78.5 (50%)	47.1 (30%)	0 (0%)
Hooked steel fibers (kg)	0 (0%)	47.1 (30%)	78.5 (50%)	109.9 (70%)	157 (100%)

3.5. Preparation of UHPC mixtures

For the purpose of mixing UHPC, special procedures and equipment were required to achieve a consistent mixture throughout the casting process. High shear capacity mixer and vibratory tables were needed for mixing and consolidating the UHPC mixture. In this experiment, the MICRONS mixer was used to mix the ingredients of UHPC, as shown in Figure 12. A summary of the mixing procedure is presented below:

- All ingredients are weighed.
- The superplasticizer is added to water and mixed carefully.
- The fine materials (cement, micro silica, and sand) are added to the mixer and mixed for approximately 2 minutes until the mixture becomes homogeneous.
- Two-thirds of the superplasticizer-water mixture is added slowly and mixed for 10 to 15 minutes until the mixture turns to granules.

- The remaining superplasticizer-water mixture is added and mixed for approximately 10 minutes until the mixture becomes a homogeneous fluid.
- The steel fibers are added slowly to the mixture in small amounts over the course of 5 minutes, and mixing should continue for three minutes to ensure that fibers are well spread in the UHPC mixture.



Figure 12: MICRONS mixer

3.6. Flow table test for UHPC mixtures

Once the mixing process is complete, a flow test is conducted in accordance with ASTM C 1437 [48] (the standard test method for the flow of hydraulic cement) prior to casting the specimens in order to check the consistency of the mix. Figure 13 shows the impact table used in the flow test. To perform the flow test, the mini-slump cone is filled with UHPC. Then it is lifted slowly to allow the mixture to flow evenly on the table. Then, the table is lifted and dropped 20 times to allow the mixture to spread on the table. The average diameter of the spread mixture is recorded as the flow of the mixture (acceptable values of flow range between 180 to 220 mm).



Figure 13: Impact table used in the flow table test

3.7. Casting of the Test Specimens

After completion of mixing and preforming the flow test, the specimens were poured into the molds on a vibratory table within 20 minutes. The molds were filled with UHPC mixture, then vibrated for 20 to 30 seconds for consolidation. After all the specimens were cast and consolidated, they were covered with polythene sheet immediately after casting and left to cure at room temperature for 24 hours before demolding, as shown in Figure 14.

3.8. Curing of the Test Specimens

The 120 specimens were demolded after 24 hours of casting. The resulted specimens were divided into two equal groups, the first group was exposed to water curing and the other to steam curing.

3.8.1. Water curing

The first group of specimens was water-cured by placing them in a water tank and submerging them completely in water. The specimens remained submerged in water for 28 days as shown in Figure 15. During the 28 days, water had an average temperature of 29 ± 2 °C.



Figure 14: Casting procedure



Figure 15: Specimens exposed to water curing

3.8.2. Steam curing

The second group of specimens was steam-cured by placing them in an oven at a temperature of 90°C for 10 hours. The most important factors in steam curing are temperature and humidity. To provide humidity, a tray filled with water was placed in the oven, as shown in Figure 16. Water vaporized under the effect of the high oven temperature which supplied the specimens with the required humidity. The specimens were then taken out of the oven and stored at room temperature (23 ± 2 °C) until the day of testing.



Figure 16: Specimens exposed to steam curing

3.9. Testing of UHPC specimens

As mentioned earlier, the specimens were demolded after 24 hours of casting and subjected to two curing regimes, water curing and steam curing. The mechanical tests performed on the UHPC specimens included the direct pullout test, compressive strength test, modulus of elasticity, and flexural strength test.

Three specimen shapes (cubes, cylinders, and prisms) were made out of each mixture. Each shape was made to suit a different test, as shown in Figure 17. Three duplicates of each specimen were cast and tested, and their test results were averaged. The mixture ID labeled on each specimen consisted of the mixture number and curing type, as shown in Figure 17 and Table 9.

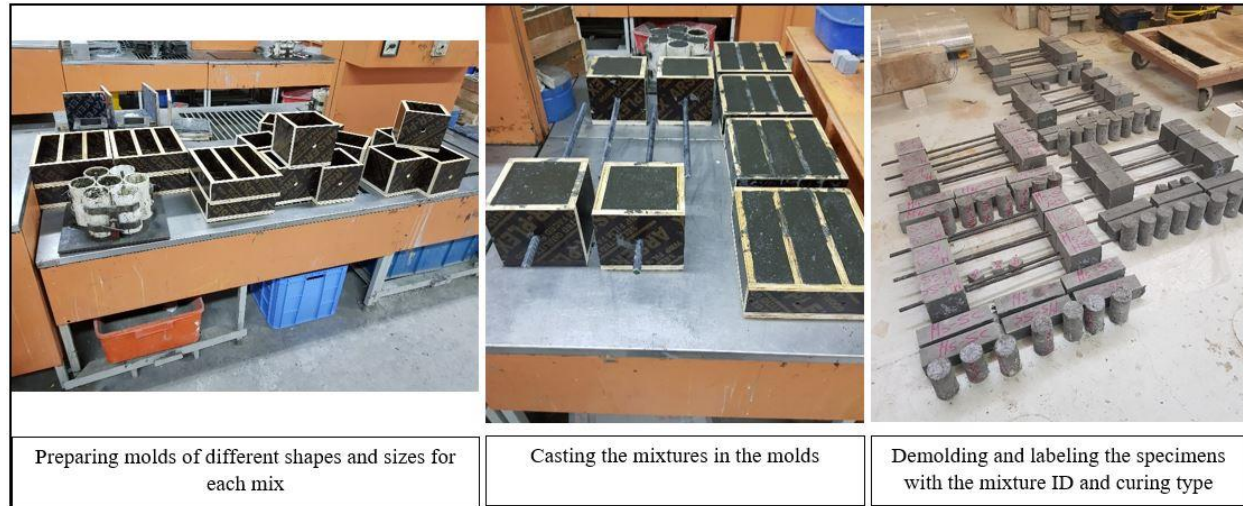


Figure 17: Preparation of specimens

Table 9: Tested Specimens

Curing regime	Mixture ID	Pullout test specimens (HSS) ⁽¹⁾	Pullout test specimens (RS) ⁽²⁾	Compressive test specimens	Flexural test specimens
Steam curing (SC)	U0H-SC	3	3	3	3
	U30H-SC	3	3	3	3
	U50H-SC	3	3	3	3
	U70H-SC	3	3	3	3
	U100H-SC	3	3	3	3
Water curing (WC)	U0H-WC	3	3	3	3
	U30H-WC	3	3	3	3
	U50H-WC	3	3	3	3
	U70H-WC	3	3	3	3
	U100H-WC	3	3	3	3
Total		30	30	30	30
(1) HSS: high strength steel (2) RS: regular steel					

3.9.1. Compressive strength and modulus of elasticity test

The compressive strength test was performed in accordance with ASTM C39 [49], and the modulus of elasticity was calculated in accordance with ASTM C469 [50]. Thirty cylindrical specimens with dimensions $\phi 75 \times 150$ mm were cast and tested. Each six specimens had the same mixture proportions, three water-cured, and three steam-cured. The test was done through an automatic compression testing machine with a capacity of 3000 kN as shown in Figure 18, and tested under a load rate of 2 kN/s. Each cylindrical specimen was clamped by two steel rings with a gauge length of 87 mm, and each ring was connected with the cylinder by three screws. On the steel rings, two Linear Variable Differential Transformers (LVDTs) were placed vertically on opposite sides of the specimen. The load was recorded by a load cell that was placed under the specimen, and the linear deformations were recorded by the LVDTs. The load cell and the LVDTs were connected to a data logger. Prior to testing, the surface of the specimens was grinded to provide a flat surface that ensures perfect contact between the specimen and the compressometer. Figure 18 shows the failure of a cylindrical specimen after testing in compression. Unlike regular concrete, UHPC specimens failed due to the development of vertical cracks on the specimen due to the fiber present in the mix.

The compressive strength is obtained using the following formula:

$$f'_c = \frac{4 \times P_{max}}{\pi \times d^2} \quad (4)$$

Where:

f'_c = Compressive Strength (MPa)

P_{max} = Maximum Load (kN)

d = Specimen diameter (mm)

The modulus of elasticity is obtained using the following formula:

$$E = \frac{f_{c2} - f_{c1}}{\varepsilon_2 - 0.00005} \quad (5)$$

Where:

E = Modulus of Elasticity (MPa)

f_{c1} = Stress corresponding to longitudinal strain ε_1 of 0.00005 (MPa)

f_{c2} = Stress corresponding to 40% of ultimate stress (MPa)

ε_2 = Longitudinal strain corresponding to f_{c2}



Figure 18: Compressive strength test

3.9.2. Flexural strength test

The flexural strength test was performed in accordance with ASTM C78 [51] for prisms with dimensions of 70 x 70 x 280 mm that comply with the French interim UHPC guideline annex [52]. Thirty specimens were tested. Each six specimens had the same mixture proportions, three water-cured, and three steam-cured. The specimens were tested using a

universal testing machine (UTM) that has a capacity of 200 kN, as shown in Figure 19. A four-point loading configuration was used with a flexural length of 210 mm (3 times the depth of the prism), and a loading rate of 0.5 mm/min. The load was recorded by a load cell, and the deflection was recorded by an LVDT that was placed at mid-span of the prism. The load cell and the LVDT were connected to a data logger.



Figure 19: Flexural strength test

The flexural strength is obtained using the following formula:

$$f_{eq} = \frac{M \times c}{I} \quad (6)$$

Where:

f_{eq} = Flexural strength (MPa)

M = Maximum moment (N.mm)

c = Distance of the neutral axis (mm)

I = Moment of inertia (mm⁴)

3.9.3. Flexural Toughness

The flexural toughness (MOT_f) is determined as an index to the amount of energy that the specimens can absorb before fracture. Flexural toughness is calculated by taking the area under the stress/deflection curve of prismatic specimens up to ultimate stress (Ahmed et al. [11]), as shown in Figure 20. The flexural toughness (in kJ/m^2) indicates the amount of energy required to fracture a specimen in flexure.

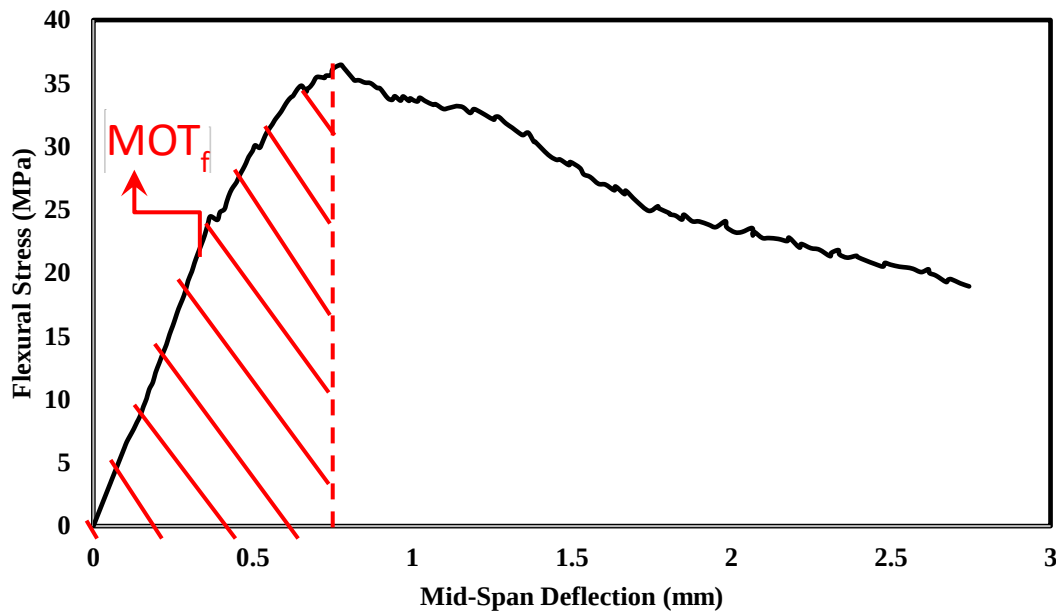


Figure 20: Calculation of the flexural toughness of UHPC

3.9.4. Direct pullout test

The pullout test was performed in accordance with the RILEM recommendations [53] to investigate the bond behavior between UHPC and steel reinforcement. Six 150 mm cubes were cast, three with regular steel bars (750 mm length) and three with high strength steel bars (750 mm length) vertically embedded along the central axis of the cube. The test setup and its schematic diagram are shown in Figure 21. The properties of the regular steel bars and high strength steel bars are summarized in Table 10 and their shapes are shown in Figure 22.

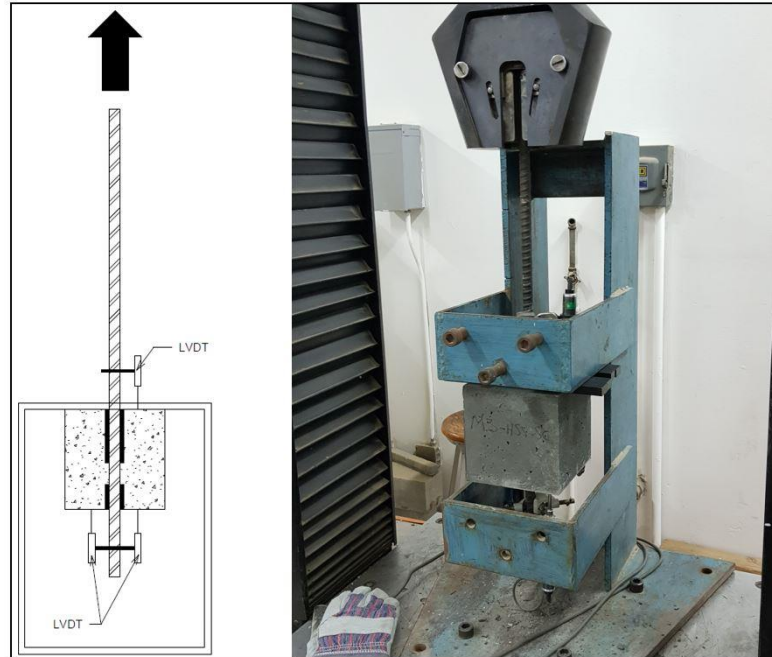


Figure 21: Direct pullout test

Table 10: Properties of steel and high strength steel bars

Bar type	Nominal diameter (mm)	Area (mm ²)	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)
Regular steel bar	15.9	199	200	586	702
High strength steel bar	15.9	199	213	1397	1602

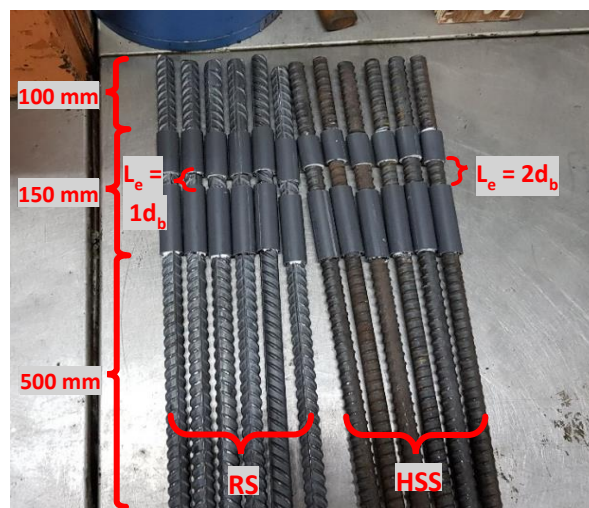


Figure 22: Steel bars used in the pullout test

The nominal diameter of the regular steel bars and high strength steel bars was 15.9 mm. The UHPC molds were 150 mm cubic molds fabricated from marine plywood, with single rebar vertically embedded along with the central access of the cube. The embedment was selected to be one time the bar diameter ($L_e = 1d_b$) for the regular steel bars and two times the bar diameter ($L_e = 2d_b$) for the high strength steel bars (instead of $5d_b$ (RILEM recommendations)). This allows the pullout failure to occur before the rupturing of steel, according to Yoo et al. [2]. As shown in Figure 23, the unbonded region of the bars is sheathed with a PVC pipe. The test was done using INSTRON 200 kN-capacity twin-screw universal testing machine (UTM). The load was recorded by a load cell, and the bond-slip between the rebar and concrete was recorded by three LVDTs placed at both ends of the specimens, as shown in Figure 21. The load cell and the LVDT were connected to a data logger.



Figure 23: Bonded and unbonded regions

The bond strength is obtained using the following formula:

$$f_b = \frac{P}{\pi \times d_b \times L_e} \quad (7)$$

Where:

f_b = Bond strength (MPa)

P = Pullout load (N)

d_b = Bar diameter (mm)

L_e = Embedment length (mm)

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results of the tests conducted to study the performance of five UHPC mixtures with different fiber combinations subjected to different curing regimes. The results of the flow table test on fresh concrete samples, and compression, flexural tensile, and bond tests on cured concrete specimens are presented. The test results are discussed to draw the useful conclusions about the effects of fiber hybridization and curing regimes on the behavior of UHPC under compression, flexural, tension, and bond with embedded steel bars.

4.1. Flow table test results

The flow tables test was conducted to assess the consistency of the mixtures. The results ranged from 185 to 206 mm as shown in Table 11. These values lie within the acceptable range (i.e., 180-220 mm) which implies acceptable consistencies of all mixtures.

Table 11: Flow table test results for all mixtures

Mixture	Flow (mm)
U0H	201
U30H	206
U50H	198
U70H	186
U100H	203

4.2. Compression test results

Thirty specimens were tested under compression. The specimens were divided into 10 groups; each group consists of 3 replicate specimens having the same steel fiber combinations and curing regime. The modes of failure of the UHPC specimens typically shown in Figure 24 (for both types of curing) indicate that the specimens experienced non-explosive cracking. The steel fibers kept particles entangled and prevented the disintegration of the cylinders into flying-off fragments. They allowed minor cracks to develop at the surface. This implies an increase in the ductility of the UHPC when steel fibers are used, contrary to the case of absence of steel fibers where failure tends to be brittle under compression and leads to explosive and complete crushing of concrete [9, 14].



(a)

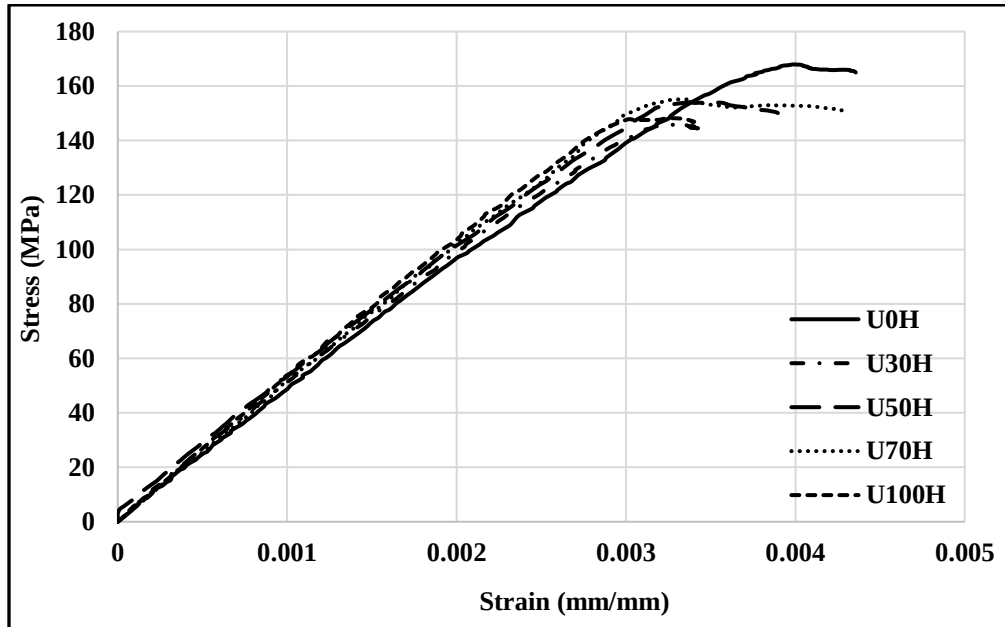


(b)

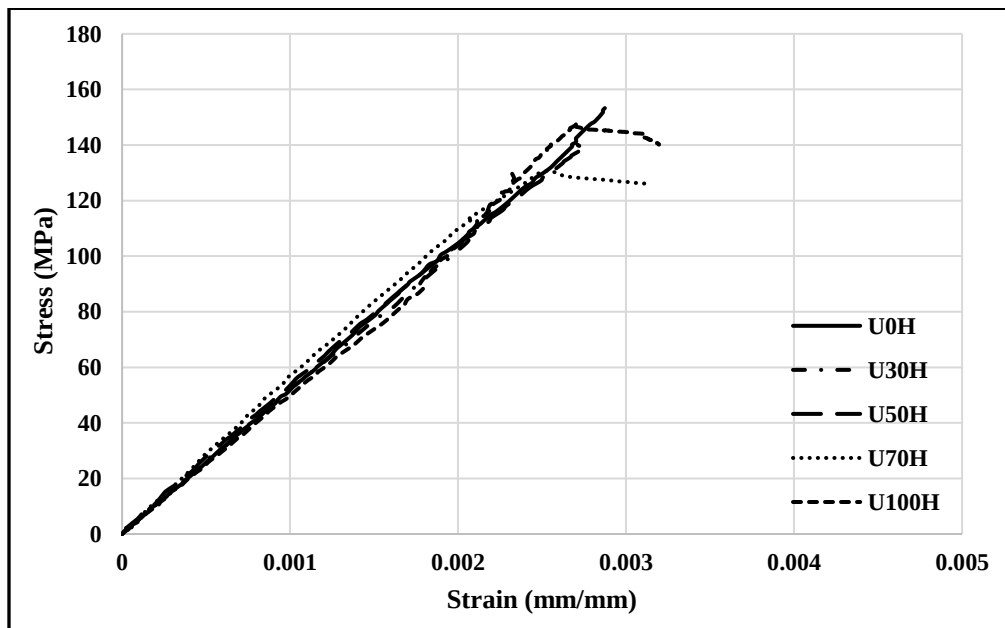
Figure 24: Compressive failure patterns in (a) steam-cured specimen (b) water cured specimen

Figures 25 (a) and (b) show the plots of compressive stress-strain diagrams of the five UHPC specimens (prepared with five selected proportions of hooked and straight steel fibers) and cured using steam and water, respectively. The data used for plotting the stress-

strain diagrams, as shown in Figures 25 (a) and (b), are not the average of three replicate specimens.



(a)



(b)

Figure 25: Compressive stress-strain curves of the different UHPC mixtures (a) steam-cured (b) water-cured

It can be observed from Figures 25 (a) and (b) that the UHPC mixtures, regardless of the proportions of fiber hybridization and curing methods, had almost a linear relationship between compressive stress and strain. Except in a few cases, all specimens exhibited yielding after reaching to the ultimate stresses. The steam-cured UHPC mixtures showed more ductility than the water-cured UHPC mixtures.

Compressive strength, ultimate strain, and the modulus of elasticity of the UHPC specimens, tested under compression, are listed in Table 12. The data presented in Table 12 are the average values of each of the three properties of the UHPC mixtures, obtained by averaging the values for every 3 replicate specimens. The results of compression test on each of thirty specimens are shown in Appendix A.

Table 12: Summary of compression test results

Specimen	Mean $f_c^{(1)}$ (MPa)	Mean $\epsilon_{at-ult}^{(2)}$ (mm/mm) ($\times 10^{-5}$)	Mean E (GPa)
U0H-SC	157.90	260.80	50.68
U0H-WC	149.63	273.00	50.20
U30H-SC	148.52	280.45	52.31
U30H-WC	128.39	191.35	52.37
U50H-SC	148.40	305.75	50.18
U50H-WC	141.98	247.15	52.59
U70H-SC	153.79	259.75	51.34
U70H-WC	131.86	227.00	53.40
U100H-SC	136.01	318.95	49.33
U100H-WC	131.11	275.30	51.23
(1) Mean f_c: mean compressive strength of 3 replicate specimens. (2) Mean ϵ_{at-ult}: the strain corresponding to the compressive strength taken as the mean of 3 replicate specimens.			

4.2.1. Compressive strength

Figure 26 shows that the steam-cured specimens had relatively higher compressive strength than the water-cured specimens did at all percentages of hooked fibers. This is because heat provided by steam curing accelerates the reaction of the cement and the silica fume (silica fume is more significantly affected). In water curing, the silica fume acts as a filler material due to the slow rate of hydration where heat is required to initialize the hydration [30, 54].

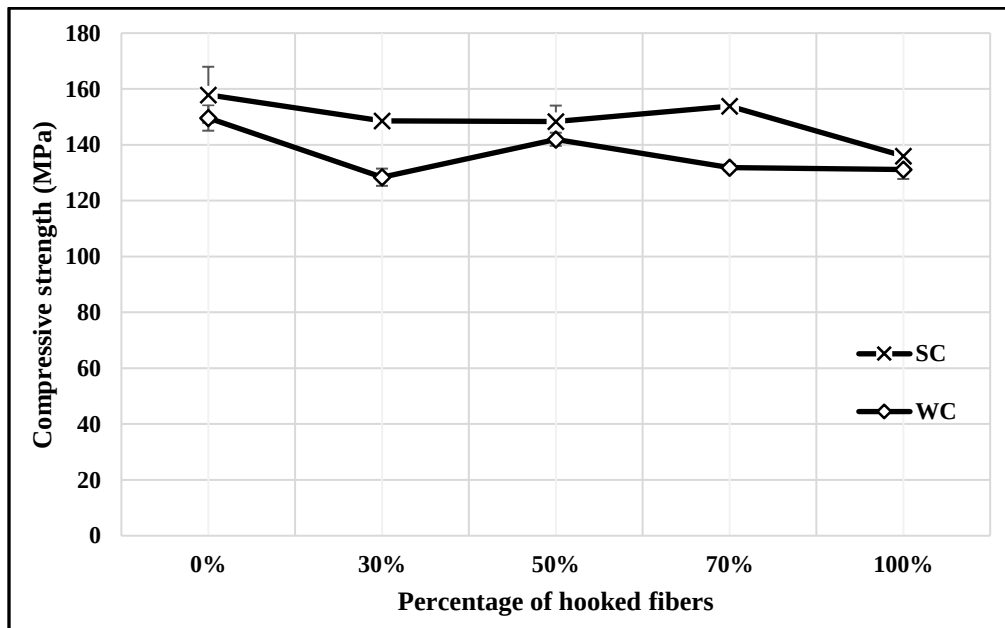


Figure 26: Effects of fiber hybridization proportions and curing methods on compressive strength

It can be further noted that the fiber hybridization has negative effect on compressive strength of the UHPC mixtures for both types of curing. In both cases of curing, the compressive strength of the specimens without hooked fibers was highest (158 MPa for steam-cured and 150 MPa for water-cured). The maximum reductions in the compressive strength due to introduction of hooked fiber were recorded as 14% in case of steam-cured mixtures and 15% in case of water-cured mixtures. The reduction in the compressive

strength due to addition of hooked fibers may be attributed to the increase in the porosity of the mixtures due to the adverse change in microstructure of the UHPC matrix in the presence of hooked fibers.

4.2.2. Compressive strain

As observed from Figure 27, the steam-cured UHPC mixtures had higher compressive strains at ultimate stresses than that of water-cured UHPC mixtures, except for the mixture U0H in case of which both steam-cured and water-cured specimen had almost same compressive strains. Furthermore, it can be observed from Figure 27 that the mixtures having 100% hooked fibers had the highest strain at ultimate compressive stress for both steam-cured and water-cured specimens.

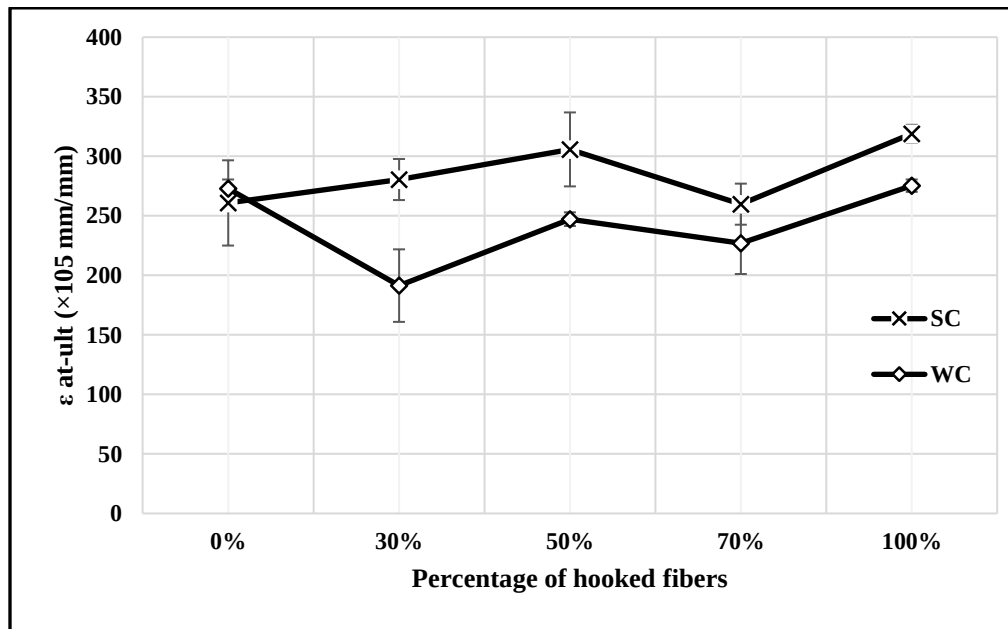


Figure 27: Effects of fiber hybridization proportions and curing methods on compressive strain

4.2.3. Modulus of elasticity

Figure 28 showing the effects of fiber hybridization proportions and curing methods on modulus of elasticity indicates that both the percentage of hooked fibers as well as curing types had negligible effect on the modulus of elasticity of the UHPC mixtures. All the specimens exhibited values of modulus of elasticity close to each other around an average value of 51 GPa.

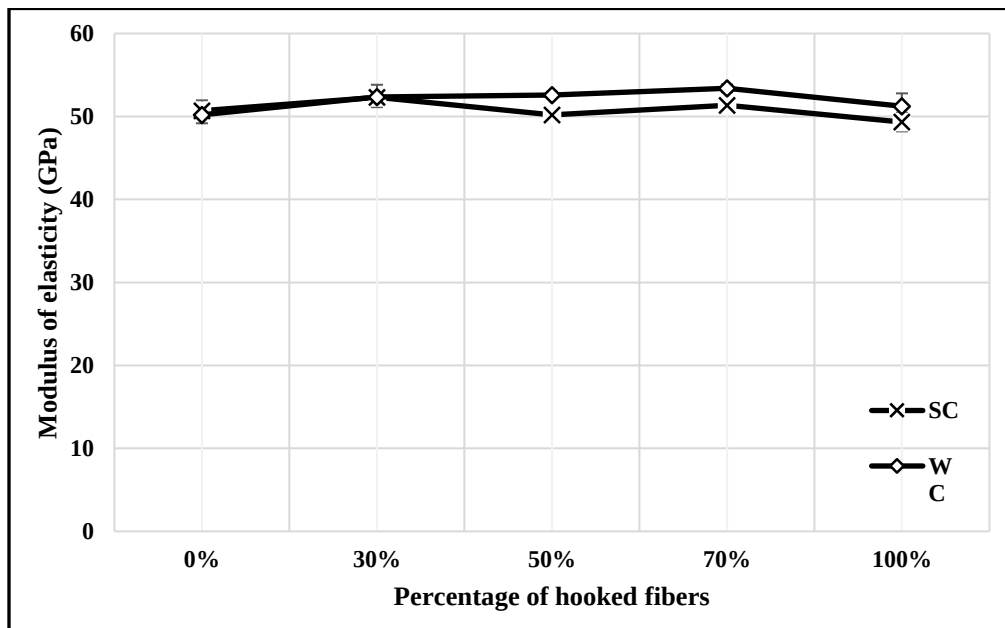


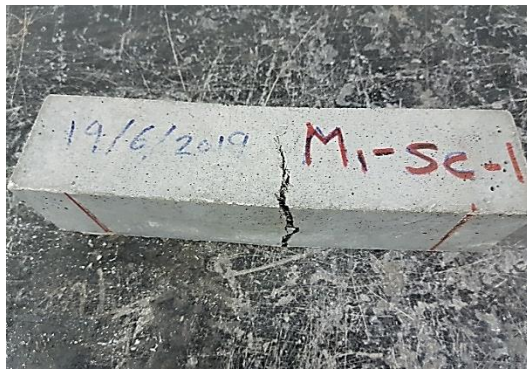
Figure 28: Effects of fiber hybridization proportions and curing methods on modulus of elasticity

A little enhancement in the modulus of elasticity of the UHPC specimens (by around 4%) belonging to both curing types was observed when the percentage of hooked fibers increased from zero to 30%. The increase in the hooked fiber content from 30 to 70% caused a small increase in the modulus of elasticity of steam-cured specimens (by around 6% of the value at 0% of hooked fibers). In case of water-cured specimens, instead of an increase in the modulus of elasticity a slight decrease was observed when the percentage of hooked fiber was increased beyond 30%.

While the curing methods did not show any effect on the modulus of elasticity up to a hooked fiber content of 30%, the specimens subjected to steam curing had a little higher modulus of elasticity than the water-cured specimens at the hooked fiber content beyond 30%.

4.3. Flexural test results

In order to study the effect of the fiber hybridization and types of curing on the flexural behavior of the UHPC mixtures, the prism specimens were tested under flexural loading. The load versus mid-span deflection data were recorded till the failure of the specimens. The loads applied at the onset of cracking and the corresponding mid-span deflections were noted. The values of the flexural strengths were calculated using the peak loads and the flexural stress when first crack occurred were calculated using the load applied when the first crack occurred. The values of flexural stresses and mid-span deflections were averaged for every 3 replicate specimens with similar mixtures and curing method.



(a)

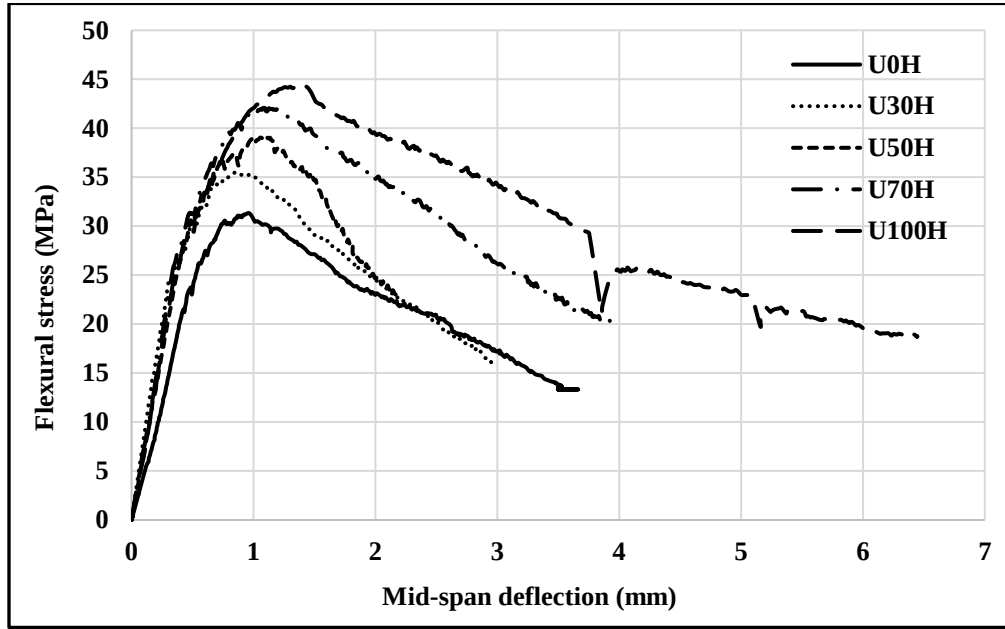


(b)

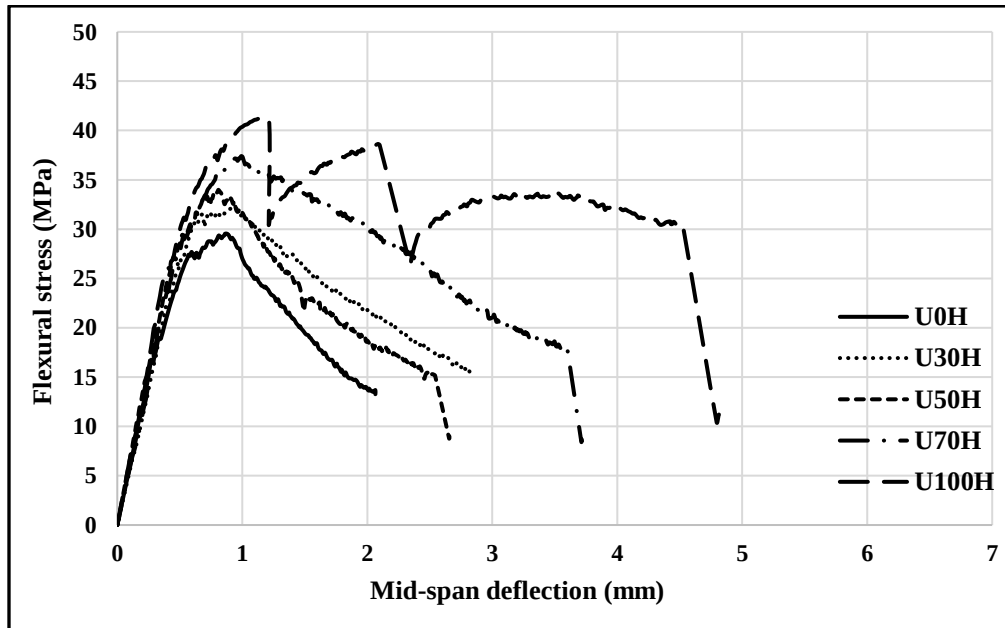
Figure 29: Flexural failure patterns in (a) steam-cured specimen (b) water cured specimen

Figure 29 shows the failure pattern of typical specimens tested under flexural loading.

It can be observed that the water-cured specimen is damaged more severely than the steam-cured specimen.



(a)



(b)

Figure 30: Flexural stress- mid-span deflection curves of the different UHPC mixtures
(a) steam-cured (b) water-cured

The flexural stress versus mid-span curves of the steam-cured UHPC specimens, as shown in Figure 30(a), indicates that the UHPC mixtures subjected to steam curing have higher ultimate flexural stress at a higher content of the hooked fiber. The mid-span deflections at ultimate flexural stresses and the ductility of the UHPC specimens are also higher at the higher percentages of the hooked fibers. It can be further noted that the stiffness of all the UHPC mixtures was almost the same except for the UHPC mixture without hooked fiber, which showed a lower stiffness as compared to the UHPC mixtures containing the hooked fibers. This indicates that the presence of hooked fibers in UHPC mixtures increases the flexural strength, mid-span deflection, ductility and stiffness. The water-cured UHPC mixtures also exhibited the same effect of the hooked fibers on the flexural behavior as that of steam-cured specimens, as can be seen from Figure 30(b). However, the performance of the steam-cured specimens was better than that of the water-cured specimens.

The flexural stress exhibited sudden drops during loading of the specimens that contained 100% hooked fibers for both types of curing. Drops in stress are attributed to the presence of high content of hooked fibers. When concrete cracks due to flexure, the very bottom fibers preserve the integrity of the specimen and prevent dismantling, and the flexural strength is thus increased. The hooked fibers geometry helps the specimen to withstand the stress until the hooked fiber breaks or the concrete around the fiber breaks, which creates a sudden drop in stress. Subsequently, the stress returns to increase again as a new upper fiber recurs the same process until complete failure.

Table 13 summarizes the results of the flexural testing that include the mean values of flexural strength, deflection at the flexural strength, cracking flexural strength, cracking

deflection and flexural toughness. The detailed results of the flexural test are presented in Appendix B.

Table 13: Summary of the flexural test results

Specimen	Mean $f_{eq-ult}^{(1)}$ (MPa)	Mean $\delta_{at-ult}^{(2)}$ (mm)	Mean $f_{eq-crack}^{(3)}$ (MPa)	Mean $\delta_{at-crack}^{(4)}$ (mm)	Mean MOT_f (kJ/m ²)
U0H-SC	31.110	0.838	23.120	0.418	18.619
U0H-WC	30.182	0.759	18.771	0.395	16.370
U30H-SC	34.542	0.976	21.327	0.357	17.672
U30H-WC	33.037	0.859	22.125	0.413	16.257
U50H-SC	38.695	0.782	26.006	0.392	17.912
U50H-WC	33.978	0.780	19.531	0.306	16.408
U70H-SC	41.736	1.116	26.100	0.383	31.504
U70H-WC	39.821	0.950	23.458	0.422	21.845
U100H-SC	44.053	1.349	22.184	0.301	41.738
U100H-WC	43.510	1.184	25.561	0.390	35.489
⁽¹⁾ f_{eq-ult} : flexural strength of 3 replicate specimens. ⁽²⁾ δ_{at-ult} : mid-span deflection corresponding to the flexural strength 3 replicate specimens. ⁽³⁾ $f_{eq-crack}$: flexural stress when first crack occurs. ⁽⁴⁾ $\delta_{at-crack}$: mid-span deflection corresponding to $f_{eq-crack}$.					

4.3.1. Flexural strength

The flexural strength of UHPC varied with different proportions of hooked and straight fibers. It can be observed from Figure 31 that, regardless of the type of curing, the UHPC mixtures that contained higher percentage of hooked fibers acquired higher flexural strength. The flexural strength of the UHPC mixtures with 100% hooked fibers was noted as around 43% more than the flexural strength of the UHPC mixtures that contained 100% straight fibers, for both types of curing.

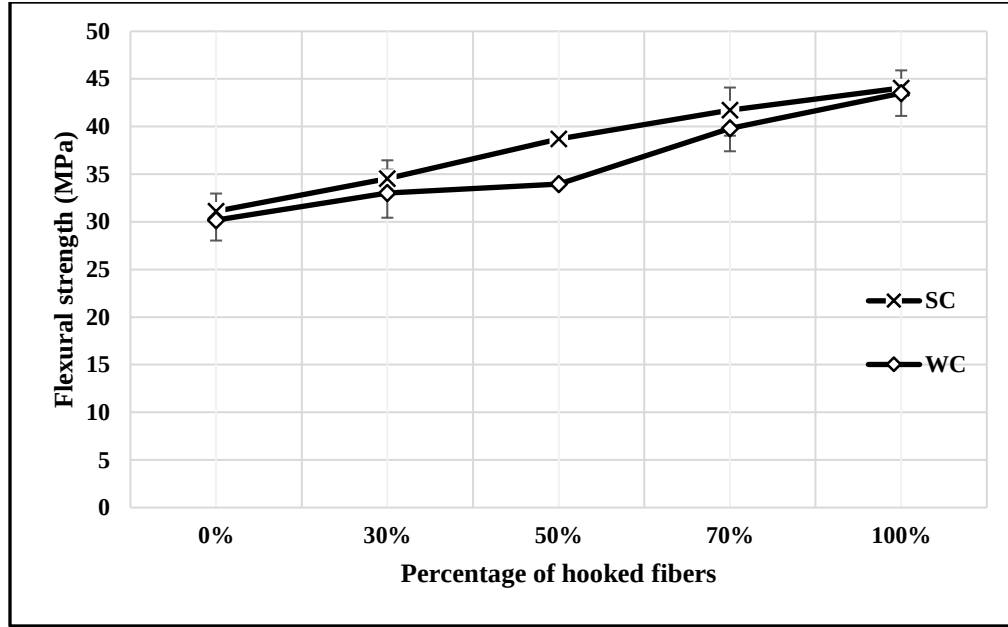


Figure 31: Effects of fiber hybridization proportions and curing methods on flexural strength

Figure 31 indicates that the specimens that were steam-cured possessed slightly higher flexural strength compared to their counterparts that were water-cured. This is attributed to the higher temperature offered by steam curing which boosted hydration of cement and, more prominently, of silica fume. In case of water-curing where ambient temperature is relatively low, silica fume contributes less in hydration and left to act merely as a filler material [30, 54].

4.3.2. Mid-span deflections at ultimate flexural stress

The mid-span deflection of the specimens at ultimate flexural stress got significantly increased when the percentage of hooked fibers increased beyond 50%, as can be observed from Figure 32. The mid-span deflections of the UHPC mixtures with 100% hooked fibers were noted as 61% (for steam-cured) and 43% (for water-cured) more than the mid-span deflections of the UHPC mixtures that contained 100% straight fibers.

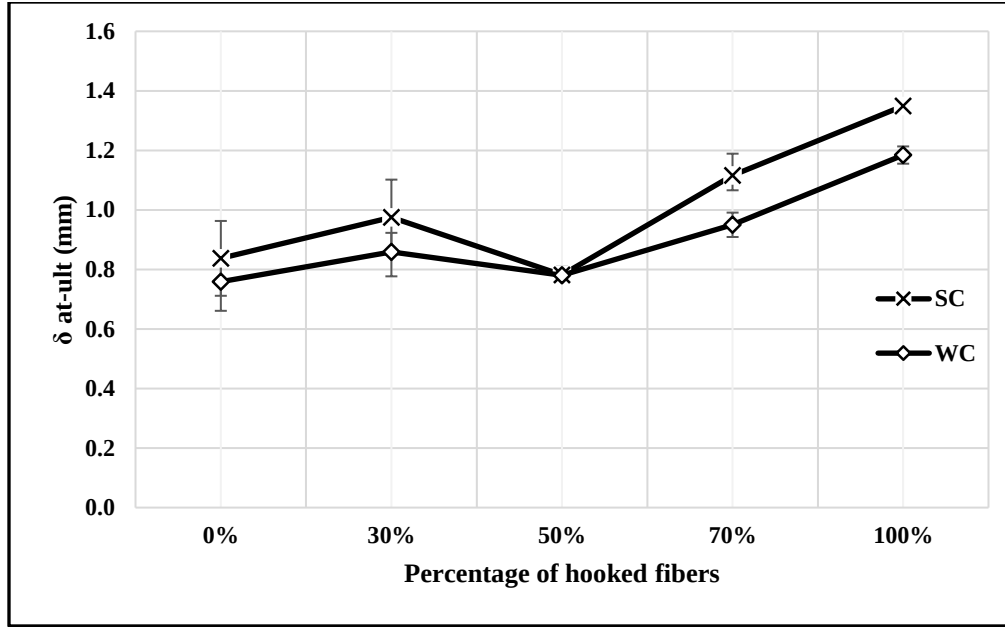


Figure 32: Effects of fiber hybridization proportions and curing methods on mid-span deflection at ultimate flexural stress

4.3.3. Flexural stress when first crack appeared and mid-span deflection

Regardless of the curing regime, cracking stress falls within the range 20-25 MPa for all mixtures (average = 22 MPa), as can be observed from Figure 33. On the other hand, mid-span deflection at cracking is in the range of 0.3-0.4 mm for all mixtures (average = 0.38 mm) (Figure 34). This implies that the fiber hybridization and the curing regime have negligible effect on the cracking stresses and corresponding mid-span deflections of the UHPC mixtures.

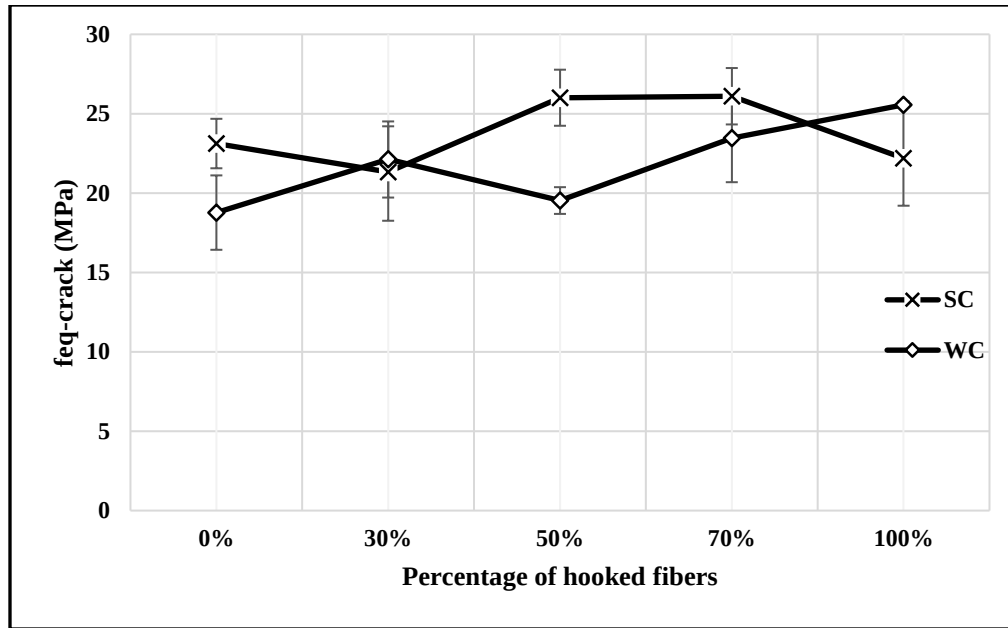


Figure 33: Effects of fiber hybridization proportions and curing methods on cracking stress

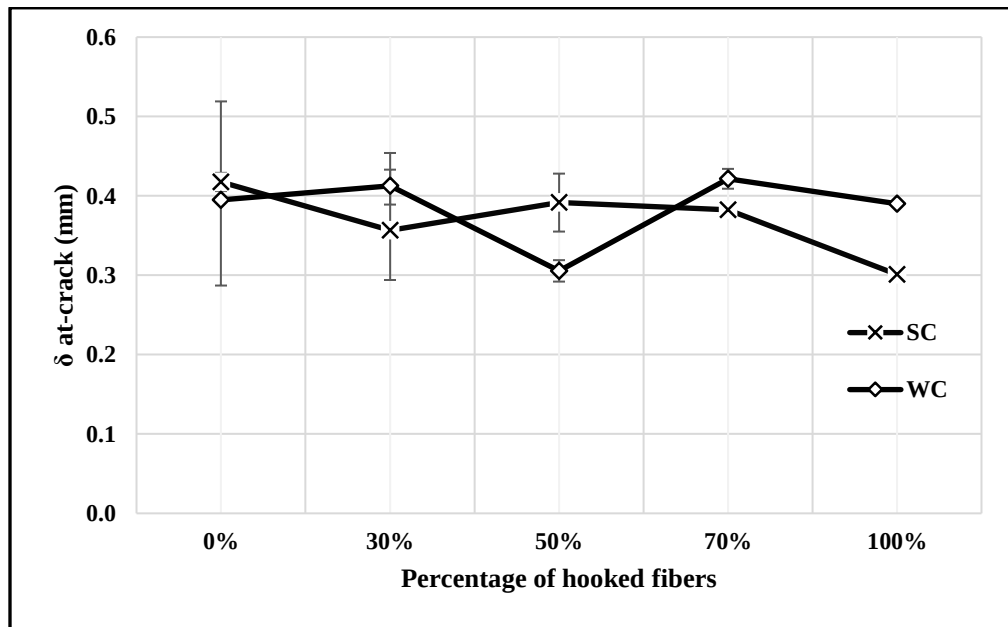


Figure 34: Effects of fiber hybridization proportions and curing methods on mid-span deflection at cracking stress

4.3.4. Flexural toughness

Figure 35 shows the plots of the flexural toughness (MOT_f) data obtained for all UHPC mixtures. It can be observed from Figure 35 that the flexural toughness remains unchanged with the increase in the percentage of hooked fiber up to 50%. However, the flexural toughness of the UHPC mixtures was increased substantially when the hooked fiber content increased beyond 50%. Further, it may be noted that the flexural toughness of the steam-cured UHPC mixtures was higher than that the water-cured UHPC mixtures at all dosages of the hooked fibers. The flexural toughness of the UHPC mixtures with 100% hooked fibers were noted as 124%, i.e., 2.24 times, (for steam-cured) and 117% (for water-cured) i.e., 2.17 times, more than the flexural toughness of the UHPC mixtures that contained 100% straight fibers.

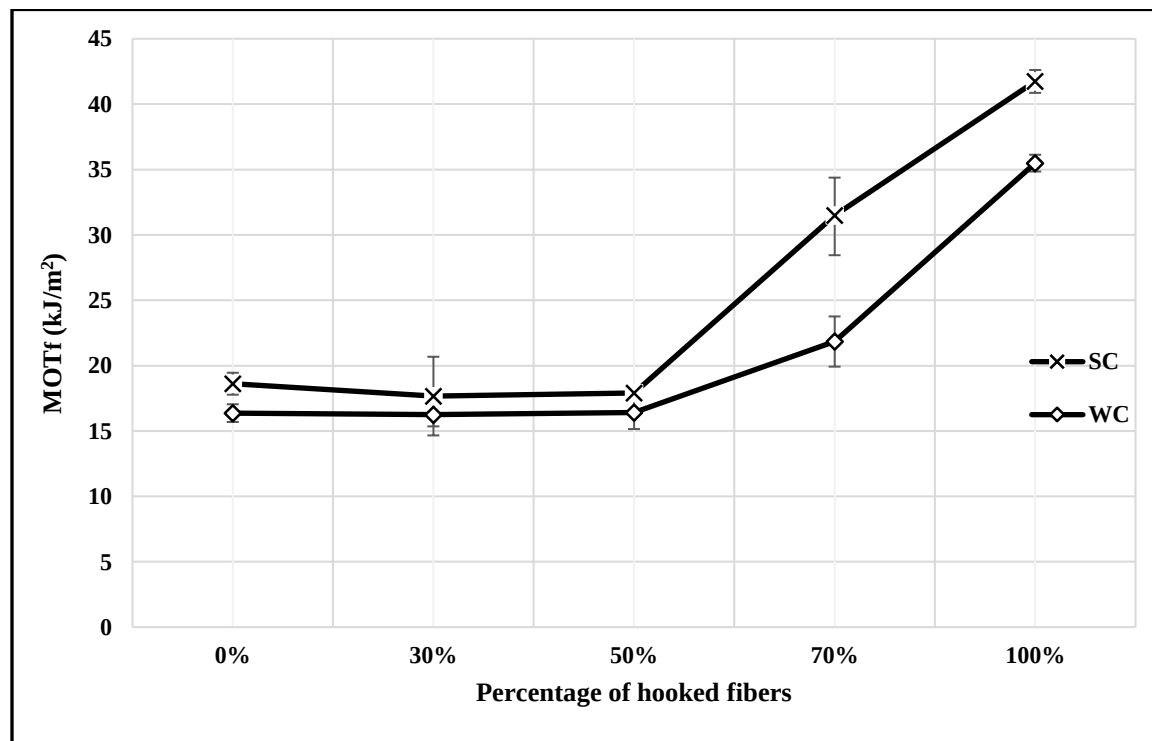


Figure 35: Effects of fiber hybridization proportions and curing methods on flexural toughness

4.4. Bond test results

A total of 60 specimens were tested under pull-out action for studying the effect of the fiber hybridization, curing types and the grades of embedded steel bars on the bond behavior of the UHPC mixtures. All specimens were divided into groups of 3 replicate specimens that had the same steel fiber combination, curing regime and embedded steel bar type.

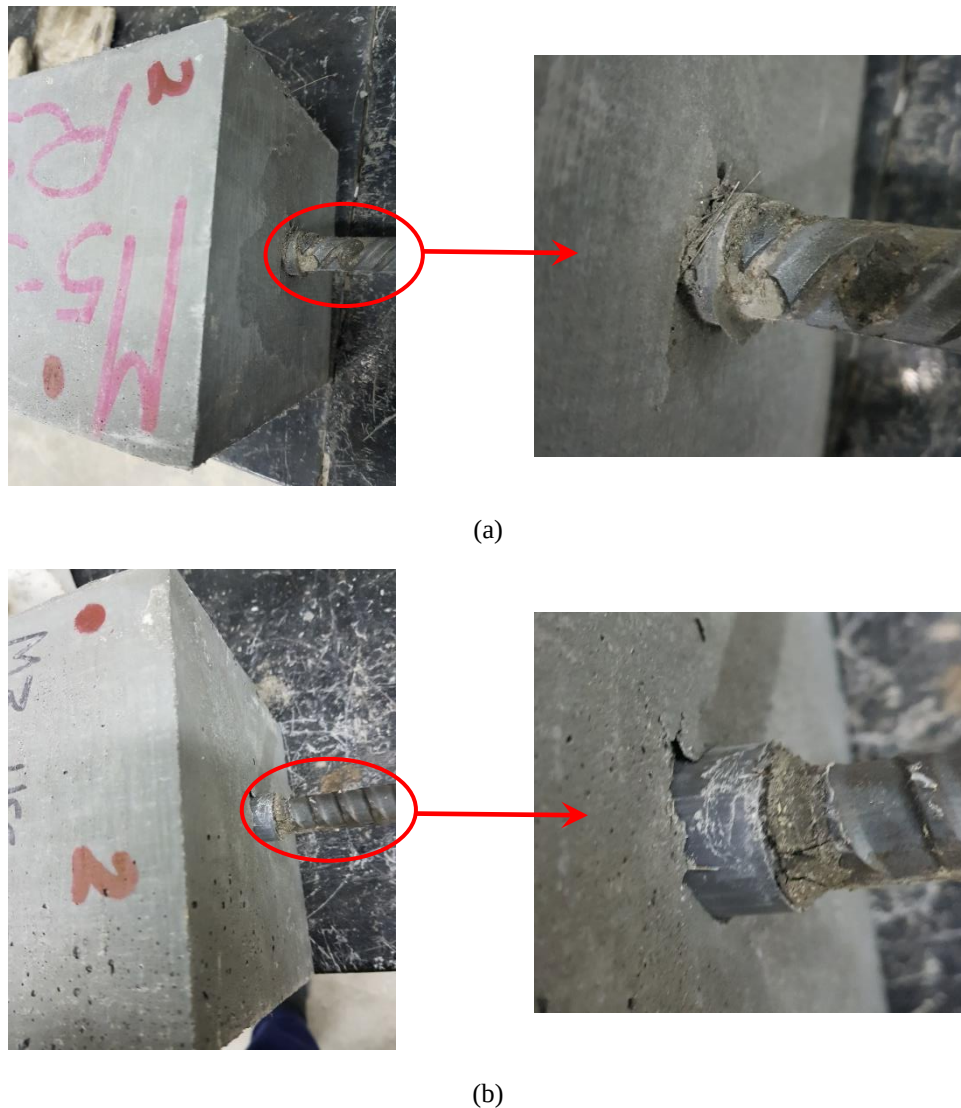
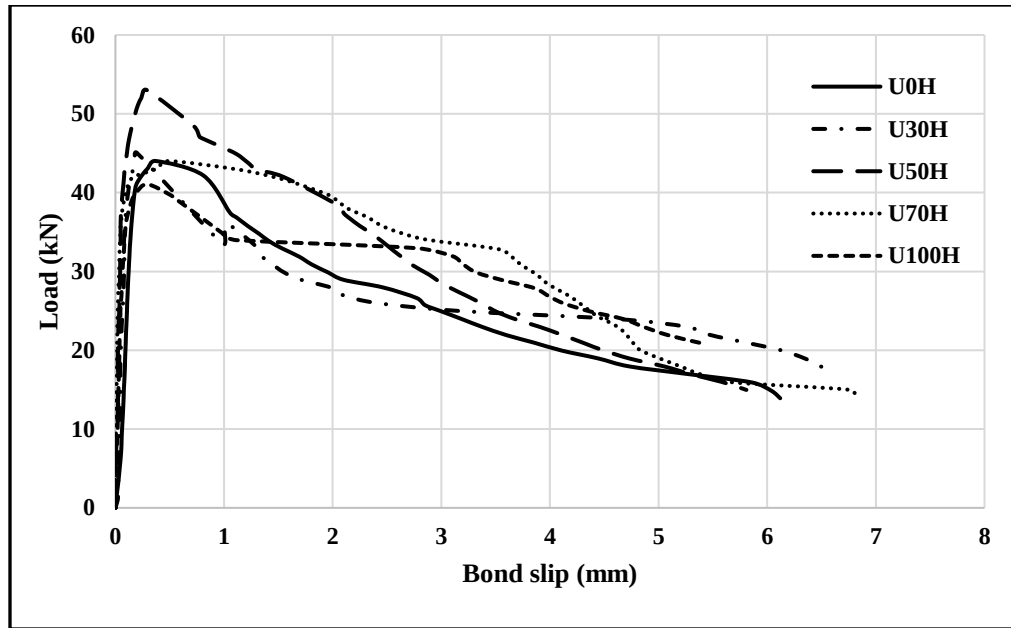


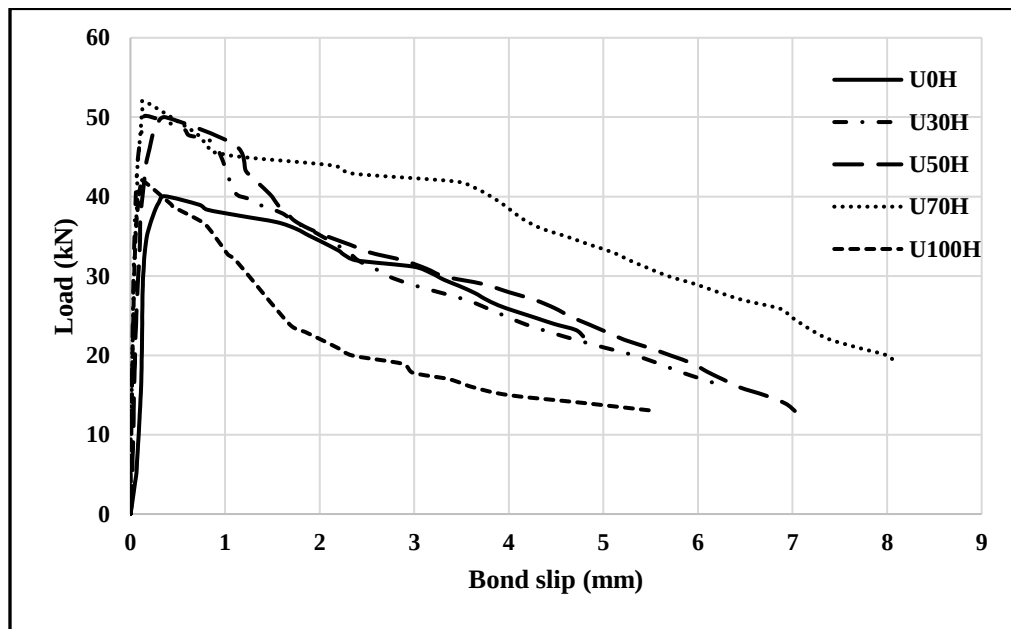
Figure 36: Failure modes resulted from the pull-out test for the case of (a) regular steel (b) high strength steel

The mechanisms by which steel rebar is attached to the UHPC are vital for interpreting failures in the rebar pull-out tests. Several factors contribute in the bond strength between rebar and UHPC including the chemical adhesion, mechanical anchorage between the ribs of rebar and surrounding contact surface of concrete, and friction. Accordingly, failure in the pull-out test can take different modes: slip of the bar from the UHPC (bond failure), bar fracture, and a conical shaped failure in which the UHPC attached to the bar separates from the UHPC cube. Bond failure occurs when surrounding concrete crushes and exfoliates off the rebar, allowing rebar to slip. This indicates that the bond strength of the steel rebar is governed by the strength of concrete [2, 55]. From Figure 36 it can be noticed that no splitting cracks had developed after tests and this reflects the excellent bond capacity of UHPC.

It can be observed in Figures 37 and 38 that all specimens reflected similar behavior during the pull-out testing where the response curves start with an initial increase in the load with a very small slip until reaching the ultimate load. The slip is resisted in the beginning due to the chemical adhesion between the rebar and UHPC. A softening stage then follows beyond the ultimate load. From Figure 37, it can be seen that the regular steel (RS) bar embedded in the mixtures U50H resulted in highest bond strength when compared to the other mixtures. Whereas in Figure 38, showing the bond-slip behavior of the high strength steel (HSS) bars embedded in the UHPC mixtures, indicates that all the UHPC mixtures had bond strengths with small differences and their load/slip curves behaved in the same manner.

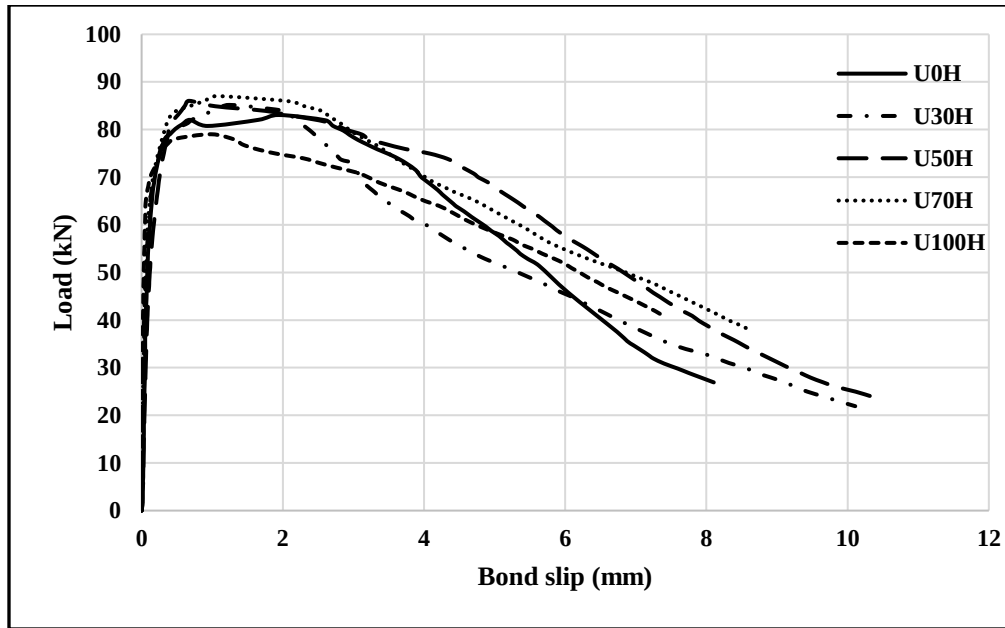


(a)

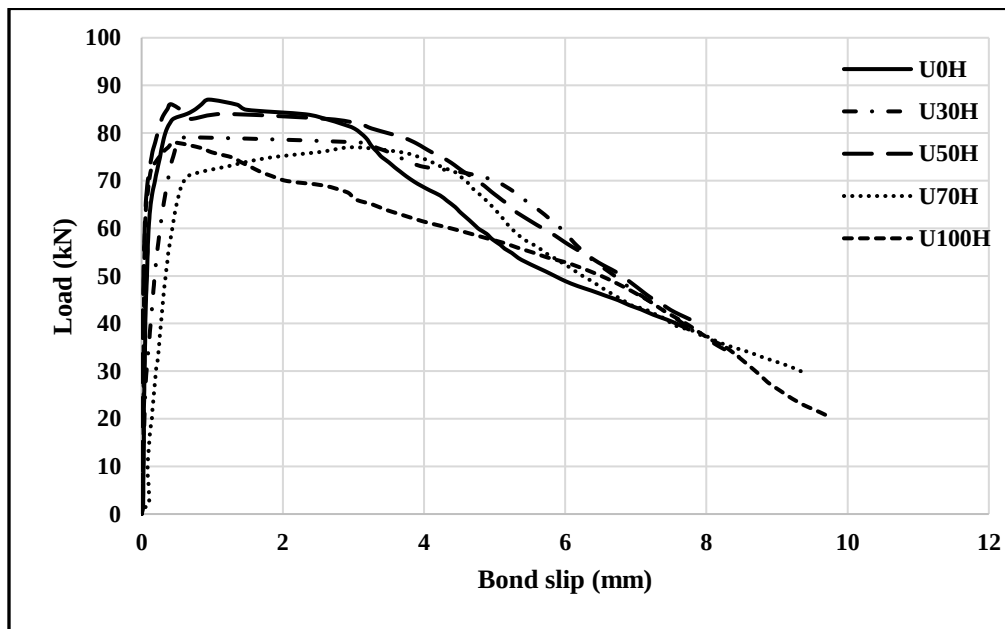


(b)

Figure 37: Bond-slip response of regular steel (RS) embedded in different UHPC mixtures (a) steam-cured (b) water-cured



(a)



(b)

Figure 38: Bond-slip response of high strength steel (HSS) embedded in different UHPC mixtures
(a) steam-cured (b) water-cured

Table 14 summarizes the mean values (averages of three replicate specimens) of the bond strength and corresponding slip of all 20 specimens (5 dosages of hooked fibers $\times$ 2 curing types $\times$ 2 types of bars). Bond test results in detail are given in Appendix C.

Table 14: Summary of the bond test results

Specimen	Mean $f_b^{(1)}$ (MPa)	Mean $s_m^{(2)}$ (mm)
U0H-HSS-SC	51.213	1.706
U0H-HSS-WC	55.993	1.147
U0H-RS-SC	49.962	0.228
U0H-RS-WC	49.789	0.274
U30H-HSS-SC	51.352	0.833
U30H-HSS-WC	49.568	0.587
U30H-RS-SC	55.519	0.349
U30H-RS-WC	54.232	0.162
U50H-HSS-SC	52.869	1.542
U50H-HSS-WC	51.310	0.515
U50H-RS-SC	60.960	0.855
U50H-RS-WC	59.070	0.221
U70H-HSS-SC	48.853	0.643
U70H-HSS-WC	46.031	0.240
U70H-RS-SC	54.831	0.283
U70H-RS-WC	59.746	0.148
U100H-HSS-SC	50.680	0.621
U100H-HSS-WC	46.328	0.770
U100H-RS-SC	49.787	0.244
U100H-RS-WC	51.645	0.109
⁽¹⁾ f_{b-ult} : the maximum bond strength of the specimen.		
⁽²⁾ s_m : the free end slip of the specimen at the maximum load.		

4.4.1. Bond strength

Referring to Figure 39, it can be observed that in case of regular steel (RS) bars embedded in UHPC mixtures, the bond strength increased with an increase in the percentage of hooked fibers up to 50% and then decreased in the further increase in the amount of the hooked fibers. For the RS bars, an increase in the bond strength by around 20% can be noted at a hooked fiber content of 50%. However, for HSS bars the bond strength remained

almost unaffected by the fiber hybridization. For both types of the bars, types of curing had insignificant effect on the bond strength.

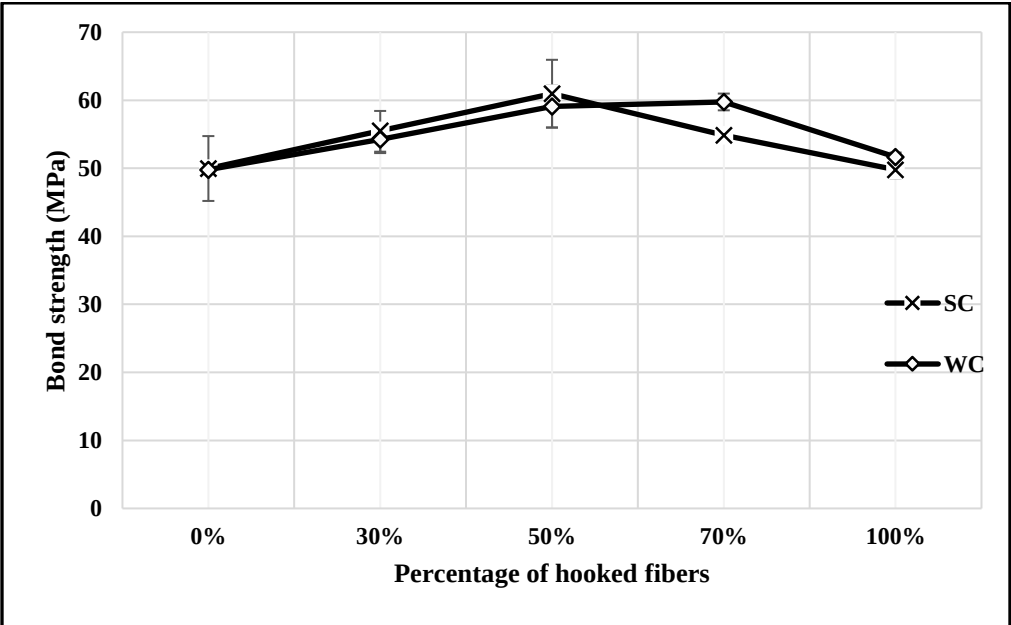


Figure 39: Effects of fiber hybridization proportions and curing methods on bond between UHPC and regular steel (RS) bars

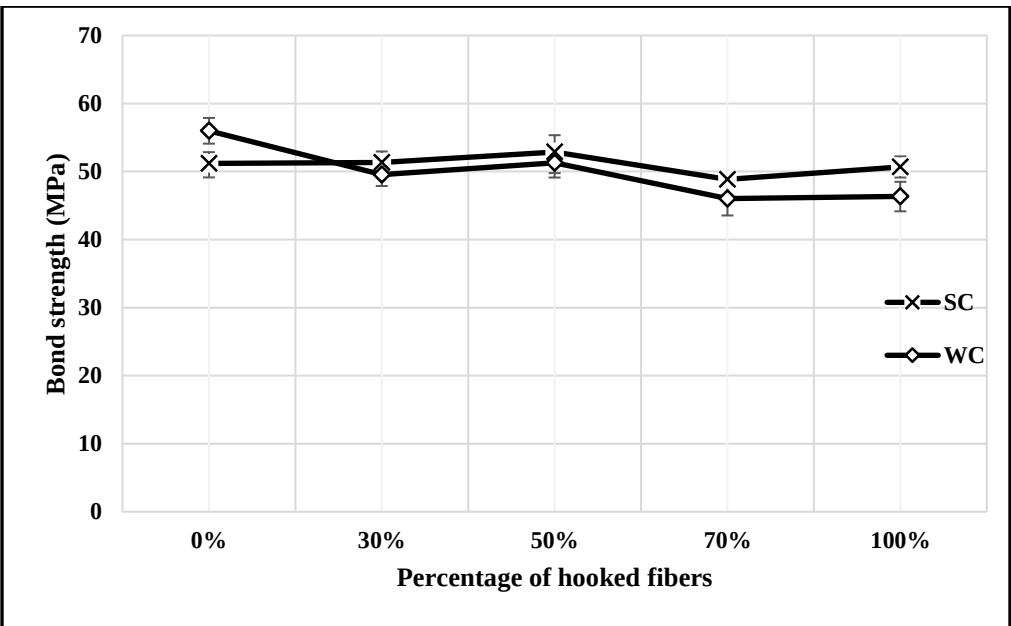


Figure 40: Effects of fiber hybridization proportions and curing methods on bond between UHPC and high strength steel (HSS) bars

4.4.2. Bond slip

It can be observed from Figures 41 and 42 that the slip in case of steam-cured specimens were higher as compared to that for the water-cured specimens. However, for the two curing methods, the slip values are very small ($< 2\text{mm}$). Accordingly, it can be said that the curing method makes no difference to the slip value.

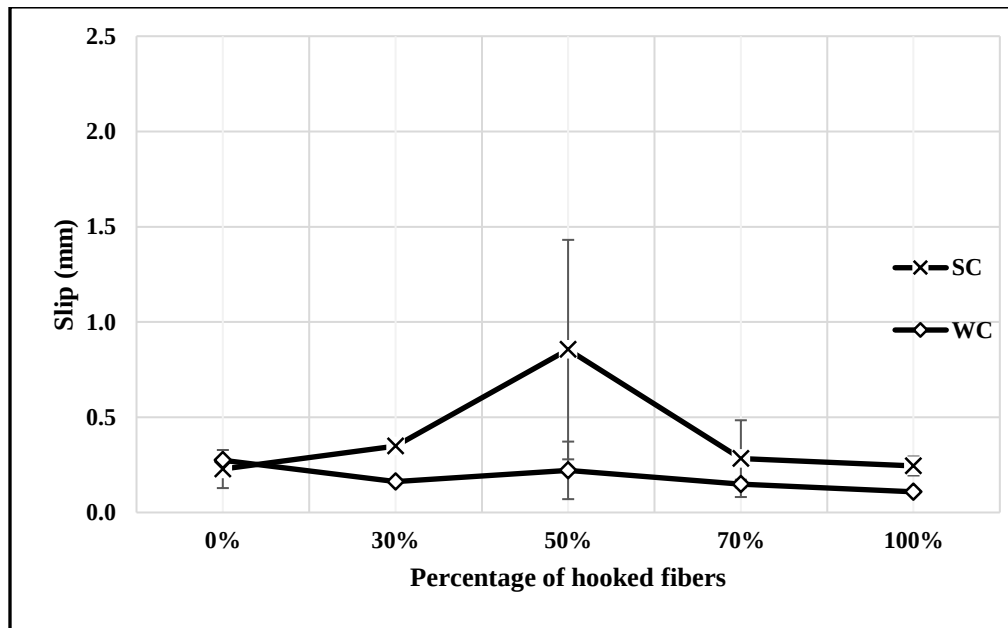


Figure 41: Effects of fiber hybridization proportions and curing methods on slip between UHPC and regular steel (RS) bars

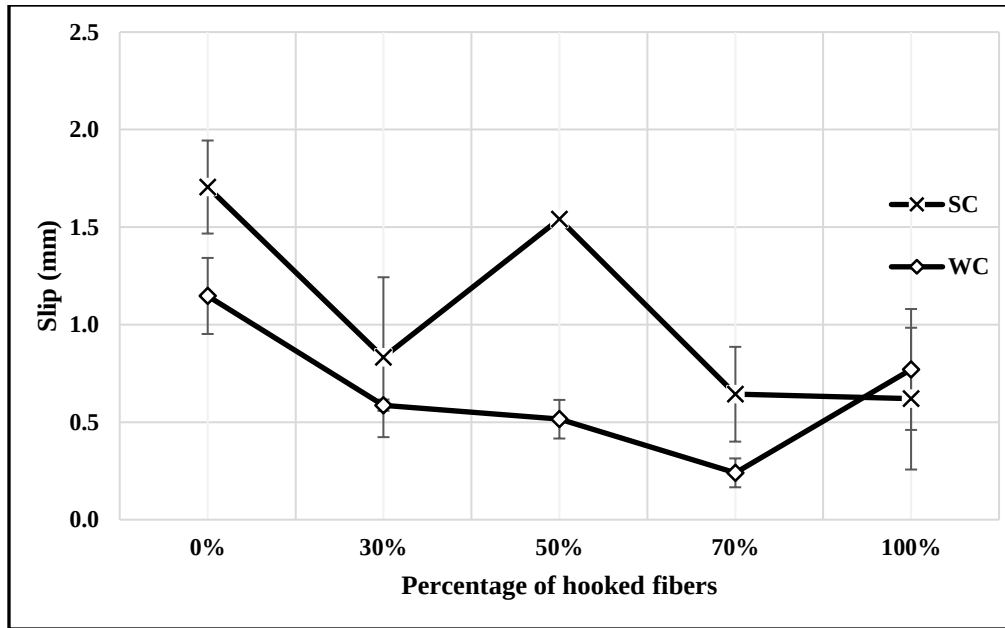


Figure 42: Effects of fiber hybridization proportions and curing methods on slip between UHPC and high strength steel (HSS) bars

CHAPTER 5

NUMERICAL AND EMPIRICAL MODELING

Numerical and empirical models were developed to simulate the bond between UHPC (produced using hybridized steel fibers and two different curing regimes) and steel rebars of two different grades. This chapter presents the description of the approach used to carry out the numerical and empirical modeling of the bond behavior and the outcomes of the models and their validation utilizing the results obtained from the experimental work of the present work.

5.1. Numerical Modeling using Finite Element Method

The various aspects of finite element modeling of bond slip between UHPC and rebar and their interfacial contact behavior are presented herein. In this study, it was found that using loading duration as one second gave good results. Two load steps were defined (initial and static general) with automatic increments and unlimited maximum time increments. The nonlinear finite element software ABAQUS was utilized to study the proposed modeling parameters. The damage plasticity model (CDPM) was utilized to model concrete. A constitutive model is available in the ABAQUS material library. In this model, compression and tension are two hardening variables that control the development of yield surface.

5.1.1. Materials constitutive laws

5.1.1.1. UHPC material modeling

The UHPC material behavior was simulated based on the concrete damage plasticity model (CDPM). The CDPM provides plastic stress-strain curves of UHPC in compression and tension as shown in Figures 43 and 44 (Dogu et al. [56]). This model is applied to reflect the behavior of concrete and other quasi-brittle materials when these materials are subjected to loading that is cyclic in nature (FIB, 2010 [57]). The CDPM is based on the concept of stiffness degradation to simulate crack propagation. Birtel and Mark [58] proposed two damage parameters for compression (d_c) and tension (d_t). The values of these parameters range from 0 (indicating fully unharmed stiffness) to 1 (indicating fully degraded stiffness). Material properties used for the definition of the CDPM of UHPC are given in Table 15.

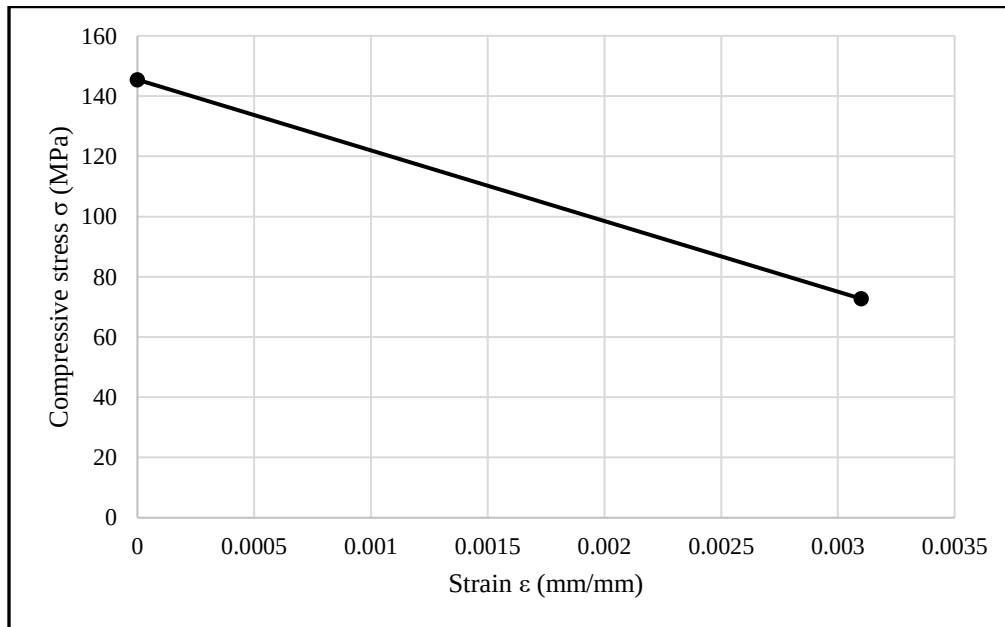


Figure 43: Compressive behavior model of UHPC [56]

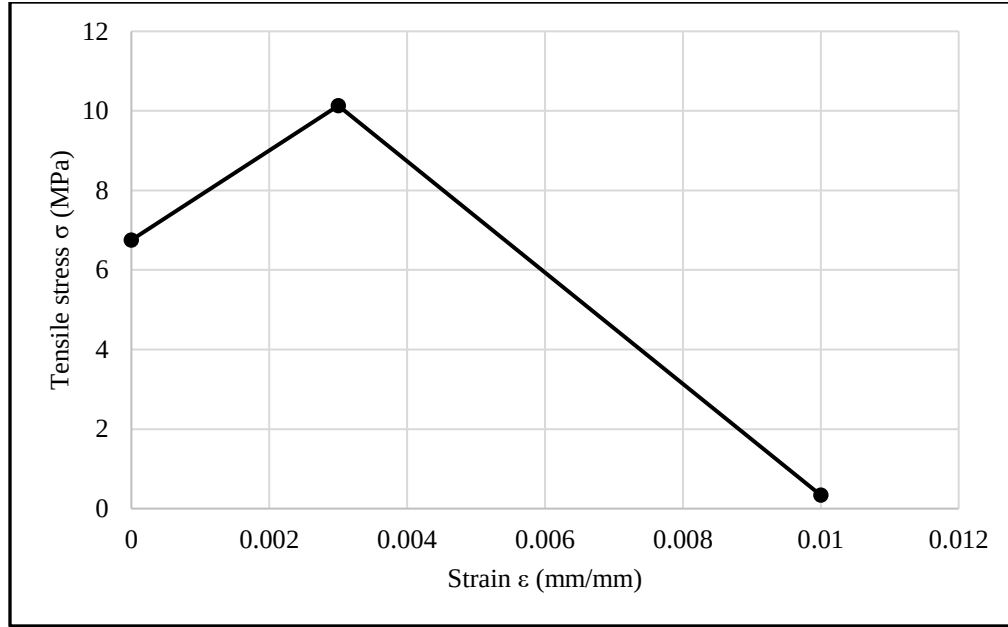


Figure 44: Tensile behavior model of UHPC [56]

Table 15: Properties of UHPC

Density (ton/mm ³)	Poisson's ratio [61]	Dilation angle ψ (Degrees) [61]	Eccentricity ϵ [61]	f_{bo}/f_{co} [61]	K [61]	Viscosity P Parameter [61]
2.5 E-009	0.21	45	0.1	1.16	0.667	0

5.1.1.2. Steel rebar model

The steel behavior was assumed as elastic- perfectly plastic, conforming to the Von Mises yield criterion. Reinforcing steel model was created out of a 3-D solid element. The parameters used to define reinforcing steel behavior are shown in Table 16.

Table 16: Properties of steel rebar

Steel Type	Regular Steel	High Strength Steel
Elastic Modulus (MPa)	200,000	213,000
Yield Stress (MPa)	586	1397

5.1.2. FE interaction modeling

The bond behavior at the interface of two contacted surfaces is governed by a linear-elastic relationship between traction (t) (bond stress) and separation (δ) (slip). Typically, ABAQUS can simulate the bonded interface behavior using the traction-separation relationship in two approaches. The first is cohesive elements, and the second is surface-based cohesive behavior. In this research, the thickness of the interface is small and therefore neglected. For this reason, the surface-based cohesive method is utilized because of its effectiveness and convenience for this case. The traction-separation model is defined by two parts in ABAQUS, which are the initial linear elastic behavior and the post-elastic behavior. These parts are identified by the point when bond damage initiates and evolves. The elastic behavior is represented by an elastic constitutive matrix, which relates the shear and normal stresses to the shear and normal separations across the interface (ABAQUS Manual 2013 [59]).

The constitutive relation for initial elastic part can be uncoupled or coupled, as expressed in Equations (8) and (9), respectively.

$$t = \begin{pmatrix} t_n \\ t_s \\ t_t \end{pmatrix} = \begin{pmatrix} K_{nn} & 0 & 0 \\ 0 & K_{ss} & 0 \\ 0 & 0 & K_{tt} \end{pmatrix} \begin{pmatrix} \delta_n \\ \delta_s \\ \delta_t \end{pmatrix} = K \delta \quad (8)$$

$$t = \begin{pmatrix} t_n \\ t_s \\ t_t \end{pmatrix} = \begin{pmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{sn} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{pmatrix} \begin{pmatrix} \delta_n \\ \delta_s \\ \delta_t \end{pmatrix} = K \delta \quad (9)$$

As the uncoupled behavior is recommended by several researchers, the values of stiffness K_{nn} , K_{ss} , and K_{tt} , have to be defined. Constants in the K stiffness matrix are expressed in the units of (Force/Length²/Length). These stiffness elements, which define the contact in normal and tangential directions, can be determined based on exponential decay.

The post-elastic behavior, which can be identified by the initiation and evolution of bond damage, can be expressed using the relationship between the bond stress and slip of steel bar. An approximation to this relationship can be obtained by the aid of the bond damage criterion which states that damage initiates as soon as any of the three separation or slip models (Equation (10)) is triggered when the corresponding stress exceeds a maximum allowable value. This criterion is given as:

$$Max \left\{ \frac{\langle t_n \rangle}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0} \right\} \quad (10)$$

The normal stress, t_n , in Equation (10) is kept within Macaulay brackets. This is to avoid compressive stress ($t_n < 0$) that causes damage initiation.

In ABAQUS, the choice is open for linear, exponential, or user defined response for this cohesive damage evolution. Linear behavior is defined by determining the maximum effective separation (δ_m) at the instant of full degradation of the bond, and is given as:

$$\delta_m = \sqrt{\langle \delta_n \rangle^2 + \delta_s^2 + \delta_t^2} \quad (11)$$

In this study, linear damage evolution is used by specifying δ_m = maximum slip in the longitudinal tangential direction because slip values in the other two directions are considerably small compared to it. This damage evolution was chosen for its simplicity and accuracy. This was evident from the clear convergence of the results of four different cohesive damage models in ABAQUS, reported by Wenkenbach [60]. Figure 45 displays the complete bond behavior and its characteristics. The damage initiation begins at point A and the behavior from point A to point B describes damage evolution.

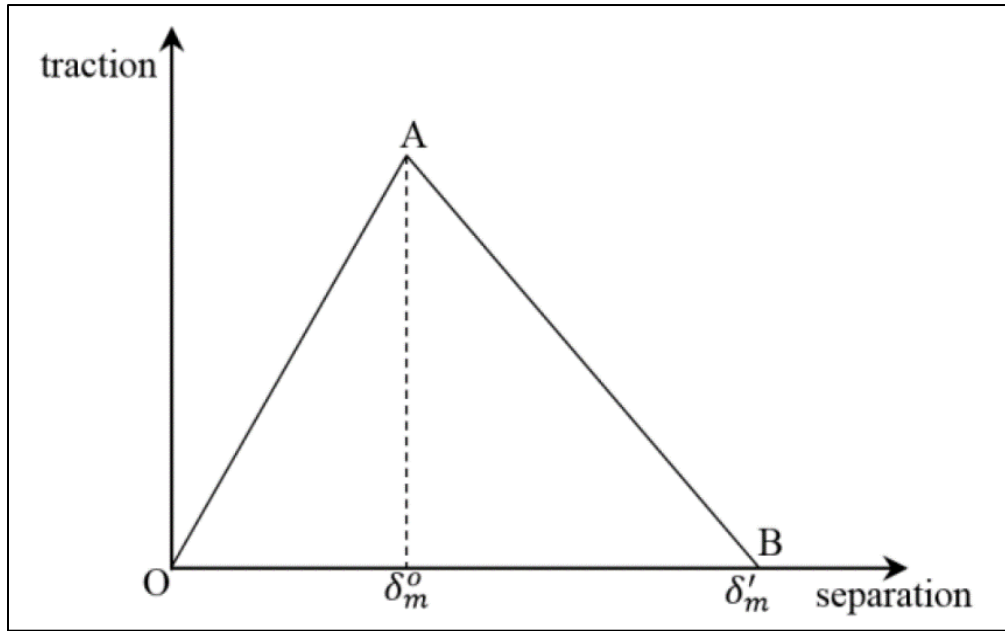


Figure 45: Bond traction separation characteristic with linear damage evolution [61]

In order to let the maximum shear stress controls the behavior, large value of the maximum t_n was used. The maximum bond strength ($t_{\max}$) was represented in ABAQUS by t_s . As for the t_t , it had no effect on the behavior since there was almost no stress in the transverse direction of the bar.

Steel reinforcement was bonded with concrete through two interfacial regions to define the interaction between UHPC and rebars. The first region extends along the top and bottom parts of the embedded rebar. This region was encased by PVC pipes. The behavior in this case is considered as tangential behavior (frictionless) and this region acts as a no-contact zone between UHPC and rebar. The second region is at the middle of the embedded rebar and it was not encased by PVC (bond length = L_e). In this case, the Surface-based cohesive model was used to model the bond. The parameters k_{nn} (normal stiffness), k_{ss} , and k_{tt} (tangential directions stiffness) were inputted to define the cohesive interaction and reflect the behavior of adhesive material between UHPC and the rebar. Since these parameters were unknown between UHPC and steel bars, trial and error methods were applied to these parameters until the proper results were obtained from the model. Cohesion contact was employed between UHPC and rebar for interaction, which presumes bond deterioration occurs due to stiffness degradation. This phenomenon was not considered because the complete de-bonding of rebar from UHPC was achieved at the ultimate stress state.

5.1.3. Finite element types and mesh sensitivity

Both concrete and steel rebar were represented using 3-D eight noded linear brick solid elements (C3D8R). Due to the symmetry of the specimen tested for pullout, only one quarter of it was modeled (Figure 46) to accelerate analysis run. The optimum mesh sizes were selected based on a sensitivity analysis which guaranteed the balance between acceptable accuracy of the results and reasonable analysis running cost. The boundary conditions and meshes are shown in Figures 47 and 48, respectively. The displacements of the concrete body were restrained in the X and Z directions along the horizontal axes of

symmetry. The load was applied as displacement loading in the direction of the positive y-axis on the top end of the steel bar.

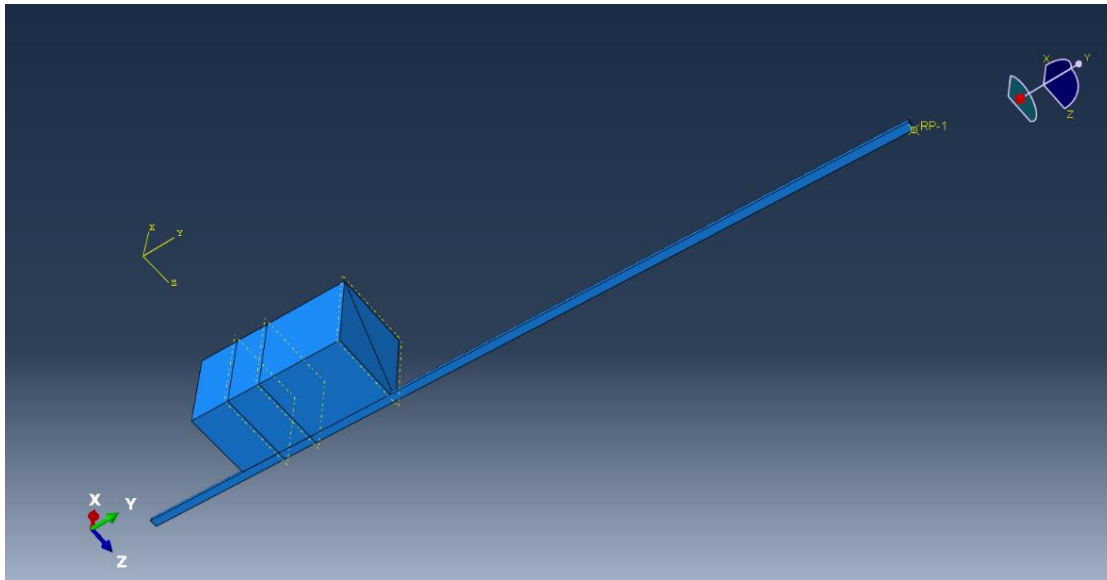


Figure 46: Element Assembly in ABAQUS

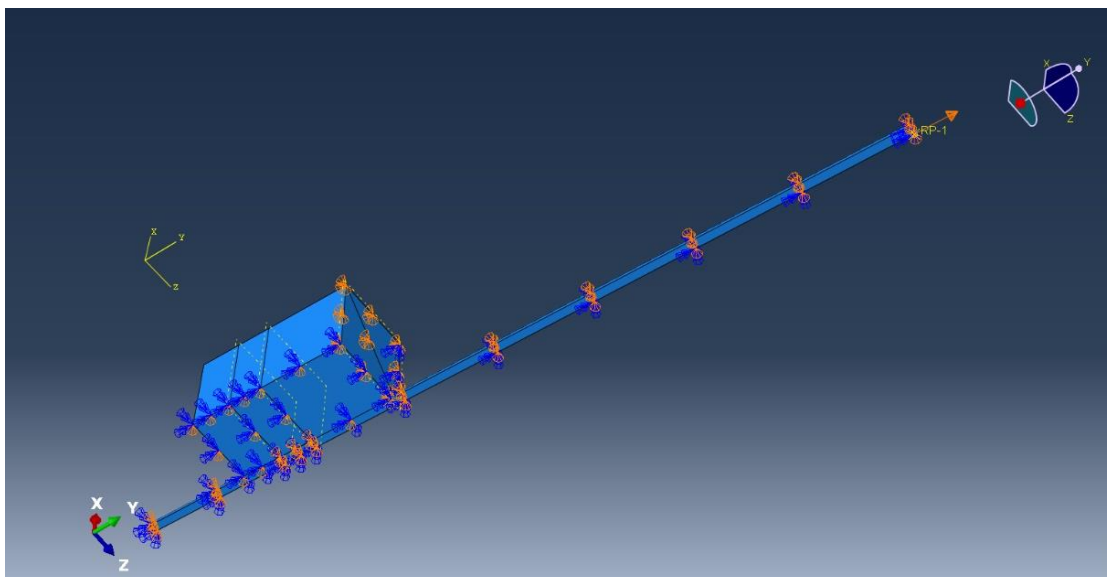


Figure 47: Boundary conditions in ABAQUS

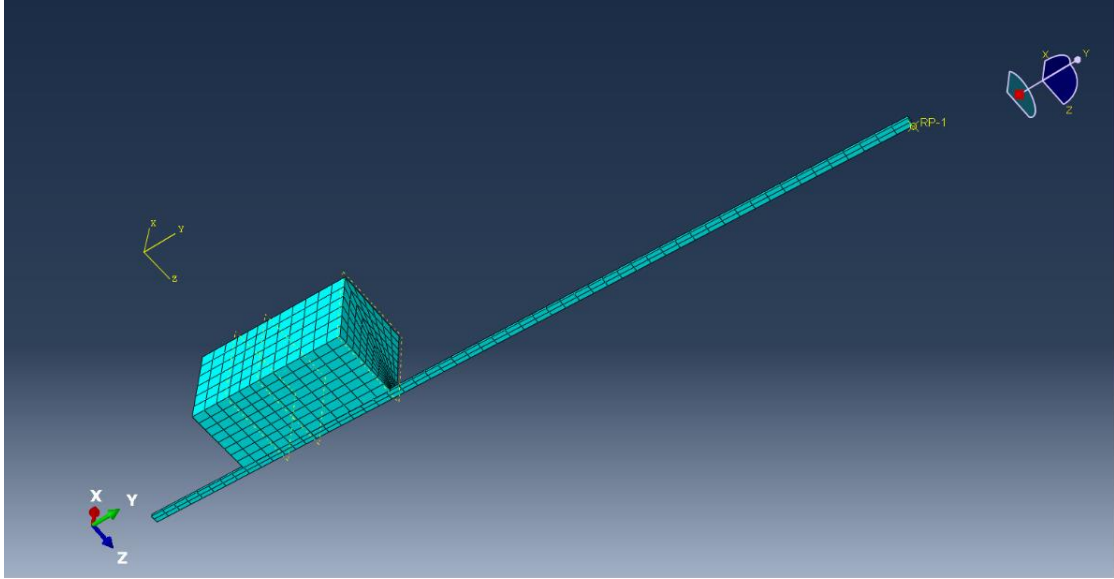


Figure 48: Meshing in ABAQUS

5.1.4. Validation of the finite element model

The bond strength obtained from the finite element models of the specimens described in Chapters 3 and 4 was validated through the experimental results. A comparison of the failure stresses between the experimental work and the finite element model results are presented to validate the ability of the FEM to predict the load at failure.

In Table 17, a comparison is established between the experimental and FEM results. Ten specimens were selected for analysis from a random curing regime, each one with a different (straight-to-hooked) fiber content proportion and different rebar type. It can be concluded that for the bond strength and the maximum load, all FEM results are in good agreement with the experimental results, with very small errors ($< 2\%$).

As for the slip, there is a difference between the FEM and the experimental results. The reason behind this is that the experimental work dealt with small displacements (0.1 mm).

It can be observed that even among the experimental results, there are significant differences in the displacement.

It can be seen in Figure 49 that the stress concentration is indicated by the colored region where there is a direct contact between UHPC and the steel bar. In addition, the failure type resulted from the FEM is similar to that observed in the experimental work, which is pullout failure.

Table 17: Experimental vs. FEM results of the bond strength and the slip

Bar type	Mixture ID	Curing regime	P _{max} (Exp.) (kN)	P _{max} (FEM) (kN)	Deviation (%)	f _b (Exp.) (MPa)	f _b (FEM) (MPa)	Deviation (%)	S _m (Exp.) (mm)	S _m (FEM) (mm)	Deviation (%)
High strength steel	U0H	WC	90.06	89.40	0.75%	55.99	55.57	0.75%	1.147	0.419	63.47%
	U30H	WC	79.73	78.73	1.25%	49.57	48.95	1.25%	0.587	0.334	43.10%
	U50H	SC	85.04	84.97	0.09%	52.87	52.82	0.09%	1.542	0.355	76.98%
	U70H	SC	78.58	79.10	0.66%	48.85	49.18	0.66%	0.643	0.335	47.90%
	U100H	WC	74.52	75.72	1.62%	46.33	47.08	1.62%	0.770	0.325	57.79%
Regular steel	U0H	SC	40.18	40.06	0.31%	49.96	49.81	0.31%	0.228	0.042	81.58%
	U30H	WC	43.62	43.53	0.21%	54.23	54.12	0.21%	0.162	0.045	72.22%
	U50H	WC	47.51	46.81	1.47%	59.07	58.20	1.47%	0.221	0.048	78.28%
	U70H	SC	44.10	43.49	1.37%	54.83	54.08	1.37%	0.283	0.045	84.10%
	U100H	WC	41.54	41.29	0.60%	51.65	51.34	0.60%	0.109	0.043	60.55%

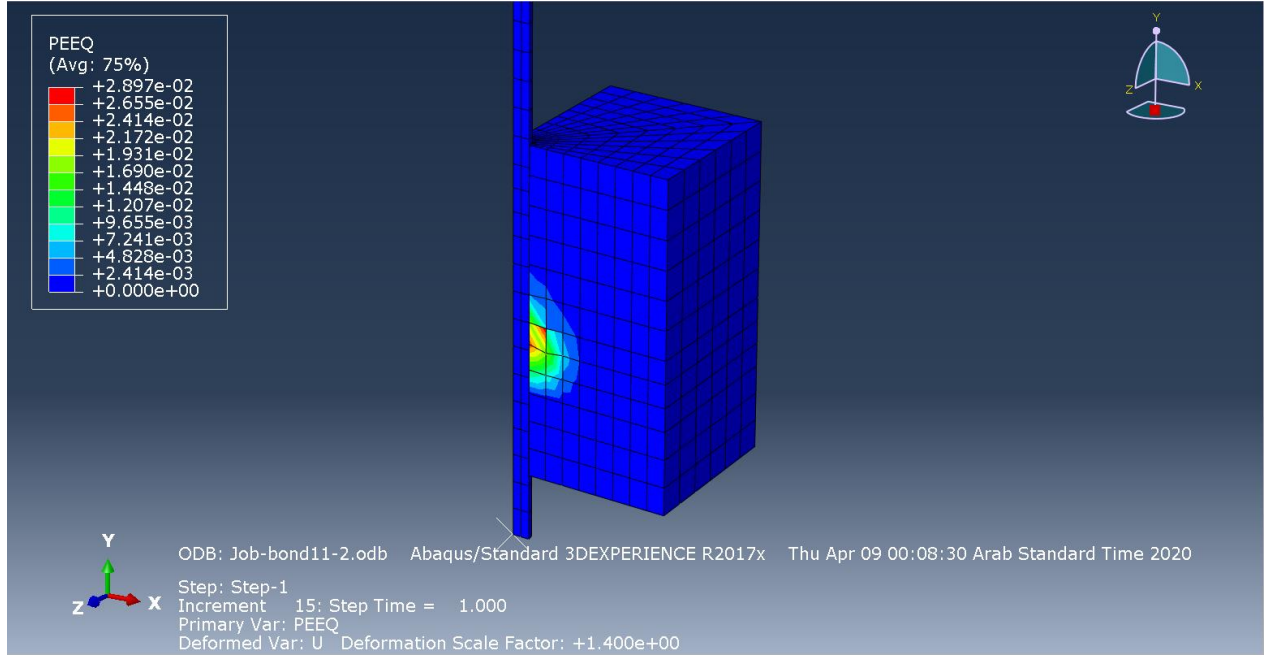


Figure 49: Stress concentration in ABAQUS

5.2. Empirical Modeling

5.2.1. Modeling of bond-slip behavior

The relative slip between reinforcement and concrete is the governing factor of the cracking behavior of reinforced concrete structures. Therefore, a bond-slip model needs to be developed to predict the bond behavior accurately. Yoo et al. [55] and Yoo et al. [2] used two empirical models, the BPE model (CEB-FIP. Model code for concrete structures [62] and Eligehausen et al. [63]), which is defined in Equation (12). In addition, the CMR model was proposed by Cosenza et al. [64] as defined in Equation (13).

$$\tau = \tau_{max} \times \left(\frac{s}{s_m} \right)^\alpha \quad (12)$$

$$\tau = \tau_{max} \times (1 - e^{-s/s_r})^\beta \quad (13)$$

Where:

τ = Bond stress (MPa)

$\tau_{\max}$ = Maximum bond stress (MPa)

s = Slip (mm)

α = Curve fitting coefficient (=0.4)

s_m = Curve fitting coefficient (=0.6)

s_r = Curve fitting coefficient (=0.07)

β = Curve fitting coefficient (=0.8)

Yoo et al. [55] and Yoo et al. [2] found that the CMR model showed better agreement with the measured experimental results than the BPE model. This led to the conclusion that the CMR model can be used for predicting the bond-slip behavior between rebar and UHPC.

In the current study, both models were examined to predict the bond/slip behavior. The results showed that using the CMR model, after imposing modification to the curve-fitting coefficients, gave better results up to the maximum value of bond strength (curve 1 as shown in Figure 50) compared to the BPE model. Beyond the maximum strength point, the CMR models cannot predict the actual behavior of bond and slip (curve 2, as shown in Figure 50). Therefore, a modified model, as shown in Equations (14) and (15) were used to predict the behavior beyond the maximum strength point.

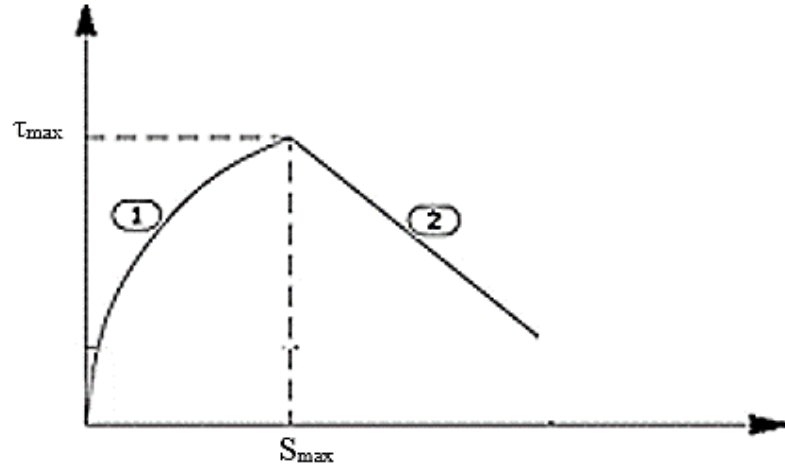


Figure 50: Modified CMR model

Developed model:

$$\tau = \tau_{max} \times (1 - e^{-s/s_r})^\beta \quad \text{For } 0 \leq s \leq s_{max} \quad (14)$$

$$\tau = \tau_{max} \times \left(1 - p \left(\frac{s}{s_{max}}\right)\right) \quad \text{For } s_{max} < s \quad (15)$$

Where:

τ = Bond stress (MPa)

s = Slip (mm)

p = Curve fitting coefficient (=0.025)

5.2.2. Validation of the developed model

The bond strength obtained using the CMR model for the specimen described in Chapters 3 and 4 is validated through the experimental results. A comparison between the bond/slip curve from the experimental data and the CMR models' predictions is presented to validate the proposed model.

The original CMR model, Equation (13), was good for predicting the bond/slip behavior up to the maximum bond strength, but there was a slight deviation.

In order to overcome this deviation, the curve fitting coefficients were adjusted. Using the statistical method, the curve fitting coefficients were deduced as displayed below:

$$s_r = 0.05 \text{ and } \beta = 0.9$$

To predict the bond/slip behavior beyond the maximum bond strength, a modified model was used (Equation (15)).

Figures 51 - 60 show comparisons between the experimental and the developed model for bond/slip results of 10 selected specimens with different mixtures of fiber types, different rebar types and different curing regime. It can be noticed that the developed model results are in good agreement with the experimental results, with minor deviations.

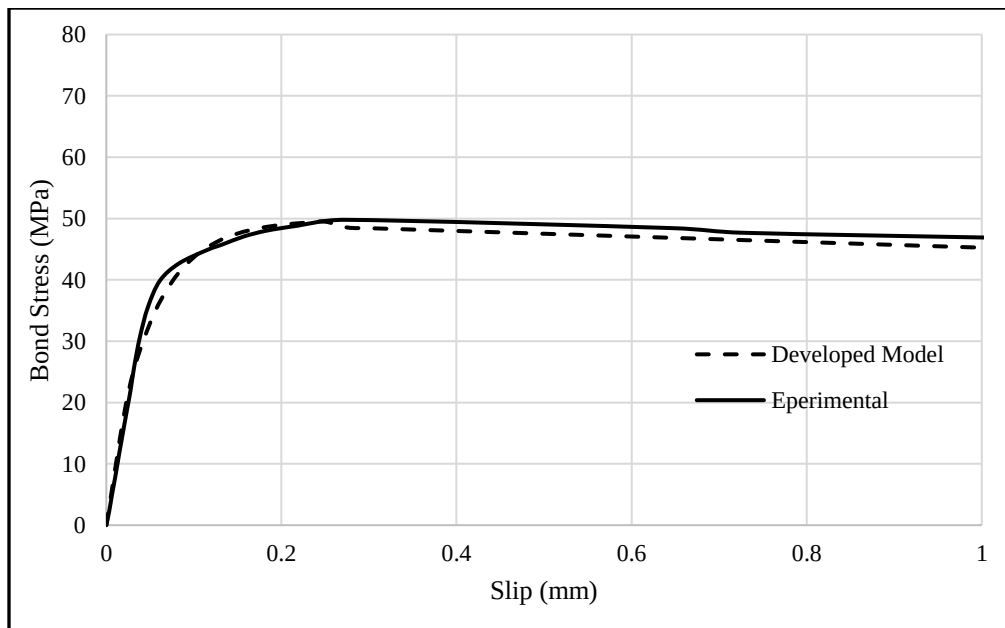


Figure 51: Bond stress – slip curves from the experimental and developed model (U0H-RS-WC)

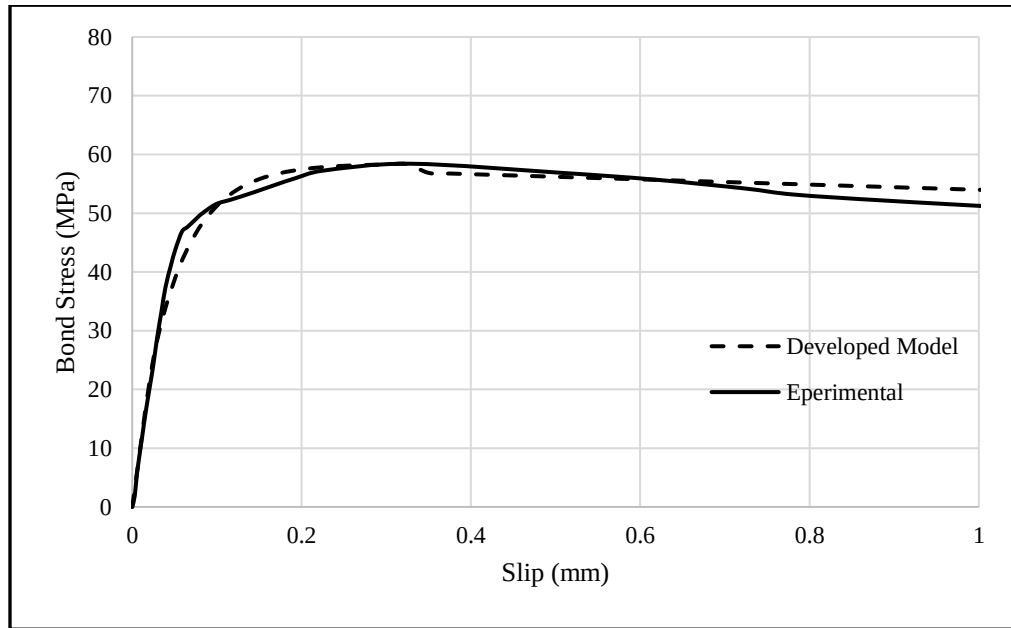


Figure 52: Bond stress – slip curves from the experimental and developed model (U30H-RS-SC)

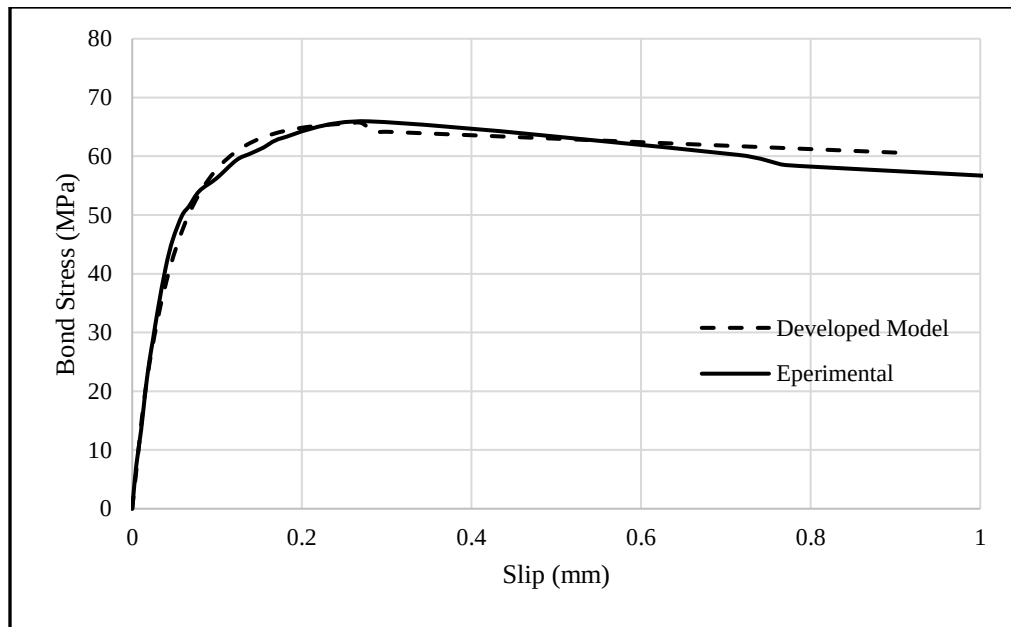


Figure 53: Bond stress – slip curves from the experimental and developed model (U50H-RS-SC)

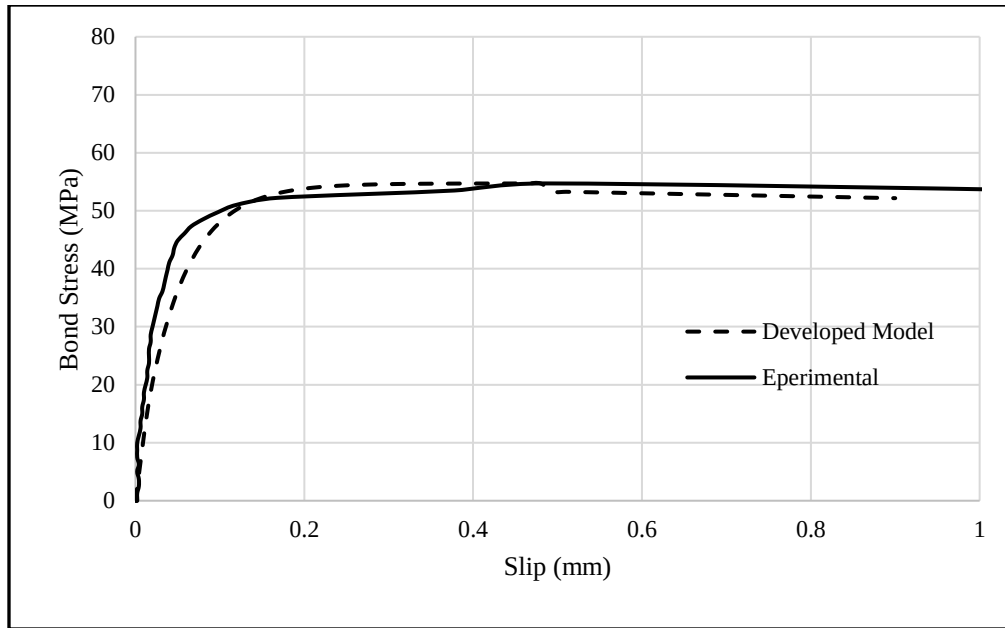


Figure 54: Bond stress – slip curves from the experimental and developed model (U70H-RS-SC)

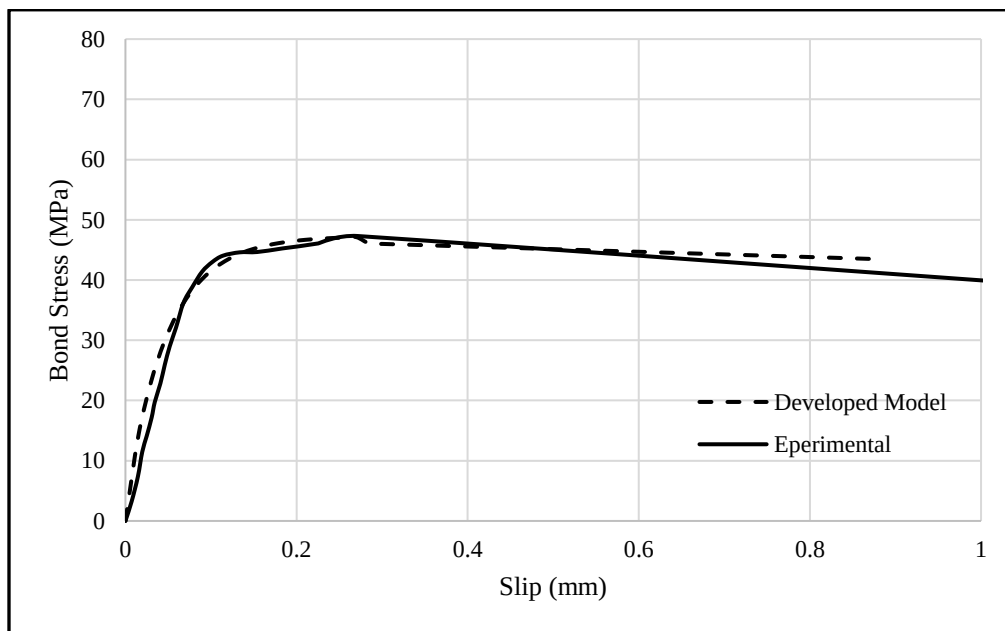


Figure 55: Bond stress – slip curves from the experimental and developed model (U100H-RS-SC)

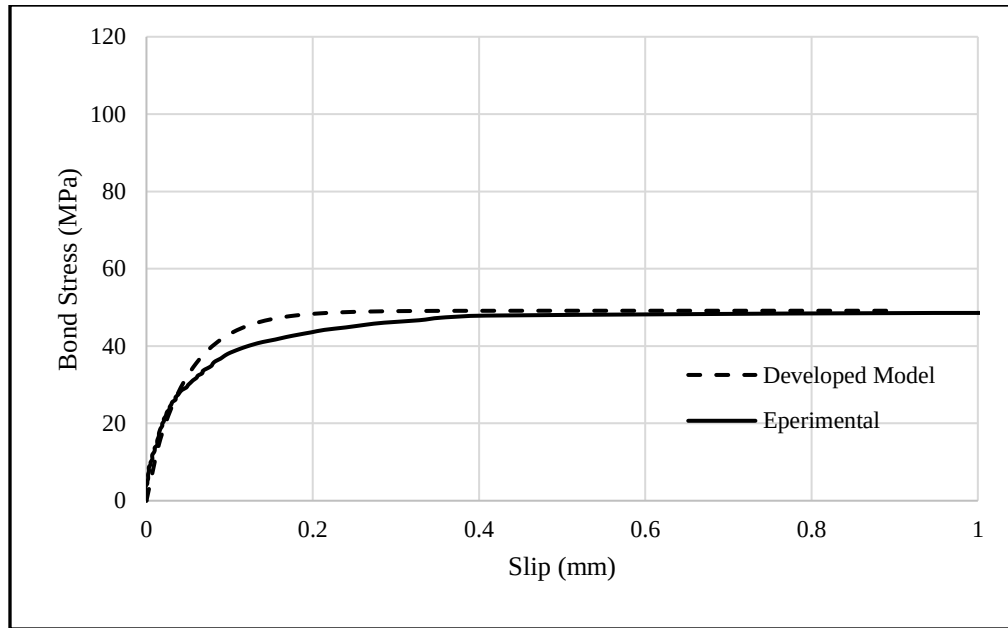


Figure 56: Bond stress – slip curves from the experimental and developed model (U0H-HSS-SC)

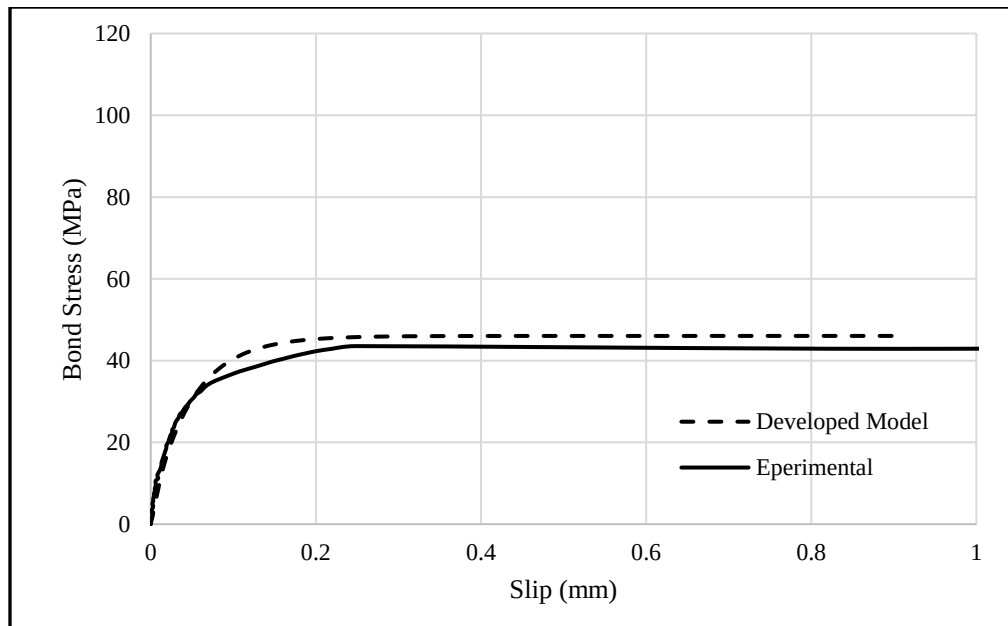


Figure 57: Bond stress – slip curves from the experimental and developed model (U30H-HSS-SC)

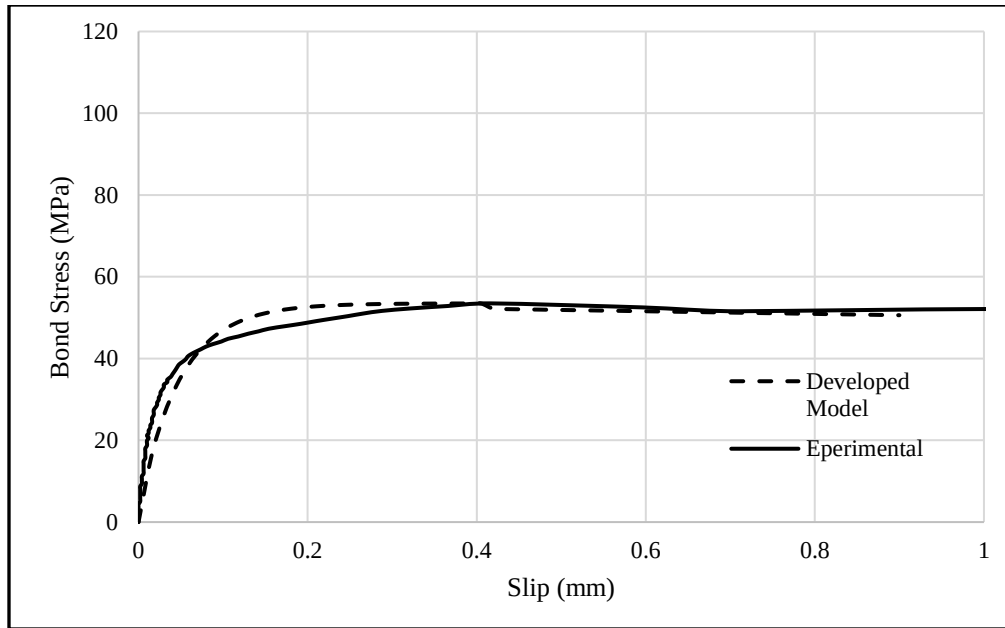


Figure 58: Bond stress – slip curves from the experimental and developed model (U50H-HSS-WC)

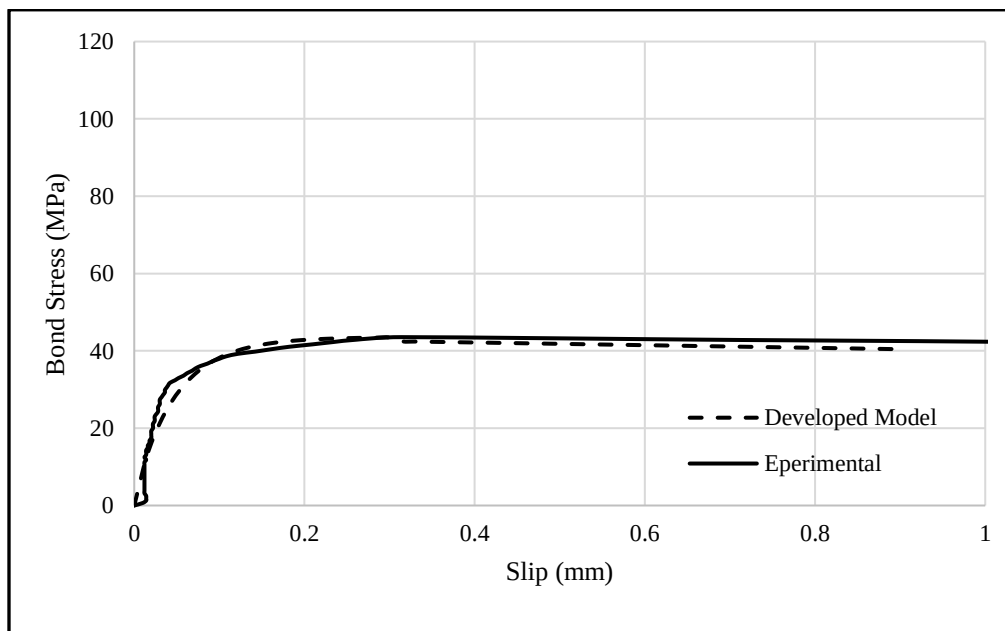


Figure 59: Bond stress – slip curves from the experimental and developed model (U70H-HSS-WC)

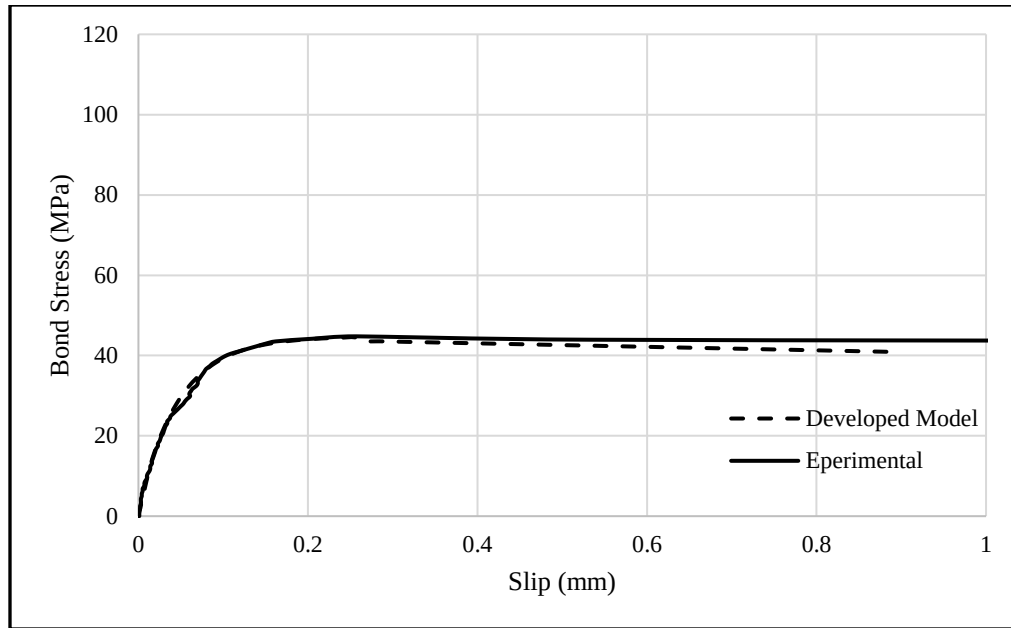


Figure 60: Bond stress – slip curves from the experimental and developed model (U100H-HSS-WC)

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Based on the study on the effects of fiber hybridization and curing types on the mechanical properties of UHPC, the following conclusions are drawn:

1. The UHPC mixtures subjected to steam curing performed better than the UHPC mixtures subjected to water curing, in compressive strength, modulus of elasticity, flexural strength, and bond strength due to the accelerated hydration of silica fume in case of the steam-curing.
2. UHPC mixtures containing 100% straight fibers and 0% hooked fibers achieved an average compressive strength of 158 MPa when cured with steam and 150 MPa when cured with water. A slight decrease in the compressive strength was noticed with introduction of the hooked fibers. The compressive strength was decreased by around 15% when the straight fibers were fully replaced by the hooked fibers.
3. The modulus of elasticity was not affected significantly by the curing regime and the fiber combination. However, there was a slight improvement in the modulus of elasticity with introduction of the hooked fibers.
4. The flexural strength of UHPC mixtures was significantly affected by the introduction of the hooked fibers for both types of curing. When the straight fibers were fully replaced by the hooked fibers (100% hooked fibers), the flexural strength and flexural toughness of the UHPC mixtures were increased by around 1.4 and 2.2

times, respectively, as compared to the UHPC mixtures containing 100% straight fibers. While the increase in the flexural strength with increase in the amount of hooked fibers was consistent, the flexural modulus increased when the percentage of the hooked fibers increased beyond 50%.

5. For high strength steel specimens, the bond strength was almost the same for all mixtures with a difference up to 5 MPa. For regular steel specimens, the bond strength was higher for the mixtures with both fiber types (U30H, U50H, and U100H).
6. The results of finite element modeling (FEM) showed good agreement with the experimental test results. Therefore, the CDPM with the surface based cohesive approach can be used to predict peak load close to the experimental test values.
7. The results of the developed empirical model showed a good agreement with the experimental test results. Therefore, the overall behavior of bond strength between UHPC and rebar can be used to predict the bond behavior between steel rebar and UHPC.

6.2. Recommendations for future work

1. The effect of high temperature on the bond strength of hybrid UHPC mixtures.
2. The effect of other factors (fiber orientation, cover, bar size, etc.) on the bond strength of hybrid UHPC mixtures.
3. Effect of different fiber combinations with different types of fibers (corrugated fibers or polyvinyl alcohol) on the bond strength.

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APPENDICES

Appendix A: Compressive strength and modulus of elasticity results

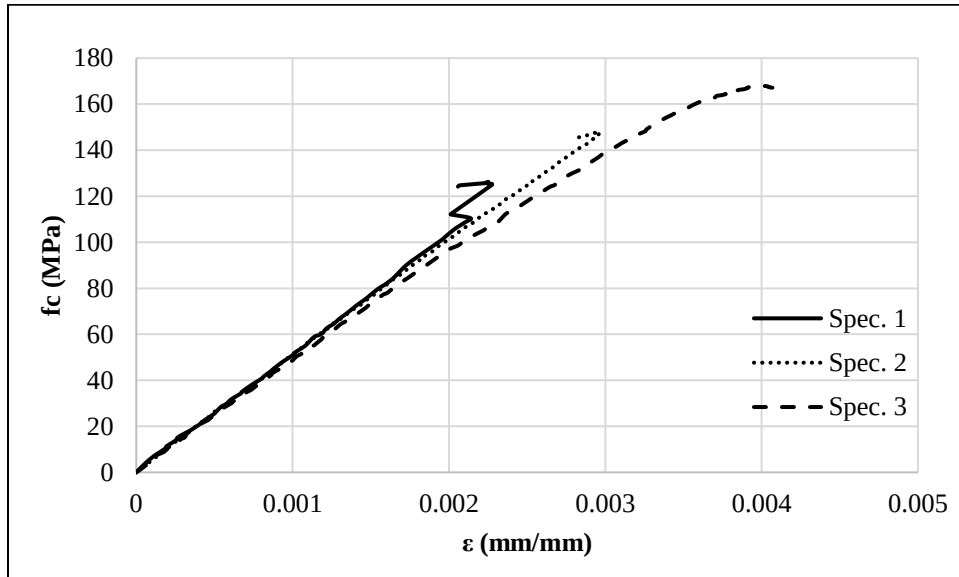


Figure A1: Stress/strain of mixture U0H steam cured

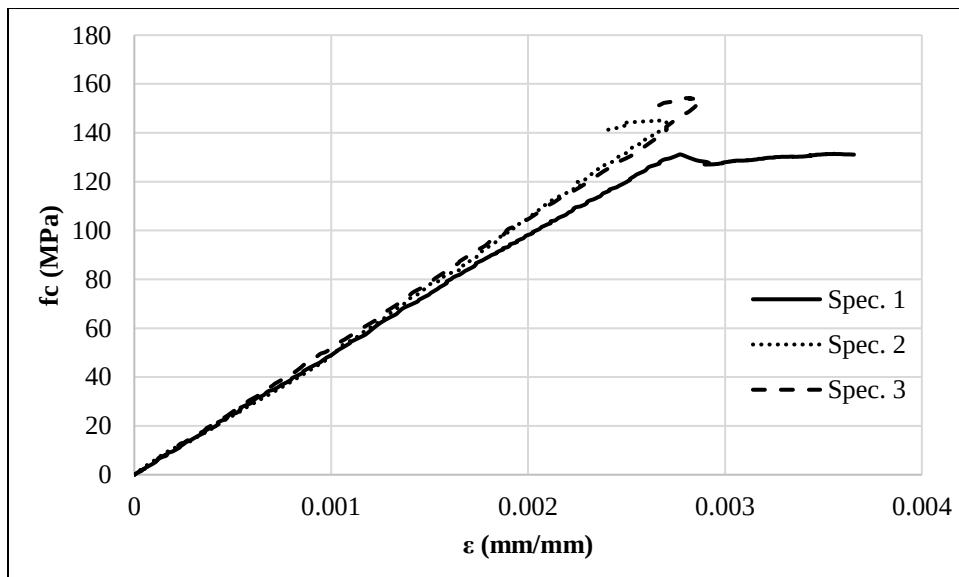


Figure A2: Stress/strain of mixture U0H water cured

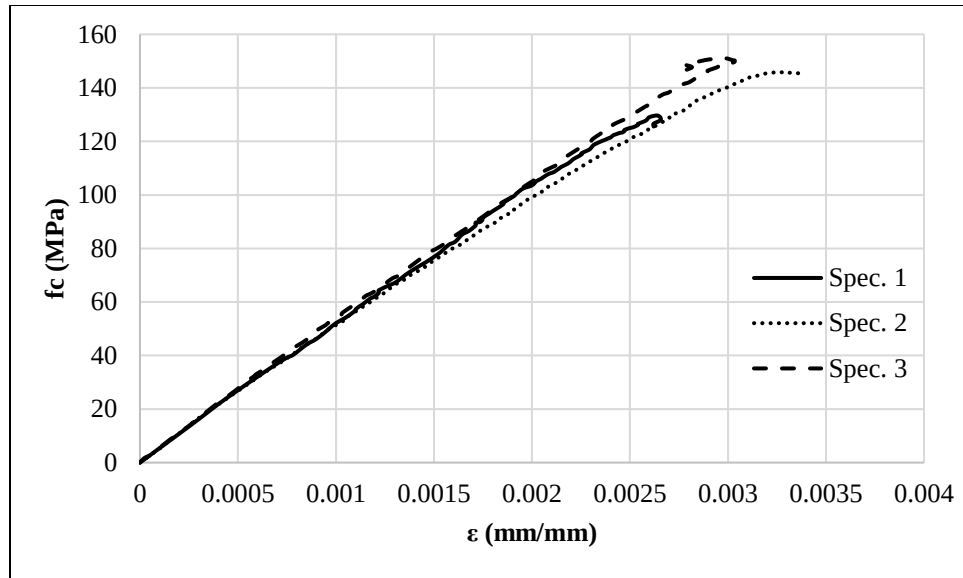


Figure A3: Stress/strain of mixture U30H steam cured

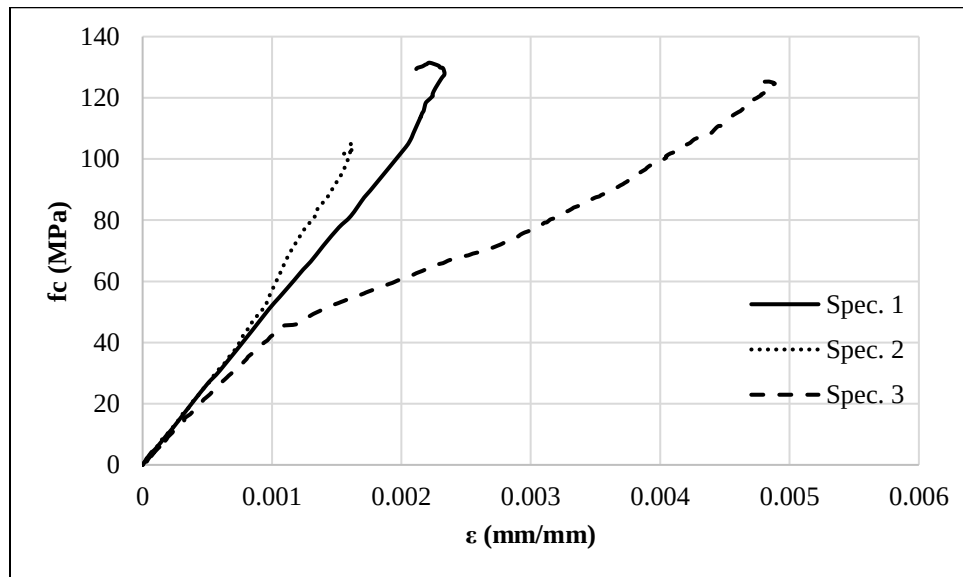


Figure A4: Stress/strain of mixture U30H water cured

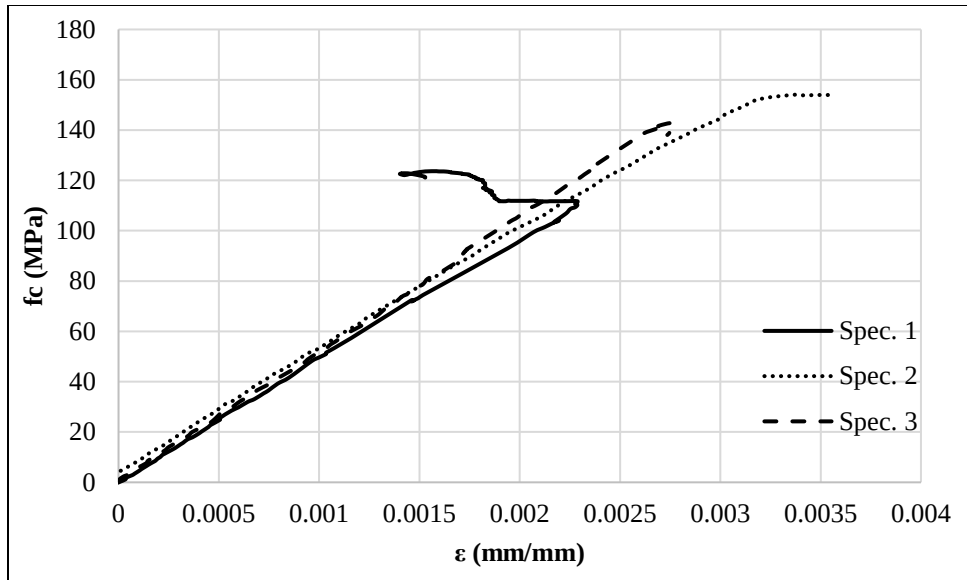


Figure A5: Stress/strain of mixture U50H steam cured

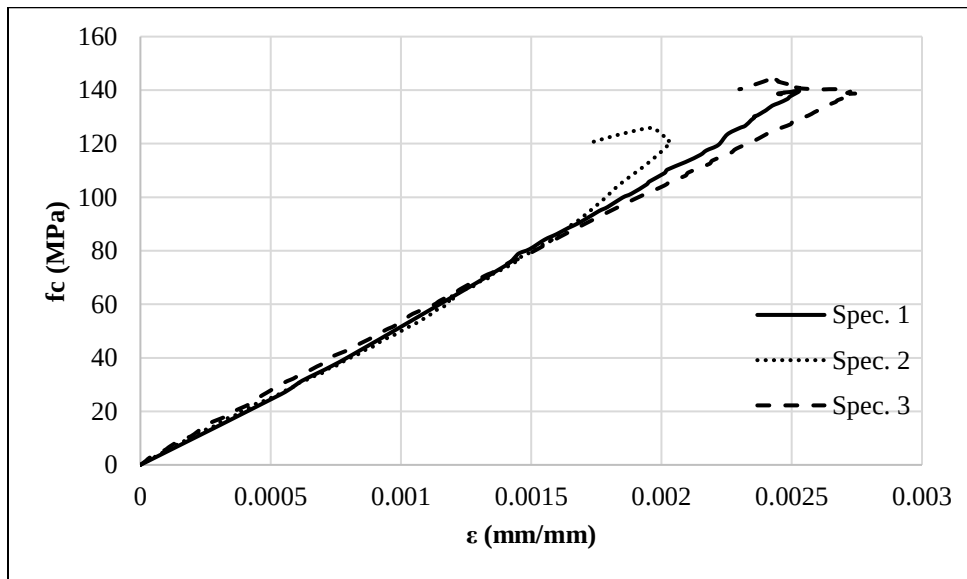


Figure A6: Stress/strain of mixture U50H water cured

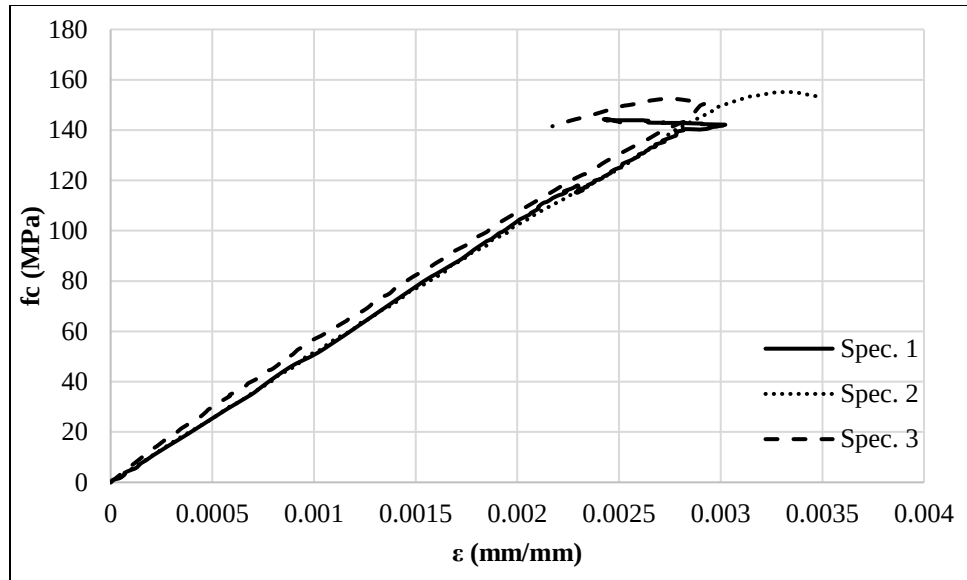


Figure A7: Stress/strain of mixture U70H steam cured

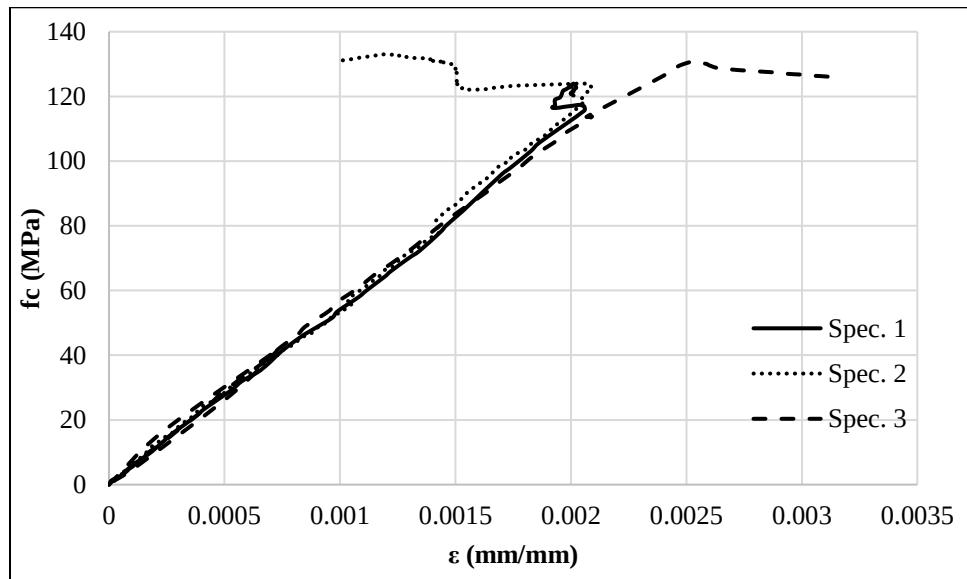


Figure A8: Stress/strain of mixture U70H water cured

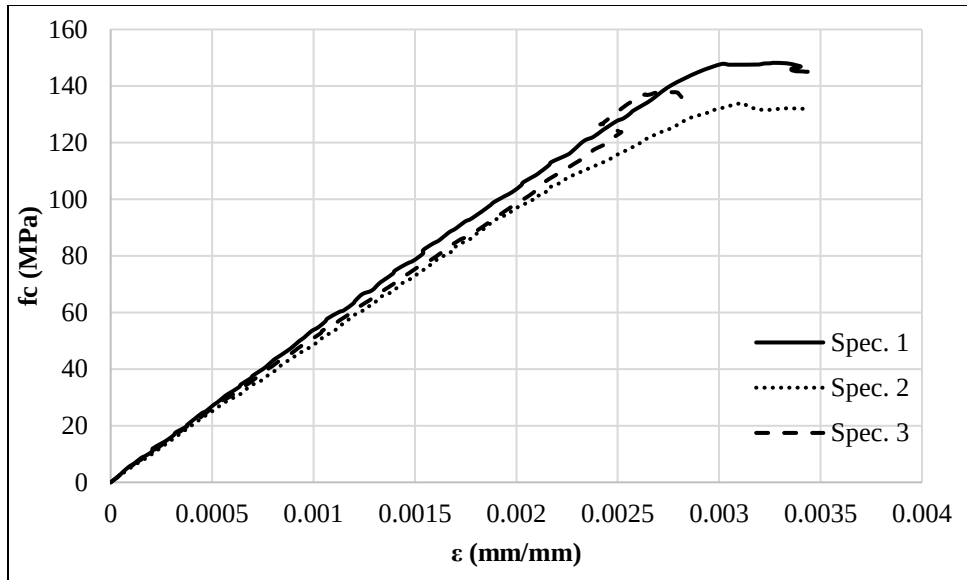


Figure A9: Stress/strain of mixture U100H steam cured

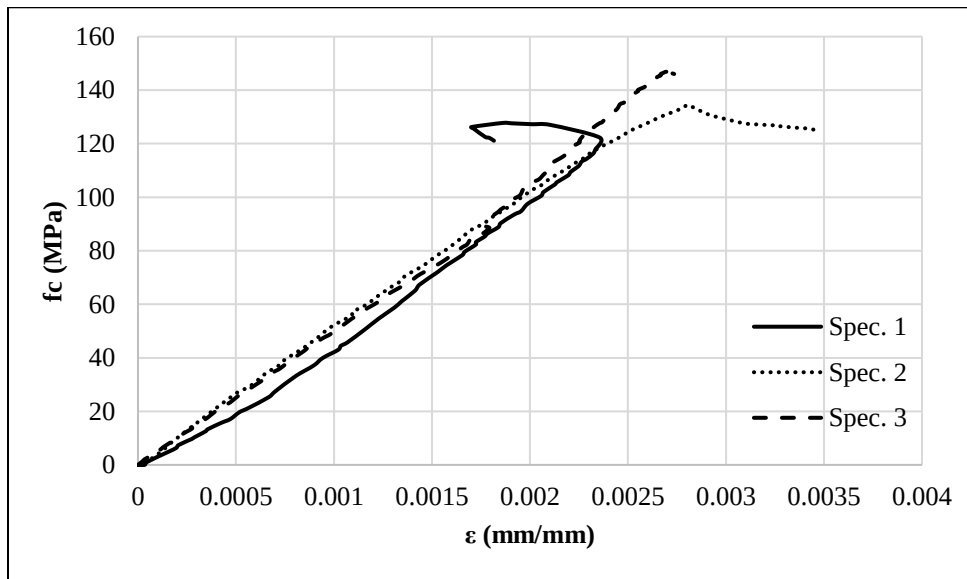


Figure A10: Stress/strain of mixture U100H water cured

Appendix B: Flexural strength results

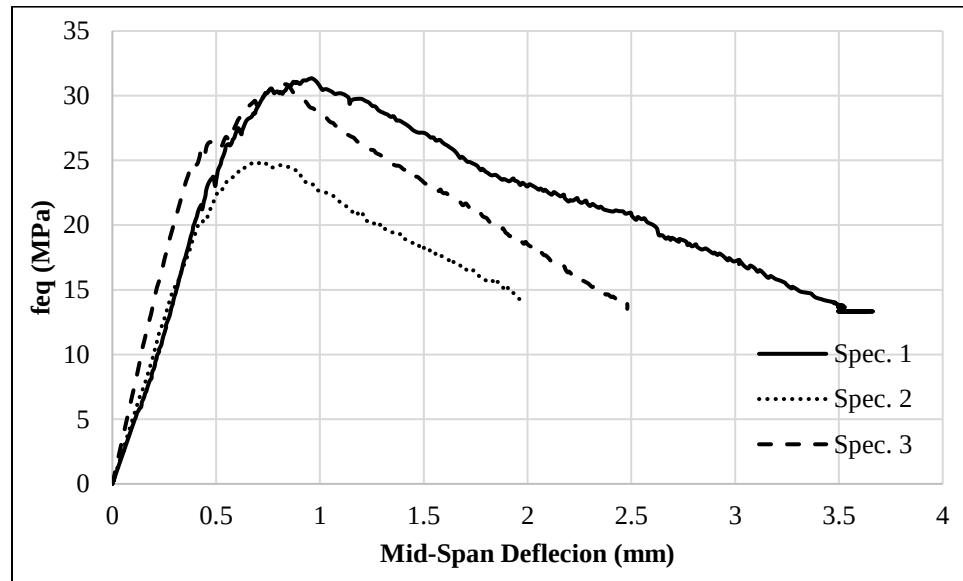


Figure B1: Stress/deflection of mixture U0H steam cured

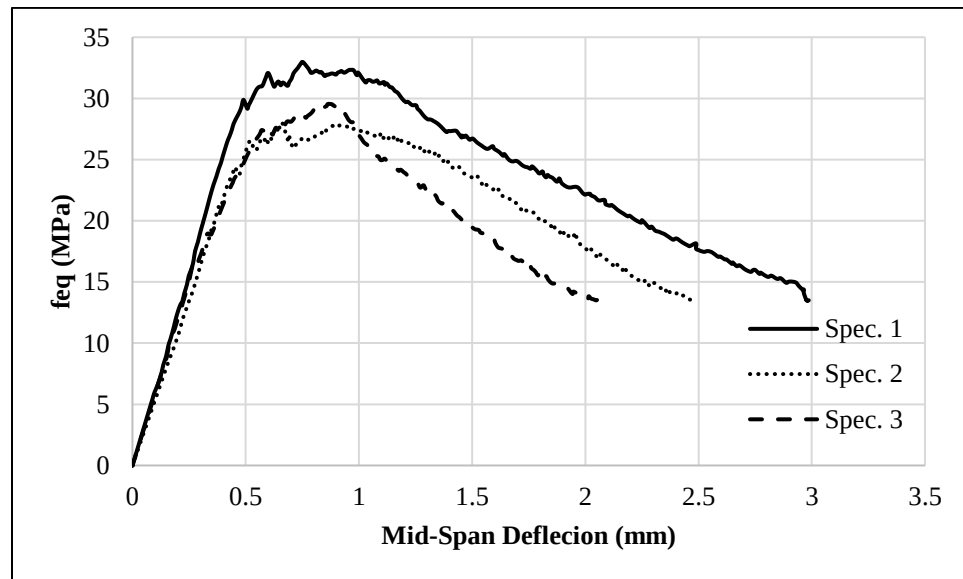


Figure B2: Stress/deflection of mixture U0H water cured

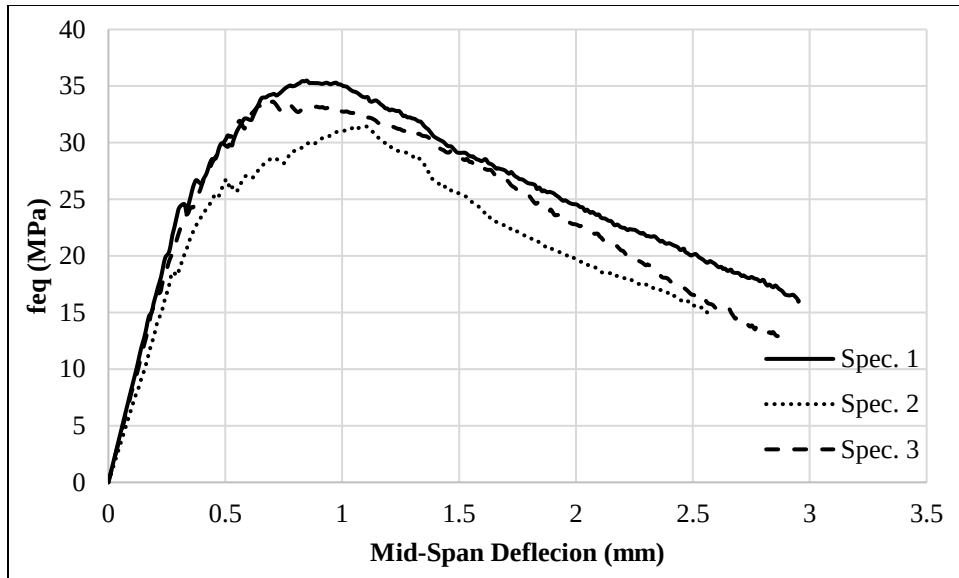


Figure B3: Stress/deflection of mixture U30H steam cured

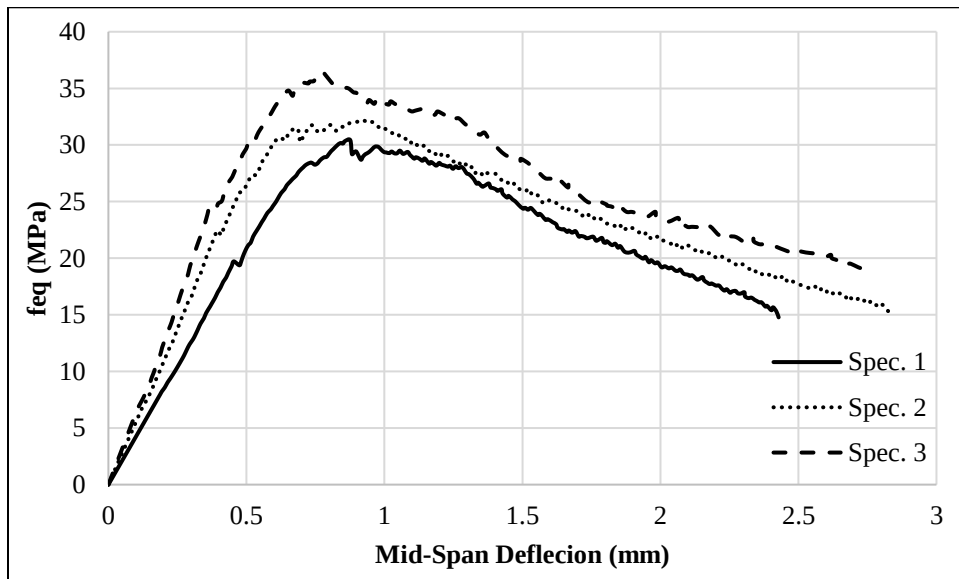


Figure B4: Stress/deflection of mixture U30H water cured

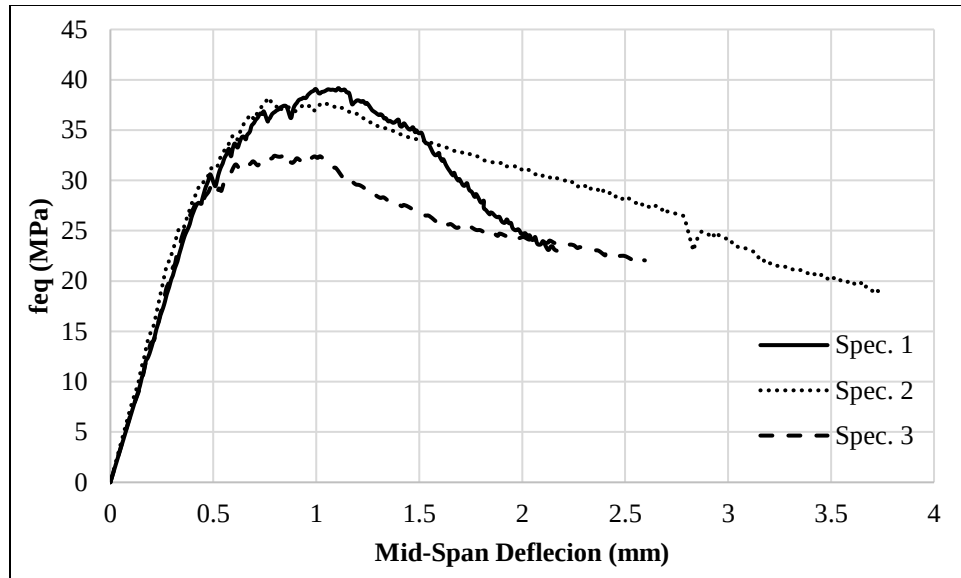


Figure B5: Stress/deflection of mixture U50H steam cured

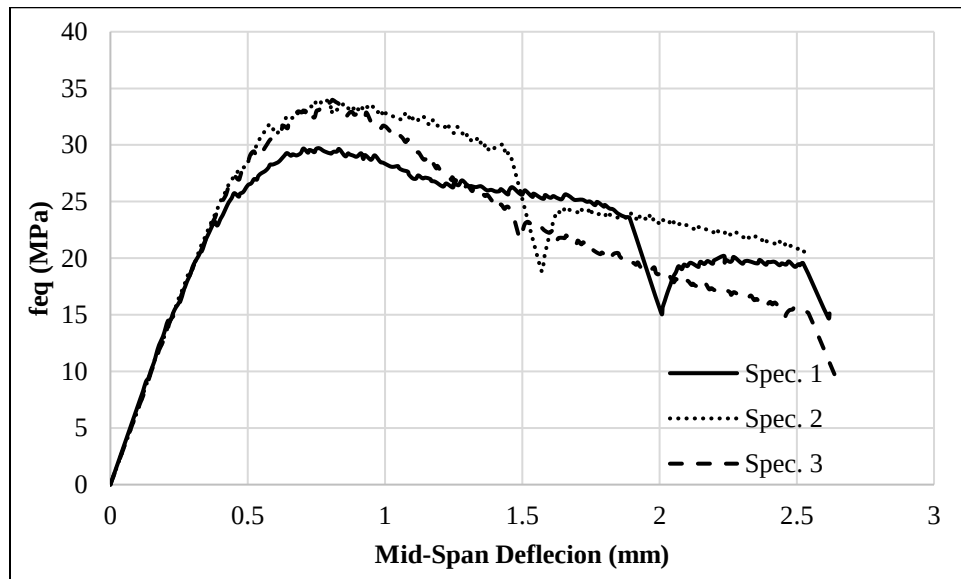


Figure B6: Stress/deflection of mixture U50H water cured



Figure B7: Stress/deflection of mixture U70H steam cured

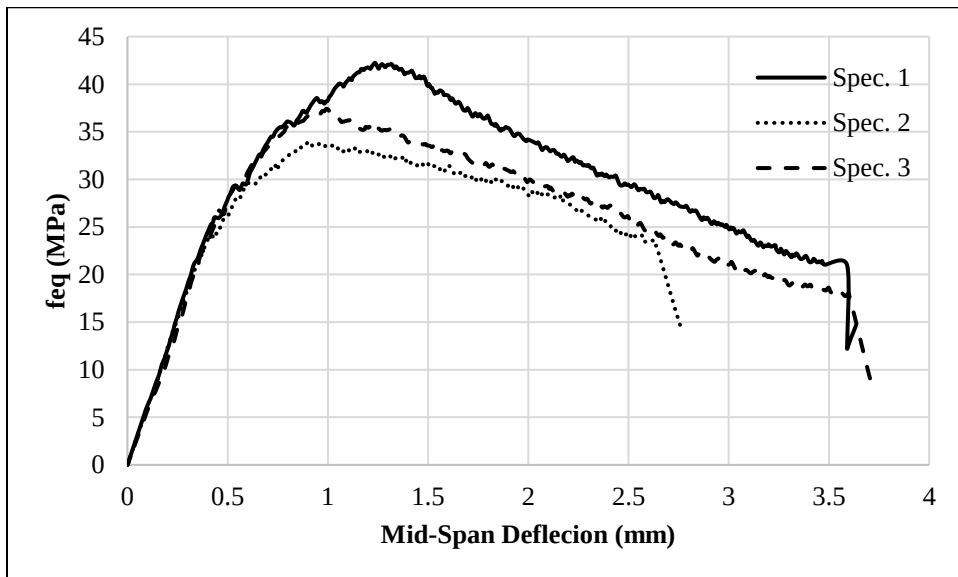


Figure B8: Stress/deflection of mixture U70H water cured

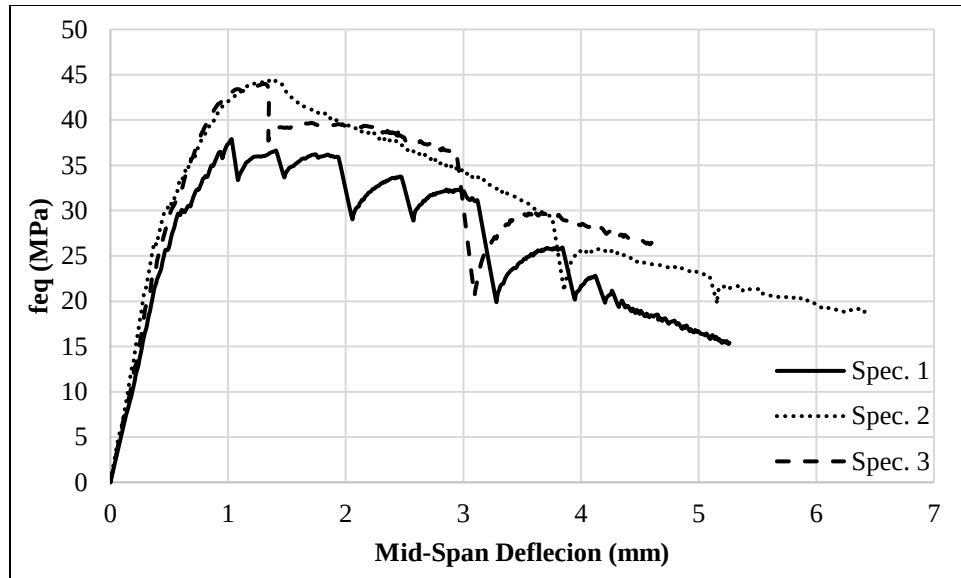


Figure B9: Stress/deflection of mixture U100H steam cured



Figure B10: Stress/deflection of mixture U100H water cured

Appendix C: Bond strength results

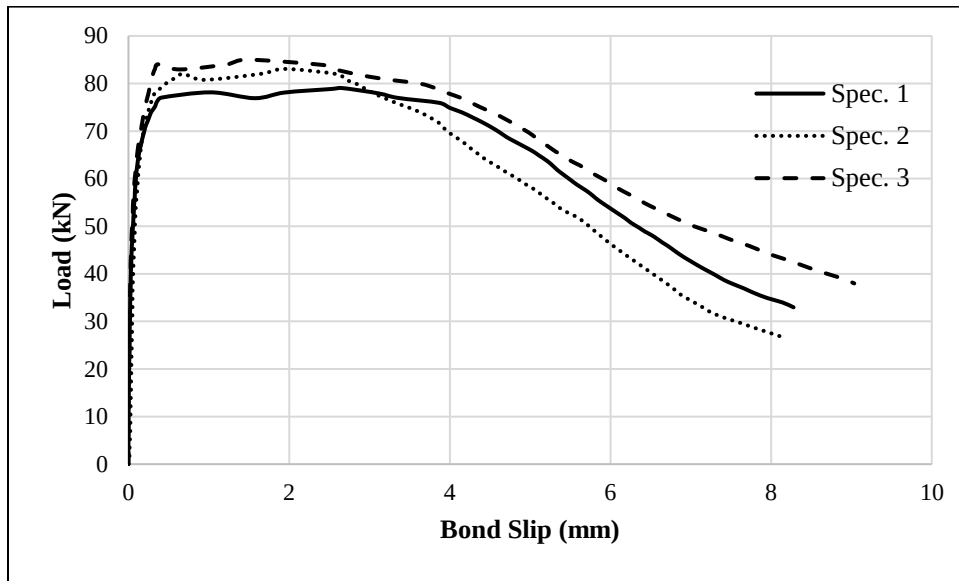


Figure C1: Bond/slip of mixture U0H-HSS steam cured

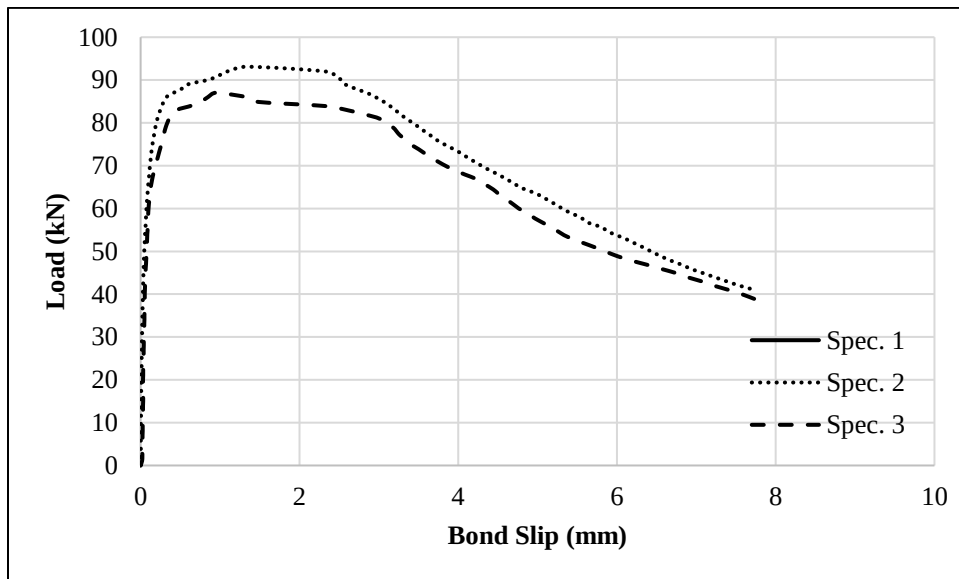


Figure C2: Bond/slip of mixture U0H-HSS water cured

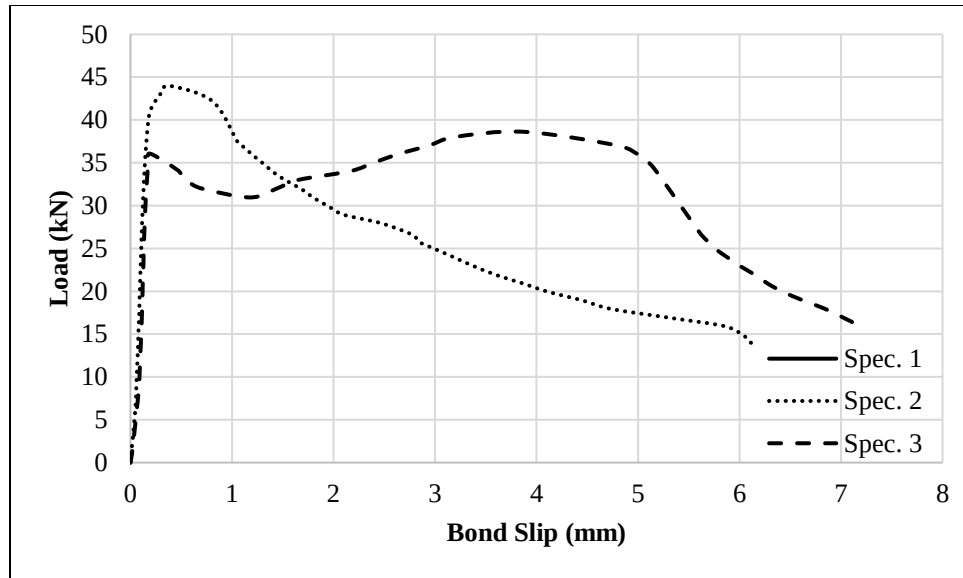


Figure C3: Bond/slip of mixture U0H-RS steam cured

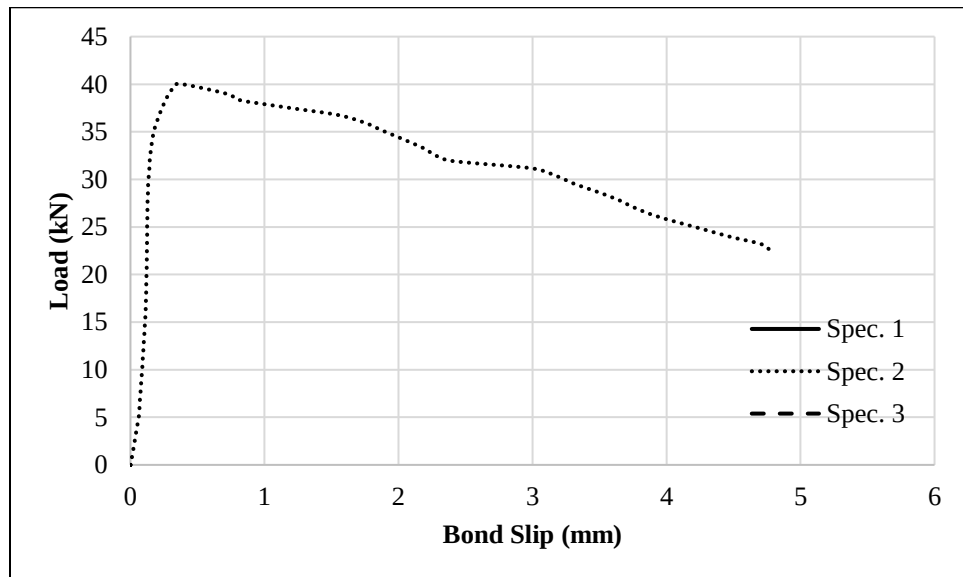


Figure C4: Bond/slip of mixture U0H-RS water cured

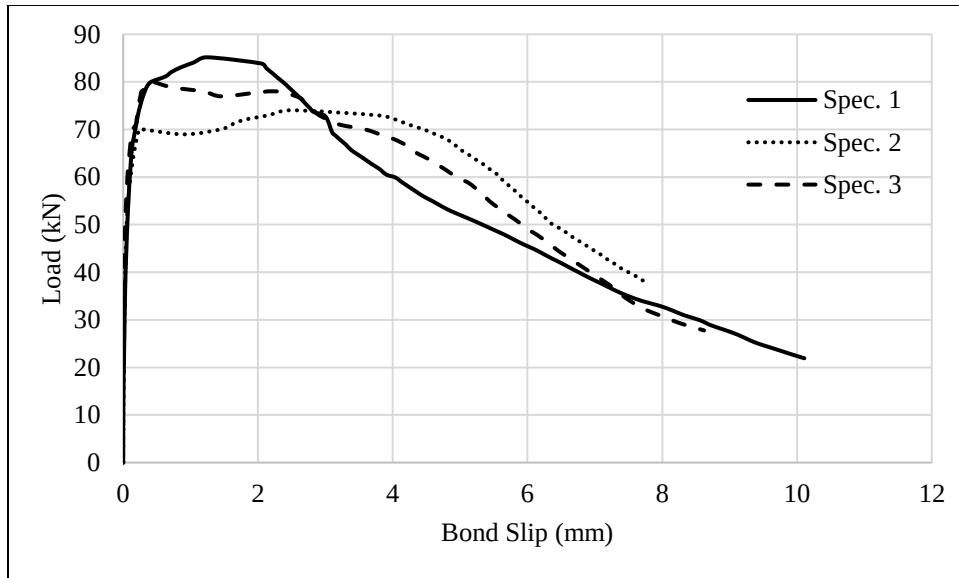


Figure C5: Bond/slip of mixture U30H-HSS steam cured

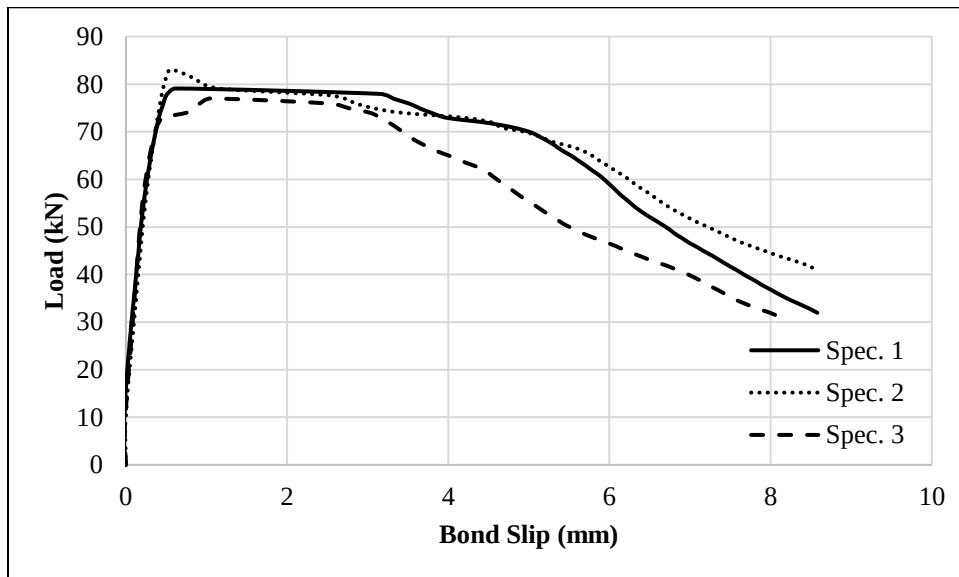


Figure C6: Bond/slip of mixture U30H-HSS water cured

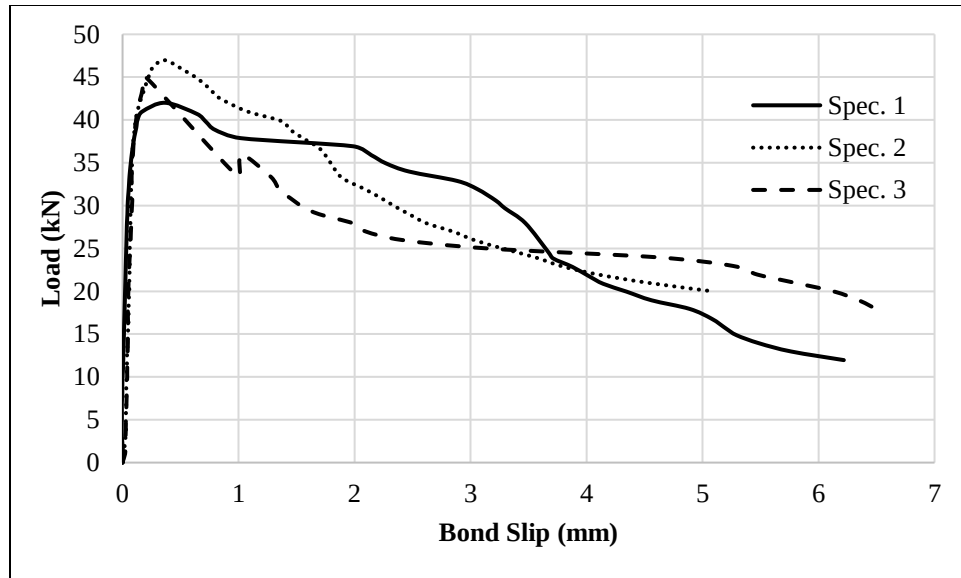


Figure C7: Bond/slip of mixture U30H-RS steam cured

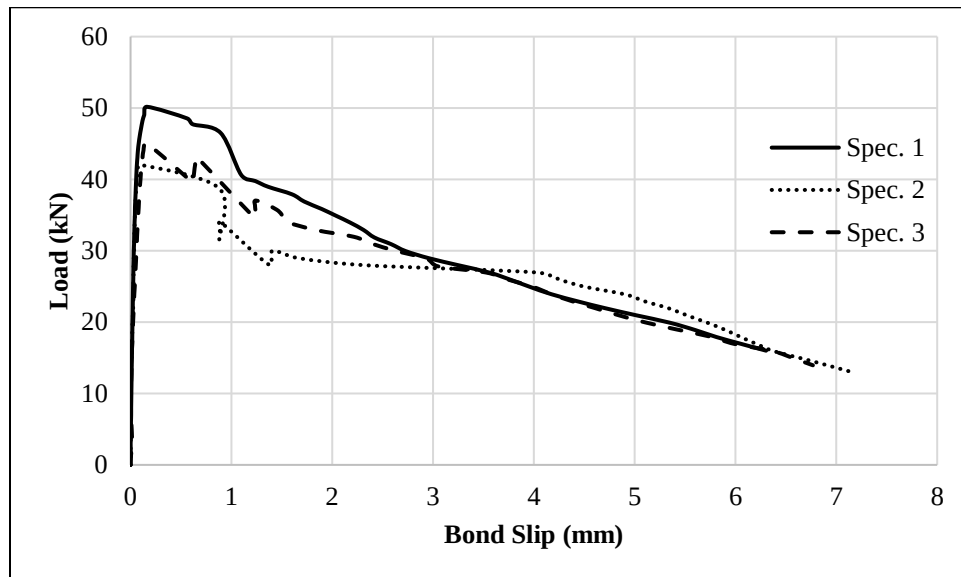


Figure C8: Bond/slip of mixture U30H-RS water cured

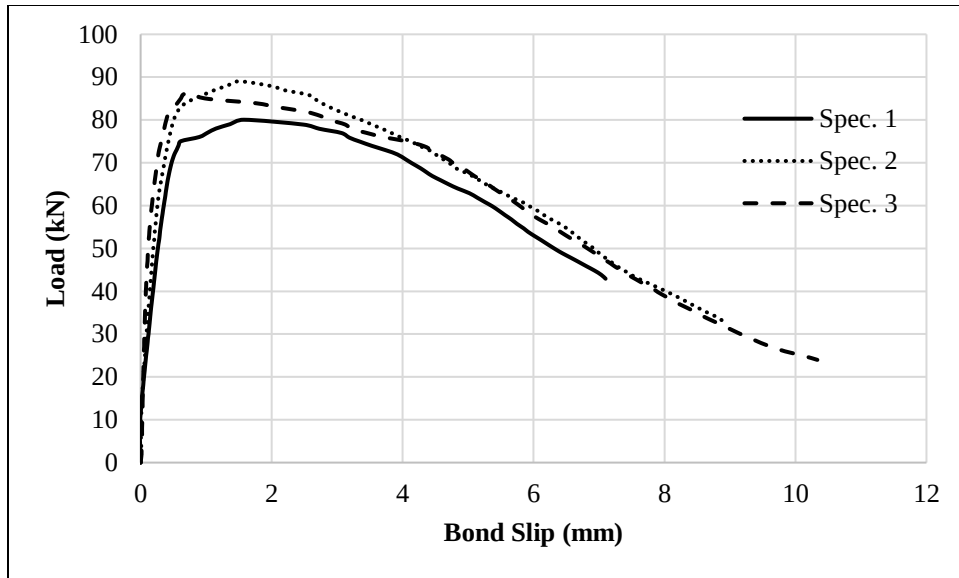


Figure C9: Bond/slip of mixture U50H-HSS steam cured

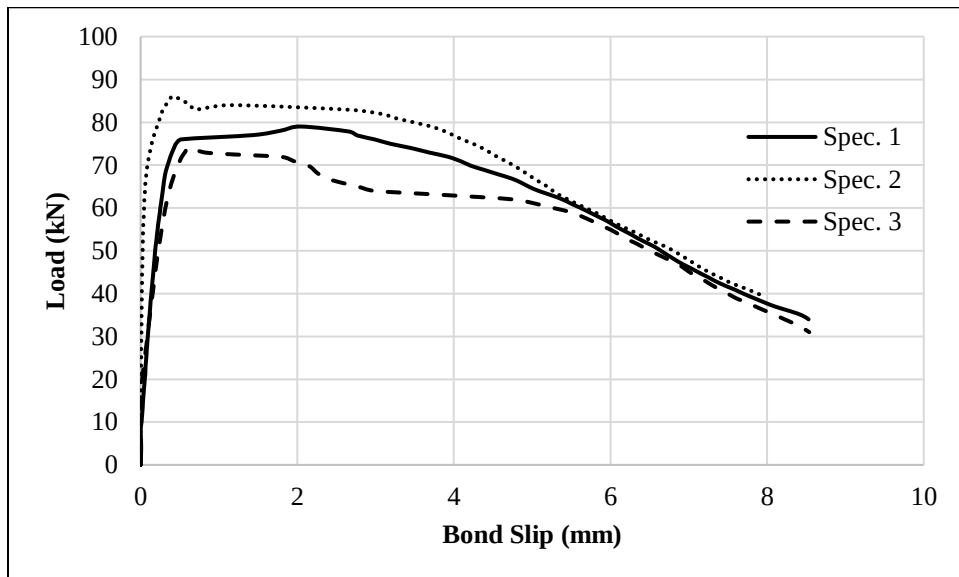


Figure C10: Bond/slip of mixture U50H-HSS water cured

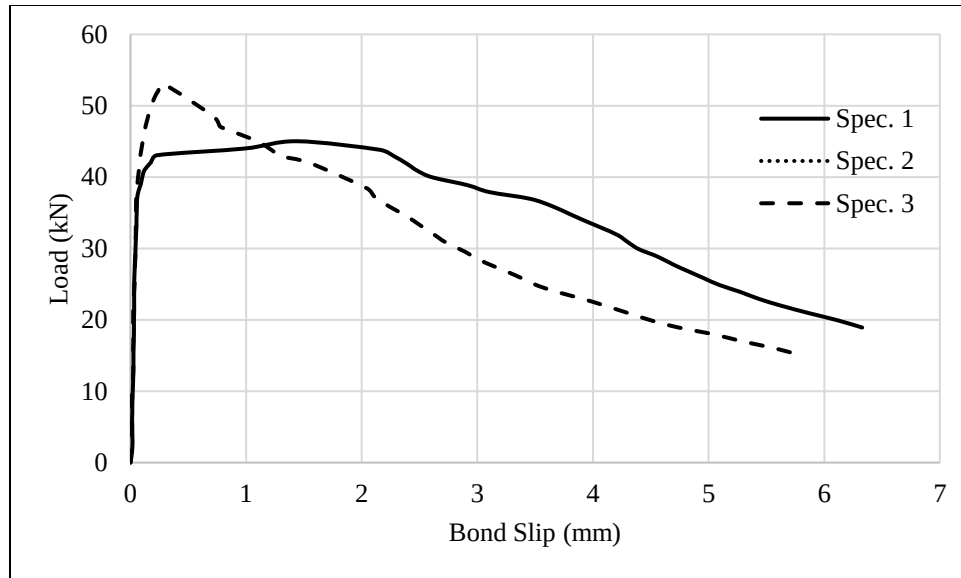


Figure C11: Bond/slip of mixture U50H-RS steam cured

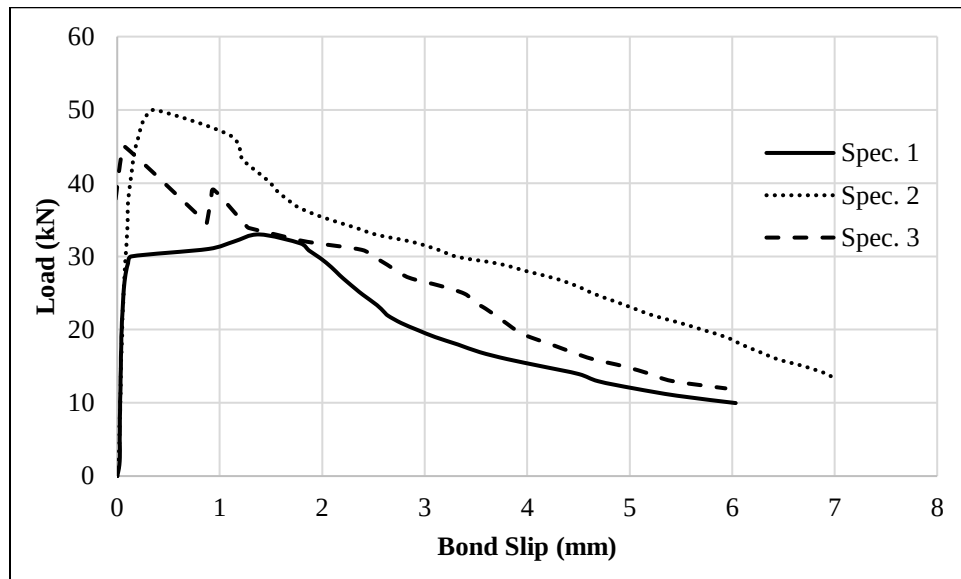


Figure C12: Bond/slip of mixture U50H-RS water cured

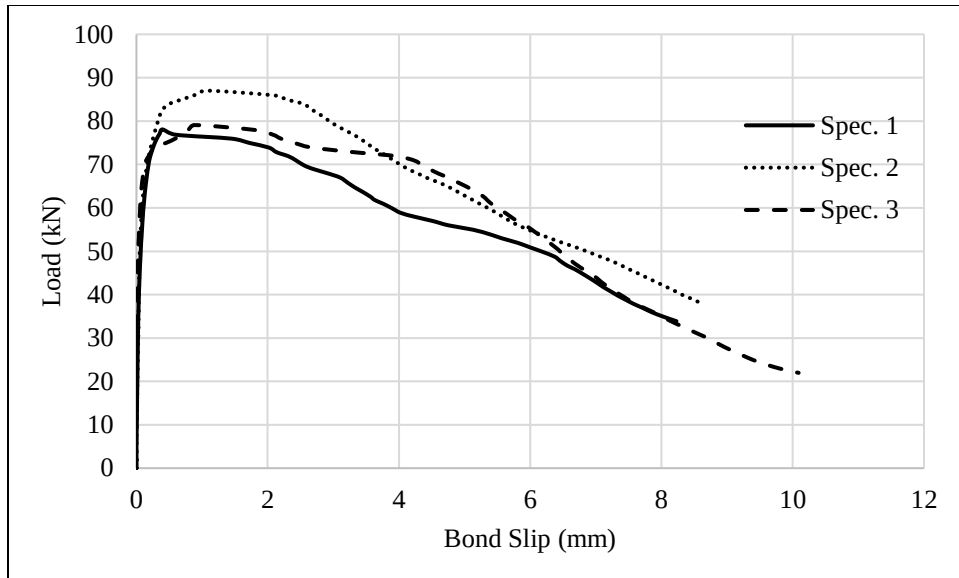


Figure C13: Bond/slip of mixture U70H-HSS steam cured

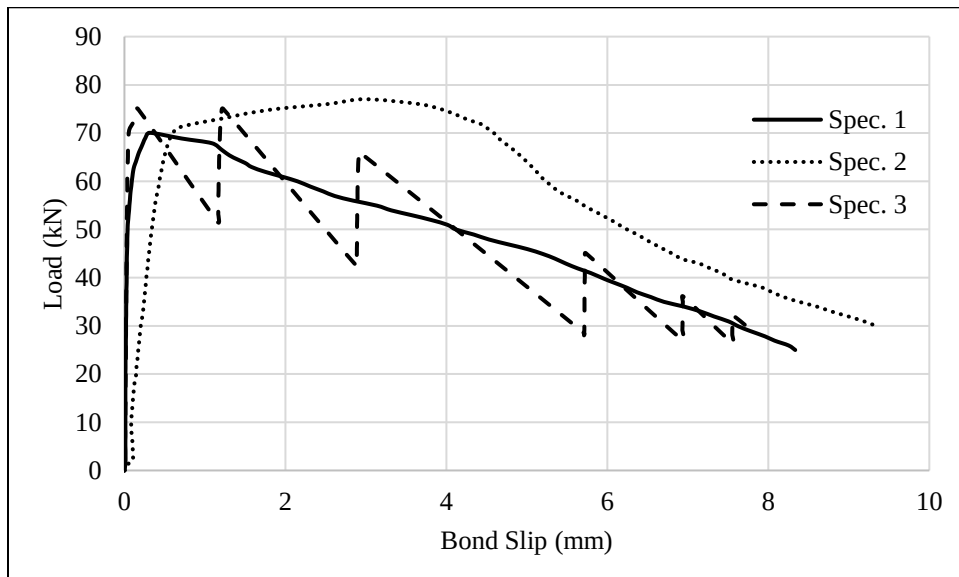


Figure C14: Bond/slip of mixture U70H-HSS water cured

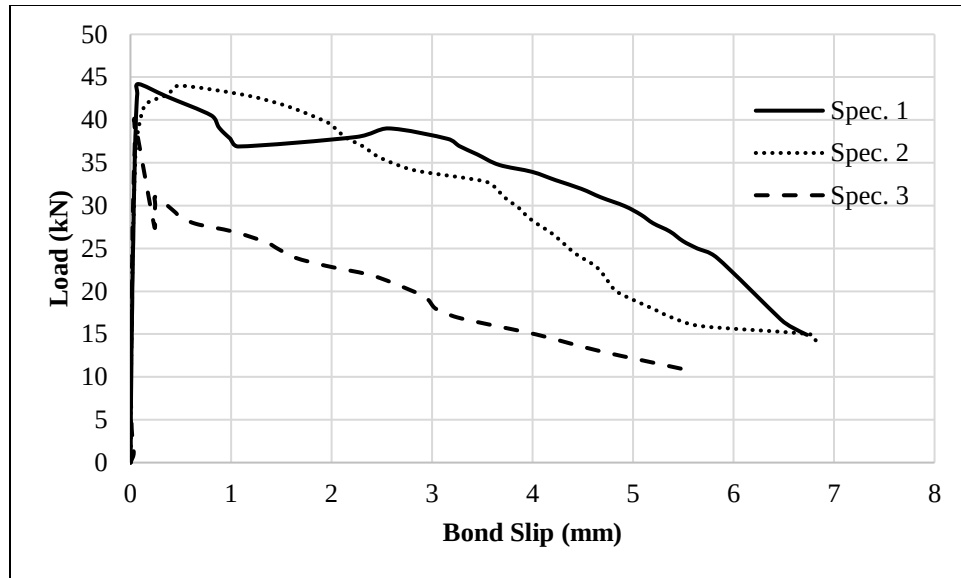


Figure C15: Bond/slip of mixture U70H-RS steam cured

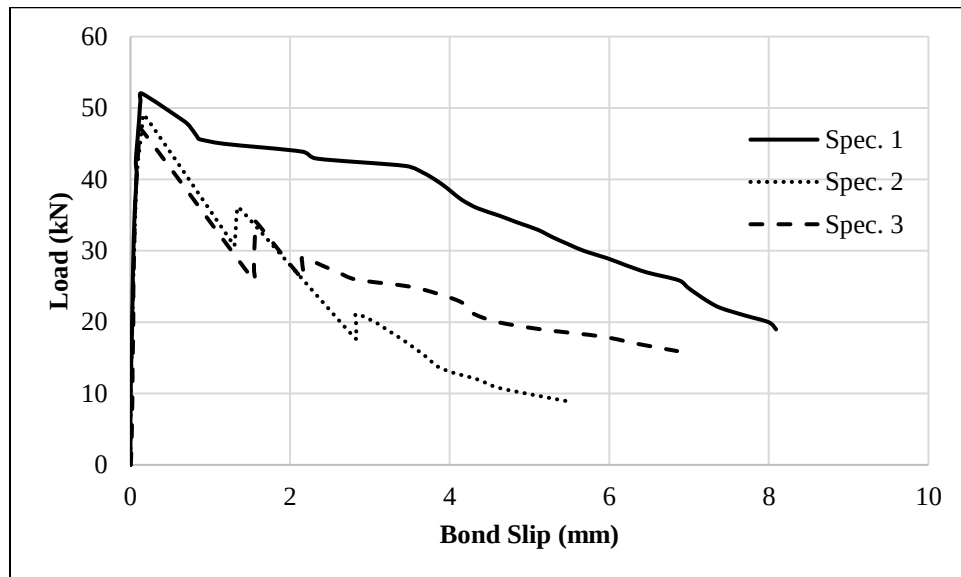


Figure C16: Bond/slip of mixture U70H-RS water cured

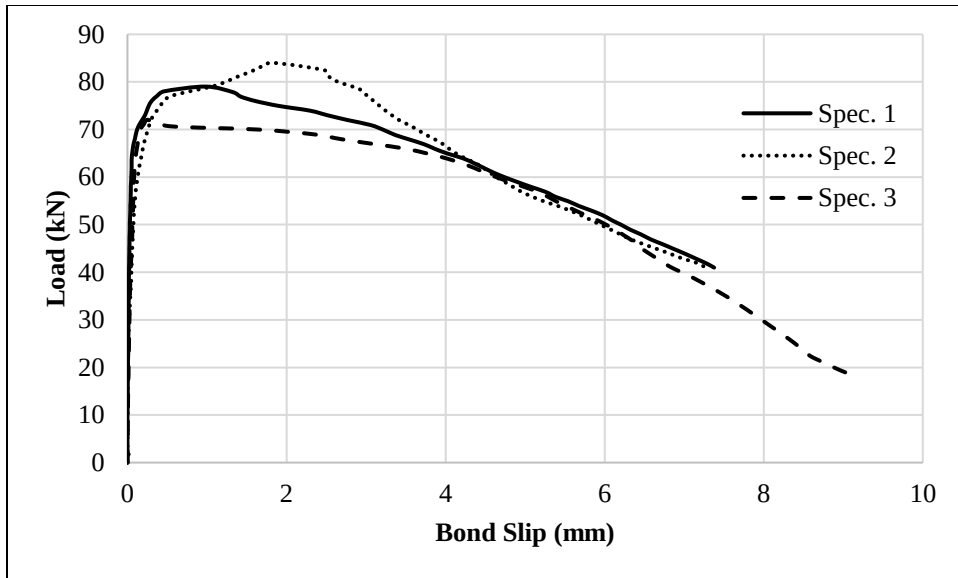


Figure C17: Bond/slip of mixture U100H-HSS steam cured

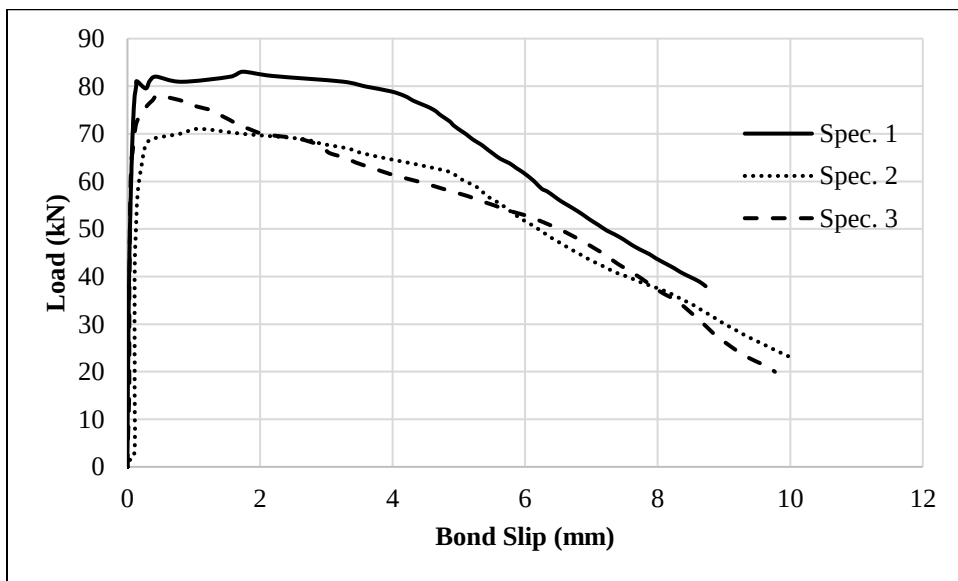


Figure C18: Bond/slip of mixture U100H-HSS water cured

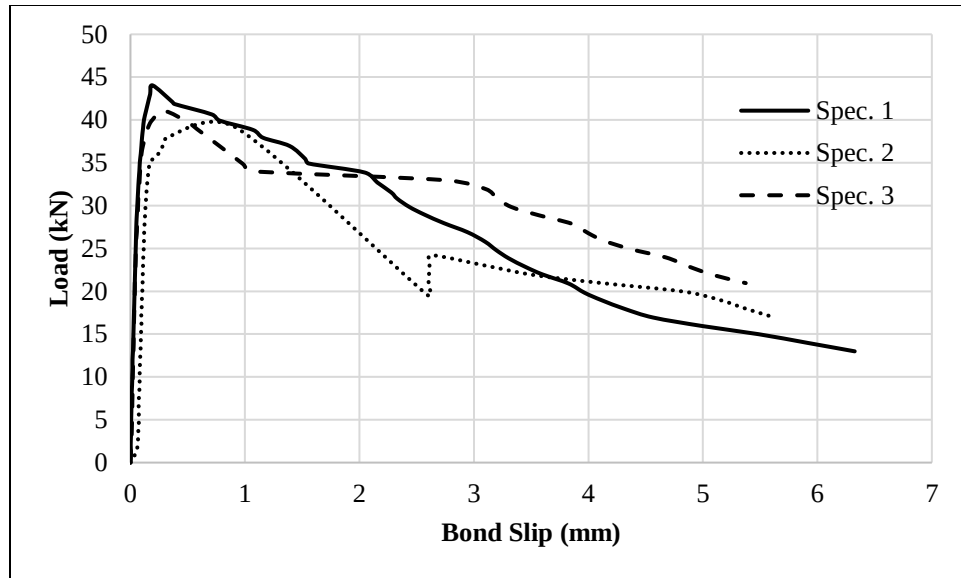


Figure C19: Bond/slip of mixture U100H-RS steam cured

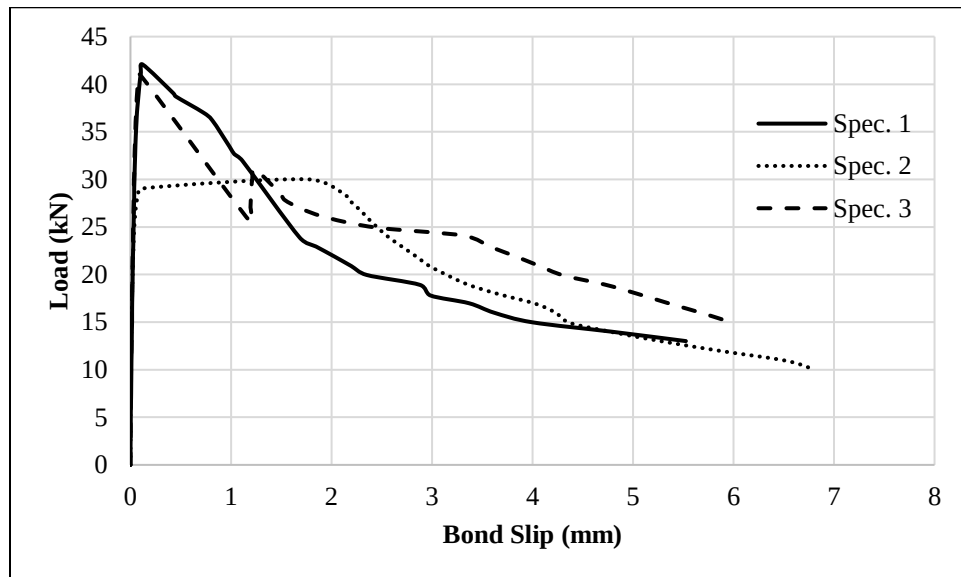


Figure C20: Bond/slip of mixture U100H-RS water cured

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