BOND PERFORMANCE OF LOCALLY MADE UHPC WITH NSC AT ELEVATED TEMPERATURES

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This thesis is dedicated to my family

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ABSTRACT

Numerous techniques have been used for the rehabilitation of existing RC structures. Concrete or steel jacketing, fiber-reinforced polymer wrapping are commonly available techniques. To improve the response of bridge piers, fundamental approach employed in experimental investigations, is the confinement of concrete. Various techniques improve the strength and durability but few drawbacks, such as increase in weight of structures in concrete jacketing, fire resistance and debonding are a few drawbacks. Cementitious composites having compressive strength greater than 17 ksi, lie in the category of Ultra High-Performance Concrete. UHPC is a composite cementitious material with superior mechanical properties as compared to normal strength concrete. High packing density, low water cement ratio, high binder ratio, addition of high range water reducing admixtures and steel fibers results in increase in compressive strength by 3-5 times as that of ordinary Normal Strength Concrete. This study was carried out to investigate the response of Ultra High-Performance Concrete using Normal Strength Concrete as a substrate under varied loading conditions to simulate the actual forces on bridge piers, namely slant shear, bi surface shear and split tensile. Variation in substrate surface treatment (As cast, drill holes and grooves), inclusion of micro steel fibers and their effect on elevated temperatures was also studied. The experiments showed that the strength of bond decreases with the elevation in temperature. Drill hole technique exhibited the highest bond strength in bi surface shear. Whereas inclusion of steel fibers in UHPC resulted in increase in strength of bond due the bridging effect created between overlay and substrate.

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LIST OF ABBREVIATIONS

NSC	Normal Strength Concrete
UHPC	Ultra High-Performance Concrete
SCMs	Secondary Cementitious Materials
HRWRs	High Range Water Reducers
HSC	High Strength Concrete
FA	Fly Ash
SF	Silica Fume
SRMs	Secondary Raw Materials
FA	Fly Ash
TC	Thermocouples
FC	Ferro Cement
GR	Grooves
DH	Drill Holes
AC	As Cast

CHAPTER 1

1. INTRODUCTION

1.1 Background

The concrete industry now faces a new challenge: the growing need to repair several buildings and infrastructure projects first put up in the second half of the 20th century. So far, engineers' primary focus has been on developing new structures. However, as a result of the development boom of the last few decades in industrialized nations, maintenance of existing buildings is becoming increasingly important. The latter is a major problem for the planet, but if we take effective measures to repair, we may extend the useful life of existing concrete structures with minimal additional resource use, so improving the industry's long-term sustainability.

Bridge piers are expensive structures, replacement of which bears high cost. Pakistan, being in high seismic zone, near active fault line is always at a risk of large-scale earthquakes, which in the past, caused devastating effects, taking lives of 0.1 million in 2005 earthquake. In Kashmir, 82 low strength concrete bridge lie within 50 Km radius of the epicenter (Ali et al., 2011)

Various retrofitting techniques have been developed over the years, where researchers have developed techniques to enhance the seismic response of existing structures. To improve the response of bridge piers, fundamental approach employed in experimental investigations, is the confinement of concrete. Which can be classified in two categories, namely active confinement & passive confinement. In the former, the pressure is always applied on concrete whereas in later type of confinement, it is made to resist the expansion of concrete upon application of load(Al-osta et al., 2022).

A range of methods have been employed to restore existing RC constructions. Fiber-reinforced polymer wrapping, concrete and steel jacketing are prevalent approaches. Although these techniques enhance strength and durability, there are few shortcomings, such as increased building weight in RCC jacketing, heat resistance, corrosion, and delamination in steel plate technology, and degradation of bonding system at FRP interface.(Zhu et al., 2020).

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UHPC offers improvement of capacity and durability of the strengthened structures with added advantage of minimal change in section size and disruption in traffic and lower cost in the whole service life owing to lower maintenance cost.

Cementitious composites having compressive strength greater than 17 ksi, lie in the category of Ultra High-Performance Concrete(ASTM C1856, 2017). UHPC is a composite cementitious material with superior mechanical properties as compared to normal strength concrete. High packing density, low water cement ratio, high binder ratio, addition of high range water reducing admixtures and steel fibers results in increase in compressive strength by 3-5 times as that of ordinary concrete(Astarlioglu & Krauthammer, 2014). (Wille et al., 2012) has reported increase in energy dissipation, durability, resistance against freeze and thaw and decrease in brittleness when UHPC with fibers incorporated was used.

However, to use UHPC as repair material the bond strength between the substrate and the overlay needs to be strong enough to transfer all the stresses to the core. Therefore, this thesis focuses on the bond performance between UHPC and Normal Strength Concrete under various different loading conditions and subjecting them to elevated temperatures.

1.2 Problem statement

RC structure especially bridge piers seek periodic maintenance/ rehabilitation due to damages or end of service life. Ultra High-Performance Concrete Jacketing: a novel technique to enhance the response by provision of external confinement has proved to be among efficient retrofitting techniques. However, efficacy of the composite system relies on the interfacial bond strength between the overlay and substrate to transfer the stresses efficiently. Therefore, there is a dire need to check the bond performance at normal and elevated temperatures.

1.3 Objectives

Main focus of this study is to evaluate the potential of UHPC as repair material. Following two objectives are focused in this study

- To evaluate the bond strength between locally made Ultra High Performance Concrete and Normal Strength Concrete substrate under three varying loading condition namely tension, pure shear and combination of compression and shear
- To evaluate the effect of heat on the bond performance between locally made UHPC and NSC with former having lower percentage of Micro Silica as SCM

1.4 Research significance

It is necessary to investigate the bond performance of UHPC made with locally available materials as the bond strength varies with variation in matrix of substrate as well. In addition, to gain confidence on using this locally made material, small scale testing is necessary to ensure transfer of stresses to the core in case of bridge piers with different kinds of surface preparation of the substrate. Moreover, lower ratio of silica fume is used in UHPC which needs to be tested if it helps in resisting heat.

1.5 Scope of the study

The scope of the study is to evaluate and enhance bond performance of UHPC made using locally available materials, which will bear loading of pure shear, tension and combination of shear and compression when applied to bridge pier as an external jacket. Variation in the surface preparation were investigated in this study to report the most effective technique to enhance the bond strength under loading conditions mentioned. Furthermore, the specimen was heated and their post fire properties were studied under residual unstressed. Using a standard heating rate of 5°C/min, the specimen was heated to target temperatures of 200, 400, 600, and 800°C.

1.6 Research methodology

Following research methodology was opted for this study

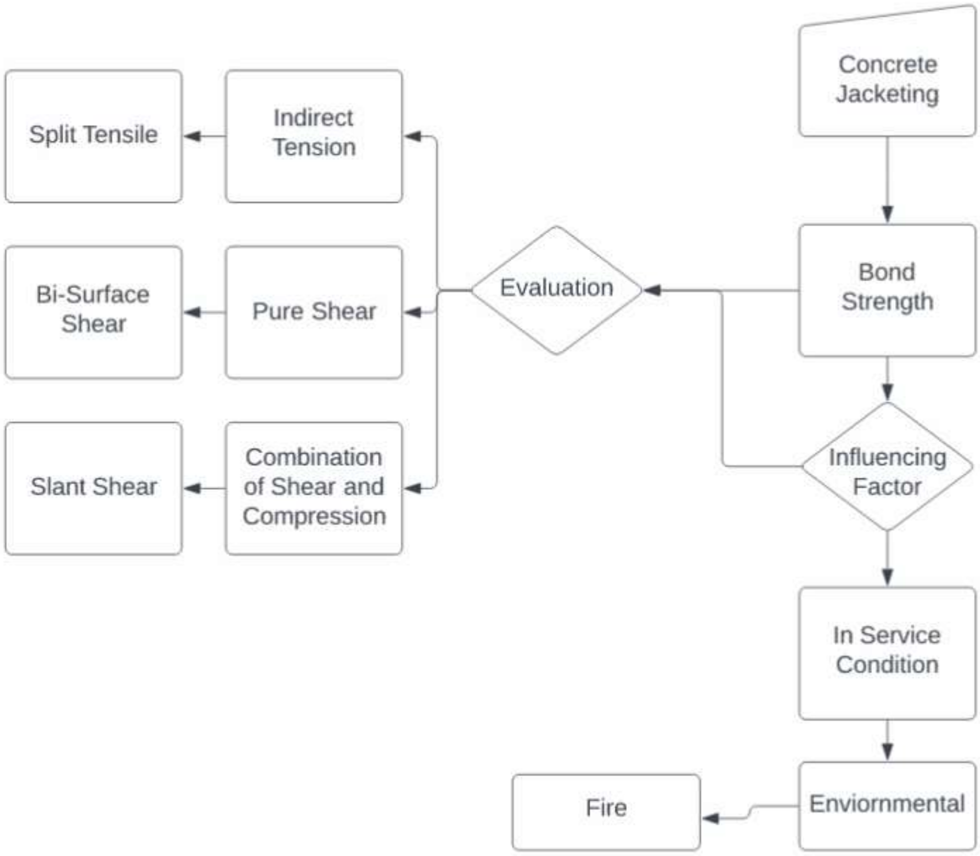


Figure 1.1 Flow chart of research methodology

1.7 Thesis layout

The research undertaken to address the objectives is presented in five

chapters.

Chapter 1 “Introduction” explains the importance of retrofitting, Ultra High Performance Concrete UHPC, research objectives, research significance, , research methodology, and thesis outline.

Chapter 2 “Literature Review” a brief revision on the previously related research regarding UHPC and NSC bond strength has been presented.

The experimental program's test techniques and methodology are covered in Chapter 3. This chapter presents the research study's target temperatures, heating rate, specimen size and instrumentation.

Chapter 4 “Results and Discussion” includes evaluation, analysis and discussion for results of bond strength tests. Tests in residual unstressed conditions are also presented.

Chapter 5 “Conclusions and Recommendations” provides the detailed conclusions based on the outcomes of this research and remarks for further studies.

CHAPTER 2

2. LITERATURE REVEIW

2.1 General

RCC structures reaching their design life or deteriorated due to natural calamities, fire or blast seek rehabilitation. With the rise of demand for strengthening of structures built in the latter half of the 20th century presents a new challenge for civil engineers working in the concrete industry. Majority of the of the engineers' efforts to date have been focused on creating new infrastructure. However, the need for structural rehabilitation is growing due to numerous structures reaching their design life.

Various retrofitting techniques have been developed over the years, where researchers have developed techniques to enhance the response of existing structures. To improve the response of bridge piers, fundamental approach employed in experimental investigations, is the confinement of concrete. Which can be classified in two categories, namely active confinement & passive confinement. In the former, the pressure is always applied on concrete whereas in later type of confinement, it is made to resist the expansion of concrete upon application of load. Concrete or steel jacketing, fiber-reinforced polymer wrapping are commonly available techniques. Despite the fact that these methods increase a structure's strength and durability, they have some drawbacks, such as an increase in the weight of the structures when jacketing of concrete corrosion, fire resistance, debonding when using steel plates, and the deterioration of the adhesion material at the FRP interface.(Zhu et al., 2020).

Ultra-High Performance Concrete offers improvement of capacity and durability of the strengthened structures with added advantage of minimal change in section size and disruption in traffic and lower cost in the whole service life owing to lower maintenance cost. Cementitious composites having compressive strength greater than 17 ksi, lie in the category of Ultra High-Performance Concrete(ASTM C1856, 2017). UHPC is a composite cementitious material with superior mechanical properties as compared to normal strength concrete. High packing density, low water cement ratio, high binder ratio, addition of high range water reducing admixtures and steel fibers results in increase in compressive strength by 3-5 times as that of ordinary concrete(Astarlioglu & Krauthammer, 2014). With the use of Ultra High Performance Fiber Reinforced Concrete (UHPFRC),(Al-osta et al., 2022) and (Wille et al., 2012) has reported increase in energy dissipation, durability, resistance against freeze and thaw and decrease in brittleness. Initiation and propagation of cracks causes damage to reinforced concrete structures. Confinement when provided externally is known as an overlay, which leads to a composite section. The ability of the composite system to resist deformation is based on the bond strength between the two surfaces to ensure the high lateral pressure is exerted by the overlay to the substrate. Therefore, the substrate treatment is essential for the transfer of pressure without the failure of bond between UHPC and Normal Strength Concrete.

This Chapter provides detailed information about UHPC and different types of test to simulate the loadings that occur.

2.2 Rehabilitation of Concrete Structures

Civil engineers all over the world are concerned about the rehabilitation of existing, deteriorated reinforced cement concrete (RCC) structures. Deterioration may be caused due to environmental corrosion of embedded steel caused by ageing of the materials. Poor concrete quality, poor operations and maintenance, design deficiencies, changes in use or imposed loading, fire damage, malpractices during construction, and natural calamities are all factors that contribute to the deterioration of a structural member.

Confinement practices such as RC jacketing, high performance fiber-reinforced jacketing, and ferrocement jacketing are used to strengthen and restore RC structures (FC) (Al-osta et al., 2022). A bigger cross-section is formed when another layer is made or casted around the degraded structural part, which also has the effect of restricting the inner core. Although reinforced bars are commonly used to support this effect, ferrocement or fiber RC jacketing creates similar confining pressure in the form of meshed wires or fibers.

2.2.1 Reason for Concrete Deterioration

Following primary reasons demand rehabilitation, repair or retrofitting of the existing structure (Muñoz, 2012).

1. **Poor Design or execution:** It may be due to construction flaws such as honey combing, bleeding, shrinking. Differential settlement can be one of the many causes in addition to poor design. (Muñoz, 2012).
2. **Excessive degeneration as a result of chemical attack or hazardous environment:** Chloride and sulphate attacks, carbonation, and freezing-thawing cycles may cause the deterioration of a structure as well.

3. **Corrosion of reinforcing steel:** It occurs when there are cracks in the concrete that let water in or when the alkalinity of Portland cement breaks down the passivity around steel bars through carbonation or bar damage. Corrosion of steel induces more cracks and breaks, hastening the corrosion process.
4. **Structural loads:** Repetitive loading for a long time caused by vehicles carrying heavy loads for a long time.
5. **Extraordinary actions:** Impact, earthquake, or fire damages.
6. **Abrasion and erosion:** Abrasion is the gradual wearing away of the surface of concrete brought on by rubbing and friction, whereas erosion is the continual disintegration of concrete brought on by the abrasion or cavitation impact of fluids, moving gases or solids.

2.2.2 Repair Material (Overlay) and Substrate Compatibility

(Decter & Keeley, 1997) suggested that most of the failures between repair and substrate occur due to high shrinkage level which cause debonding and cracking. (Emmons & Vaysburd, 1996) According to this definition, the new overlay's compatibility with the old concrete substrate is determined by a balance of the new overlay's physical, chemical, and electromechanical properties and sizes. According to this definition, the new overlay's compatibility with the old concrete substrate is determined by a balance of the new overlay's physical and chemical characteristics. However, among the variations discussed the main aim is that the repair material should have the capacity to withstand volume variations without loss of bond strength. Following parameters need to consider in order to decide the best suitable repair materials

1. **Bond strength at the interface:** An acceptable bond has strength that is at least equal to that of the substrate under various loading scenarios. Some repair materials, such as epoxies or slurries, require the use of adhesives to conform to the criteria which is acceptable. The interface must withstand stresses caused by volume changes and different types of loading.
2. **Curing requirement:** It is preferable that the material used for repair harden as quickly as possible to limit the structure's downtime. Rapid setting materials are beneficial in today's economic context for faster building and repair scenarios.

3. **Dimensional stability:** Significant changes in the volume of the overlay material may result in disintegration in the new material and an increase in shear loads at the interface, risk of delamination ,cracking and spalling increases.
4. **Shrinkage:** (Rangaraju Rao & Pattnaik Ranjan, 2008) Tensile stresses are formed in the concrete substrate as a result of the overlay's shrinkage restraint. When new and old materials come into contact with each other, these stresses can lead to cracks or delamination.
5. **Creep:** Deformation under sustained loading is defined as creep. (Rangaraju Rao & Pattnaik Ranjan, 2008) was suggested that the overlay should have a low creep rate.
6. **Heat Ressistance:**(ACI-Committee 546, 2001) states that this factor is of utmost importance in structural elements which are going be frequently subjected to large temperatures. In case of huge difference between coefficient of thermal inspection between the overlay and substrate, it may result in failure of strengthening process..
7. **Modulus of elasticity :** (Bank, 2010; Rangaraju Rao & Pattnaik Ranjan, 2008) suggest that the modulus of elasticity of overlay and substrate should be similar to ensure a uniform distribution of stresses, otherwise if the overlay having high modulus of elasticity will attract large forces and vice versa.
8. **Constructability:** Using repair materials that are constructed in the same manner as normal concrete is recommended to reduce the risk of failure due to construction errors. Materials with self-consolidating behavior can be placed without the use external energy and have showed good performance with the substrate as well.

2.3 Common Cementitious Overlay Material Recommended by ACI-546

(ACI-Committee 546, 2001) has sorted available overlay materials which can be used for rehabilitation of existing concrete structure into two groups: polymer materials and cementitious materials in Table 2.1 below.

Table 2.1 Summary of Cementitious Overlays (ACI-546)

Ser	Material	Advantages	Limitations	Applications
1	Normal Strength Concrete	Easy handling and low cost	Inappropriate for harsh environment	Used in repairs of thick section and large volume
2	Conventional mortar	Can be placed in thinner sections	Low freeze thaw resistance and higher shrinkage drying	Can be used in same sections as that of NSC but for thin sections as well
3	Dry pack	Low shrinkage, durable and more water tightness	Not goof for shallow depressions	Used to fill large cavities/ holes
4	Ferrocement	Increased weight-to-tensile strength ratio and cracking behavior No formwork is needed.	Difficult to execute	Can be applied on structures with curved surfaces
5	Fiber reinforced Concrete	Less prone to plastic shrinkage and inclusion of fibers provides reinforcement in think sections	Lower workability	Can be used for slope stabilization, overlay of rigid pavements
6	Cement grouts	Economical, readily available	Can only be applied on cracks wider than 3 mm	Bonding old concrete to new concrete and filling of cracks

7	Chemical grouts	Larger setting time and low viscosity	More expensive, skilled labor required	Repair of finer cracks
8	Low Slump Dense Concrete	Reduced Chloride Permeability	Require more consolidation effort	Final wearing course in composite layer
9	Magnesium phosphate concrete mortars	High early strength	Very less setting time	Best for repair in cold weather
10	Preplaced aggregated concrete	Drying shrinkage is half of Normal Strength Concrete	More effort required in formwork	Underwater concrete placement
11	Shotcrete	Used in small surface with irregular contours	Highly skilled labor required	Used for tunnels
12	Shrinkage compensating concrete	Eliminates shrinkage by expanding in prior	Not suitable for bonded overlays in NSC substrate as it will exert higher pressure	Used in structures exposed to single face drying and carbonation shrinkage
13	Silica-Fume Concrete	Higher strength	More plastic shrinkage	Repair of abrasion-erosion-damaged hydraulic structures

2.4 Introduction to UHPC

Ultra-high-performance concrete, also known as UHPC, is an innovative material which provides high mechanical and durability . It can make construction more cost-effective by reducing the cross-sections of structural members, which results in material savings as well as lower installation and labor costs. Ultra-high-performance concrete was developed in the late 1990s. Figure 2.1 below shows comparative size of section design for the same loads

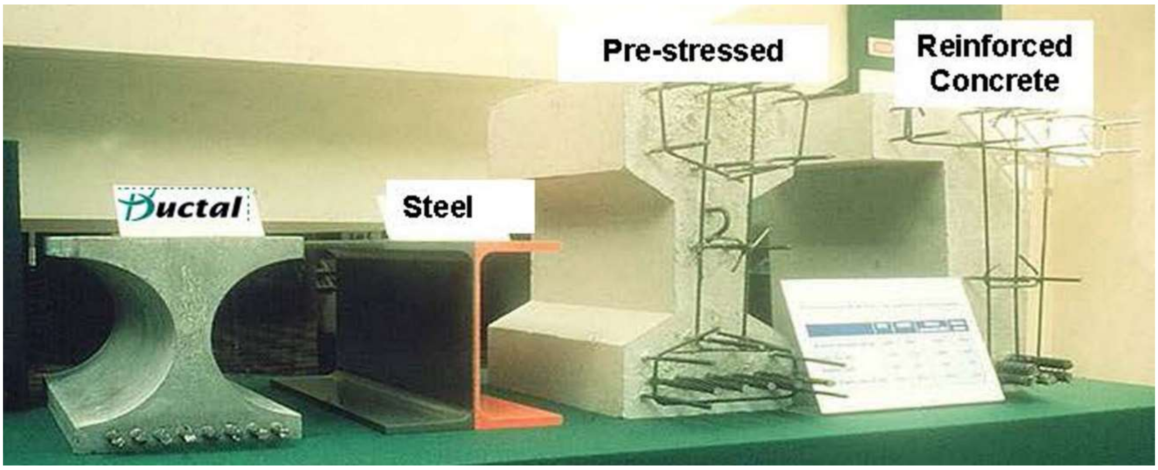


Figure 2.1 Comparison of UHPC section with steel, NSC and pre-stress (Muñoz, 2012)

Ultra-High-Performance Concrete (UHPC) is a high-strength, ductility, and durable concrete. Reinforced concrete structures may have a smaller cross-section and a lighter self-weight due to the higher compressive strength of UHPC. UHPC can be produced using fibres with a very low water/binder ratio (w/b) (less than 0.25) and a well-defined particle-size distribution (containing small particles such as Supplementary Cement Replacement (SCM) materials like silica fume and fine aggregate and coarse aggregates). To compensate for the low w/b, a high-range water-reducing admixture and viscosity-modifying chemicals are required. The high complexity of the mix composition, which is mostly proprietary, significantly increases the UHPC manufacturing costs. Many consumers are concerned about the cost-effectiveness and performance of UHPCs. The compressive strength of normal strength concrete ranges from 4,000 to 7,000 psi, while that of high-performance concrete ranges from 7,000 to 14,000 psi. UHPC, on the other hand, has a compressive strength greater than 17,000 psi.

Furthermore, UHPC has higher tensile and bending strength (750-1500 psi) than standard concrete and even higher tensile and bending strength than high-performance concrete. High dosage of fibers in UHPC, typically 1% to 3% equivalent steel fibers, improve ductility and allow the material to bear tension and bend loads without the need for passive or active reinforcement. Low w/b and optimal particle packing significantly increase the lifespan of UHPC by preventing moisture and other harmful particles, such as chloride ions and sulphates, from entering in the material.

2.4.1 Main Constituent of UHPC

Primary ingredients of UHPC are cement, SCM, water, sand , silica fume, super plasticizer and micro steel fibers. These ingredients are explained below as follows

1. OPC : Normally OPC accounts for 20% of the total matrix of UHPC. Ordinary Portland Cement produces C_3S, C_3A, C_2S and C_4AF. Upon hydration of C_2S and C_3S, contribute mainly toward strength of concrete.
2. Fly Ash (FA): It is a byproduct of coal-fired power plants. The amount of calcium in fly ash determines whether it is classified as high calcium (Class C) or low calcium (Class F).The spherical shape of fly ash particles may improve concrete workability. Fly ash improves the properties of concrete by interacting with the byproduct of cement hydration, calcium hydroxide (CH), to produce hydration products. Although fly ash (Class F) reactions in cement systems begin slowly, the inclusion of fly ash in concrete results in delayed setting times, delayed early-age reaction kinetics, and lower early-age strength development. Fly ash, when combined with other materials (Krishnan et al., 2019)
3. Silica Fume (SF): A popular pozzolanic material used to produce UHPC is a byproduct of the manufacturing of ferrosilicon alloys. This product can be used to raise the packing density of UHPC while preventing the creation of pores. When silica fume combines with Ca(OH)2 during the pozzolanic reaction, C-S-H, the principal product responsible for hydration of concrete's strength, is generated. (Ribeiro & Mendonca, 2019) . Additionally, silica fume can improve the interfacial transition zone of concrete by reducing its initial porosity. Researchers have proposed various silica fume concentrations. Despite its benefits, its enormous surface area and consequent high water demand can diminish the UHPC's practicability.. (Scrivener et al., 2004)
4. Limestone: Improved properties can be achieved by using the correct size of limestone powder. Cement replacement with limestone powder is permissible in Ultra-High Performance Concrete (UHPC) because it can provide adequate particle packing and produce space-filling reaction products when aluminate-rich materials are present. As

a result, limestone powder can be used effectively in ultra-high-performance concrete (UHPC). Chemical reaction between limestone powder and aluminate phases may result in a carbo aluminate phase in cement(Arora et al., 2018).

5. Admixture: High-range, water-reducing (HRWR) admixture (also known as "superplasticizer") is the most commonly used chemical admixture in UHPC. Adding HRWR admixture cuts down on the amount of water used in the mix. While working with working with UHPC, the admixture is critical because it's low in weight-to-volume (w/b).(Ribeiro & Mendonca, 2019)

6. Aggregates : In most mixes coarse aggregates are not used because they influence the Maximum Paste Thickness (MTP) , which is related to the mean distance between two aggregates when they are covered by cement paste with thickness (de Larrard & Sedran, 1994). However, in later research (Federal Highway Administration, 2014) stated that with particles size less than 5 mm in size can be used to achieve strength similar to that of UHPC. Coarse aggregates having high strength, low water absorption and chemically stable are recommended.
7. Steel Fibers: Post-cracking tensile strength is reported to increase through steel fiber reinforcement. (*DANIEL Norman, Oklahoma 2017*, 2017) reported that with inclusion of steel fibers, it also enhances the compressive strength of UHPC.

2.5 Applications of UHPC As a Repair Material

In a study conducted by (Chao et al., 2016), two full scale columns were tested in undamaged state. One column was casted with Normal Strength Concrete (NSC). The second column was casted with UHP-FRC up to plastic hinge region and NSC was used in the rest of the column. The column casted with UHP-FRC in the plastic hinge region exhibited higher strength, increase in drift capacity as compared to the RC column. The specimen showed no signs of concrete spalling, concrete crushing, bar buckling or failure of hoops.

Use of UHPC in earthquake resistant frame members is preferable in comparison to High Strength Concrete (HSC), as the later demands more amount of transverse reinforcement (Chao et al., 2016).Failure in conventional concrete columns, subjected to earthquake loading, typically fail by concrete cracking followed by crushing. Further causing yielding of hoop followed by buckling and fracture of longitudinal reinforcement, causing the column to fail. However, as evident from Figure 2.2 below, no spalling, concrete crushing, buckling or failure of hoops was reported in the test.

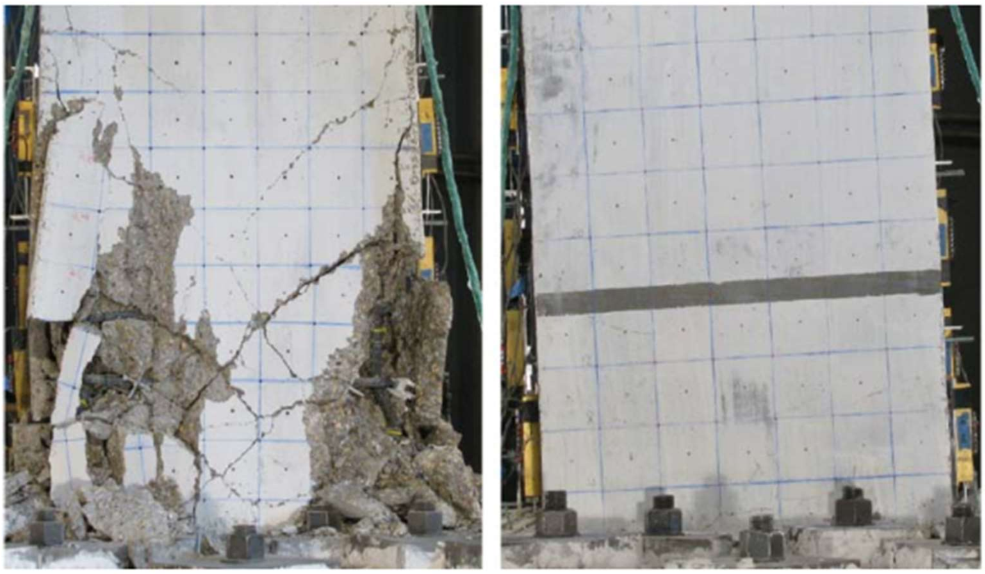


Figure 2.2 By Chao et al., 2016, Comparison of RC(left) and UHP-FRC (right) Specimens at 5.25% Drift

Test on 11 Reinforced Concrete (RC) columns, scaled ¼ was carried out by (Farzad et al., 2019). Specimen were artificially damaged to simulate effect of corrosion. Various alterations in the 1.5 X plastic hinge length were made, spalling of covers, missing longitudinal and transverse reinforcements. The specimen was repaired and tested with UHPC, Normal Strength Concrete (NSC) and a column with no repair was taken as the control sample. The study shows increase in strength, deformation, and energy dissipation of the damaged columns with the use of UHPC, without increasing the size of columns.

2.6 Affecting bond strength factors between UHPC and NSC

There are times when new concrete must be placed next to old, i.e., existing concrete in the repair and strengthening of concrete structures. Concrete overlays are used on highway structures, for example, and new concrete must be poured to repair corrosion-damaged concrete structures. It is common in these cases for the old and new concrete to form a weak link in the repair. The strength of a bond can be determined using a variety of methods(Momayez et al., 2005).Following factors are presented which affect the bond strength between the overlay and substrate.

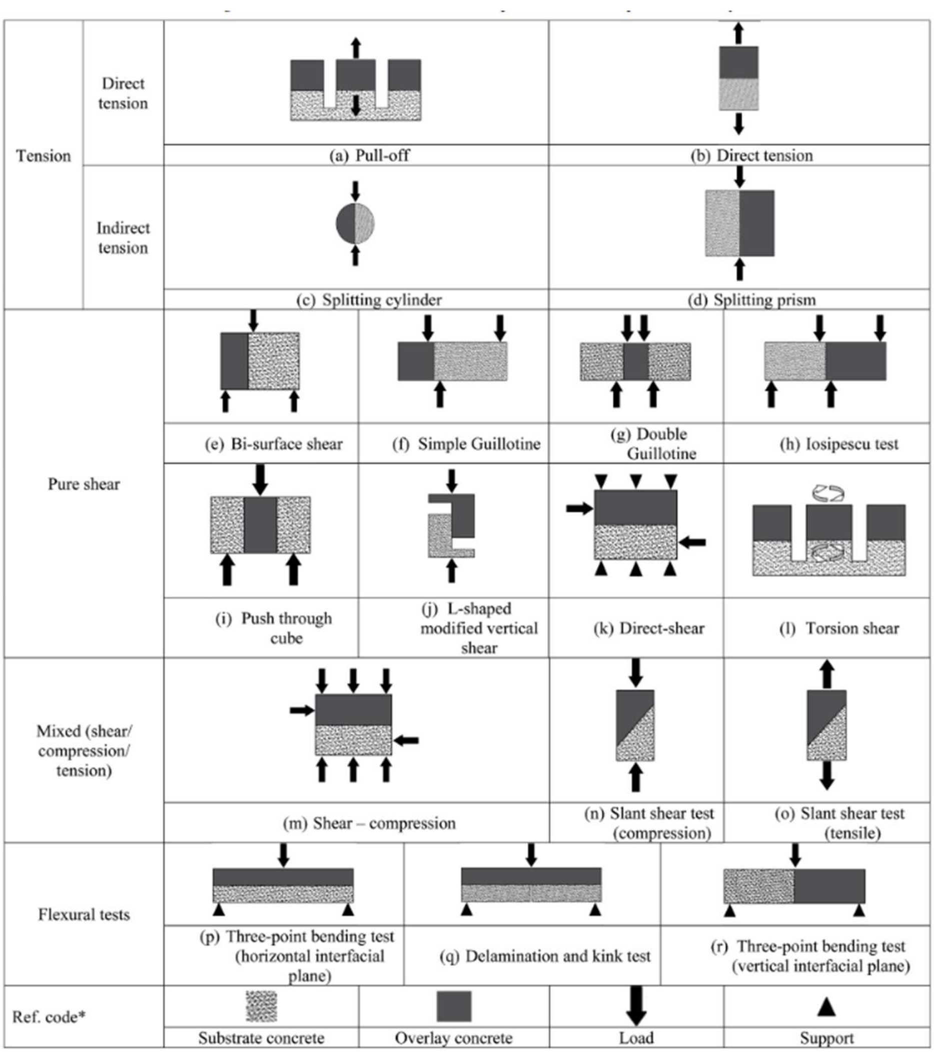
Mechanical properties of substrate and age of UHPC : In a study conducted by (Yang et al., 2022), it is reported that with the increase in strength of substrate concrete the interfacial bonding strength increases. In addition, the specimen can be tested after 7 days of casting of UHPC as there is a difference of 6.9% to results compared at an age of 180 days. (Bentz et al., 2018) studied the effect of wet and dry surfaces of substrate under slant shear test and it was found that excessive water in substrate will lead to weak interfacial bond and similarly a very dry surface will lead to absorption of moisture from freshly casted overlay causing weak interfacial bond. Therefore, it is suggested to keep the substrate in SSD condition so that no excess water goes in the UHPC or moisture is absorbed from overlay by the substrate. The shear capacity of the interface decreases with accelerated heat curing due to large shrinkage development in the overlay material. Therefore, literature suggests to cure at normal tempratures (I. & H.S, 2008). In addition to this, surface roughness, microcracks, cleanliness, compaction method, aggregate gradation and use of bonding agents.

Surface roughness is one of the most critical factor affecting the interfacial bond strength. Removal of unsound concrete and preparation of substrate surface usually doesn’t affect the mechanical properties of the substrate if carried out it in limits.

2.7 Testing methods to evaluate bond strength

(Momayez et al., 2005) and (Espeche & León, 2011) Three primary categories of stress exist: tension, pure shear, and combined shear and compression stress. Therefore, testing must be done in order to simulate the loadings described above on the sample. Table 2.2 displays numerous test types that can be carried out to replicate the various forms of loading that may happen at the interface of the overlay and substrate during the course of the material's design life. (a) to (d) indicate all the that evaluate the bond strength under tension. Whereas, for pure shear test (e) to (l) are used in the researchers conducted. The third group (p) to (r) shows the kind of bond test used to examine how an interface would react under flexural loading.

Table 2.2 Different types of test to simulate various loadings (Baloch et al., 2021)



2.8 Bonding concept between two materials

Two distinct mechanisms, bond-adhesive (micro-scale) and binding-cohesion, produce the bond strength between two cementitious materials (macro-scale) (Muñoz, 2012). The concept of an adhesive bond is the result of microscopic chemical forces. Several academics, to explain the adhesion between the old and new concretes, have proposed the existence of three distinct layers, as depicted in Figure 2.3 from. (Espeche & León, 2011)

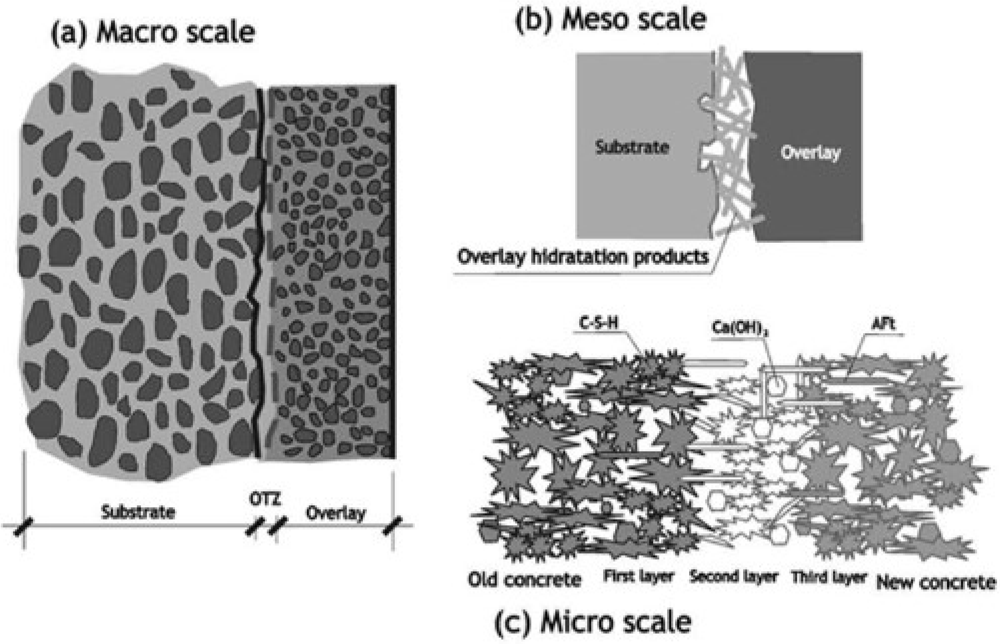


Figure 2.3 Interface between old and new concrete

The first layer, also known as the penetration layer, is created inside the old cementitious material, and is made of fresh components (calcium silica hydrate with little amounts of AFT or calcium hydroxide) that react chemically with the substrate's active ingredients. The second layer is made up of calcium hydroxide and strongly aligned AFT crystals and is very porous. The majority of the new cementitious material and the third layer's microstructure are extremely similar. The bond-cohesive notion is a material characteristic related to the overlay transition zone of the new cementitious material at the macroscale.

Casting new concrete (rapid-hardening Portland) on old concrete without the use of bonding chemicals can result in a strong bond.(Clímaco & Regan, 2001) According to the study, the tensile bond strength and slant shear strength of cementitious materials are each around 40% and 67% of those of a monolithic sample, respectively.

2.9 Summary

This chapter has demonstrated the potential usage of UHPC as repair material. UHPC demonstrates a number of traits that make it suitable for this use. This material is suitable as a protective barrier that prevents any water or chemical infiltration into the substrate due to its extremely low permeability. Additionally, an increase in bearing capacity would be expected given its extremely high compressive strength and post-cracking tensile capacity. Its employment in the field is facilitated by its cementitious nature and capacity for self-consolidation. However, it must be shown that the link between UHPC and NSC will operate well without the aid of any bonding agent in order to get wide adoption. The UHPC-NSC interface must demonstrate strong performance under tensile, shear, and compression loads, from young to old ages, and in extreme climatic conditions. The bond interface must be able to withstand the various combinations of stresses that it will experience throughout its service life as a result of various processes, such as overlay shrinkage, CTE mismatch, or carrying loads, in order for the rehabilitation to be successful.

CHAPTER 3

3. EXPERIMENTAL PROGRAM

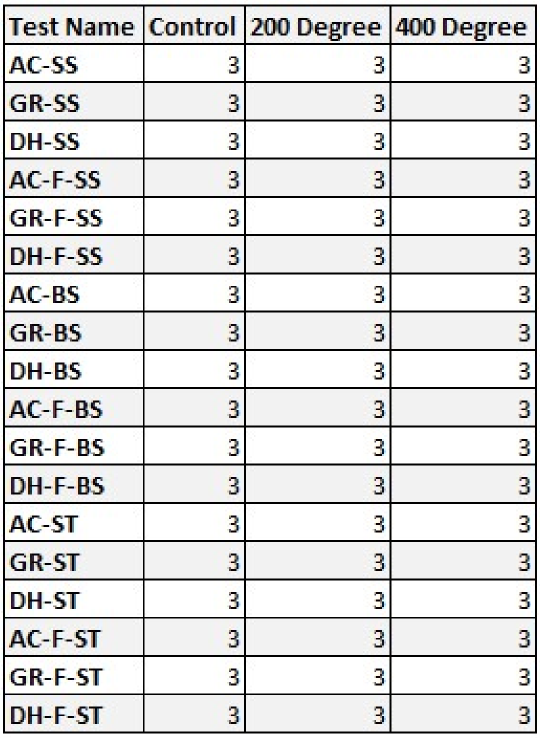
3.1 General

The methodology used to achieve research aims has been addressed in this chapter. The procedures for preparing the specimen as well as the testing procedures used to acquire the results are described in full. This chapter discusses three separate methods for preparing the surface of the substrate: cutting, casting, and testing at different temperatures.

3.2 Test Matrix

As shown in Table **3.1** In addition to including fibres and heating them to a high temperature, three unique methods surface preparation of the substrate were utilized (as cast (AC), drill holes (DH), and grooved (GR)), respectively. Every specimen was put through a series of shear tests, including bi-surface shear, slant shear, and indirect tensile strength using split tensile. For each test, three duplicates were carried out, and for each modification in surface, fibers, and heat exposure, the tests were carried out. This resulted in a total of 162 specimens being produced.

Table 3.1 Test Matrix



Test Name	Control	200 Degree	400 Degree
AC-SS	3	3	3
GR-SS	3	3	3
DH-SS	3	3	3
AC-F-SS	3	3	3
GR-F-SS	3	3	3
DH-F-SS	3	3	3
AC-BS	3	3	3
GR-BS	3	3	3
DH-BS	3	3	3
AC-F-BS	3	3	3
GR-F-BS	3	3	3
DH-F-BS	3	3	3
AC-ST	3	3	3
GR-ST	3	3	3
DH-ST	3	3	3
AC-F-ST	3	3	3
GR-F-ST	3	3	3
DH-F-ST	3	3	3

Key	
AC	As Cast
GR	Grooves
DH	Drill Hole
F	Fibers
ST	Split Tensile
SS	Slant Shear
BS	Bi-Surface Shear

All the surface treated specimens (i.e. GR and DH were roughened with wire brush attached to a grinding prior to grooving and drilling holes)

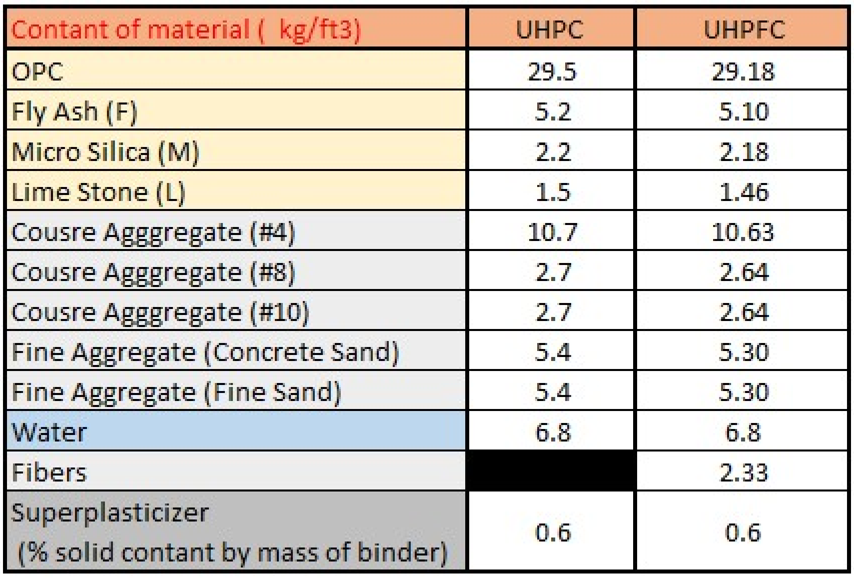
3.3 UHPC Mix Design and Mixing

Mixing UHPC can be accomplished in virtually any standard concrete mixer. The fact that ultra-high-performance concrete (UHPC) requires more energy to produce than traditional concrete, however, means that the mixing process will take longer. Due of the increased energy input, reduced or eliminated coarse aggregate, and low water content, it is required to adopt modified practices in order to prevent the UHPC from overheating while it is being mixed. This is because of the situation. This problem can be fixed by utilizing a mixer with a lot of power, lowering the temperatures of the individual components, and substituting ice for some or all of the water used in the mixing process.(Gray Beal et al., 2013)

For five to ten minutes, the powders were dry-mixed in a Hobart mixer shown. Initially aggregates were added in the mixer, followed by addition of silica fume to de coagulate the particles and mixed for 5 minutes. Limestone and fly ash were mixed for 3 minutes each. Cement was added in the end with the shear mixer was then filled with the dry mixed powder as. The dry powder was combined for at least five minutes after receiving a third of the necessary water and superplasticizer. Until all the water and superplasticizers were combined, the process was repeated several times at a high rate of speed. Up until a cohesive final mixture was attained, the mixing process was continued. Mix design of the locally made UHPC is shown in

and pictorial procedure of mixing UHPC is shown in Figure 3.2(a) to (c). 28 days compressive strength of UHPC and UHPFC is displayed in Figure 3.1

Table 3.2 UHPC Mix Design



Contant of material (kg/ft3)	UHPC	UHPFC
OPC	29.5	29.18
Fly Ash (F)	5.2	5.10
Micro Silica (M)	2.2	2.18
Lime Stone (L)	1.5	1.46
Cousre Agggregate (#4)	10.7	10.63
Cousre Agggregate (#8)	2.7	2.64
Cousre Agggregate (#10)	2.7	2.64
Fine Aggregate (Concrete Sand)	5.4	5.30
Fine Aggregate (Fine Sand)	5.4	5.30
Water	6.8	6.8
Fibers		2.33
Superplasticizer (% solid contant by mass of binder)	0.6	0.6

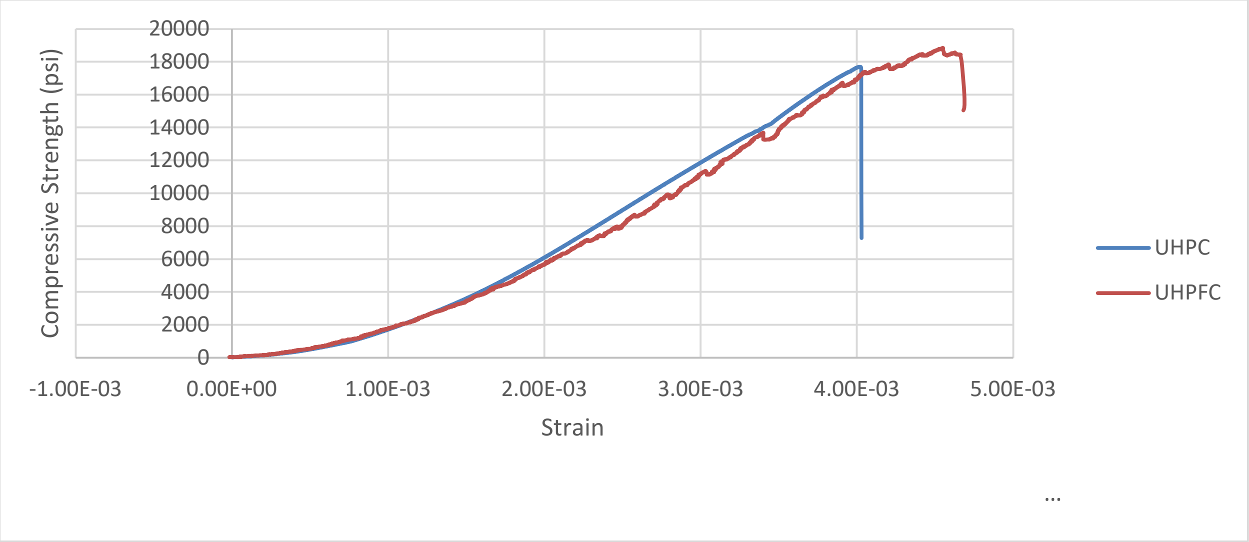
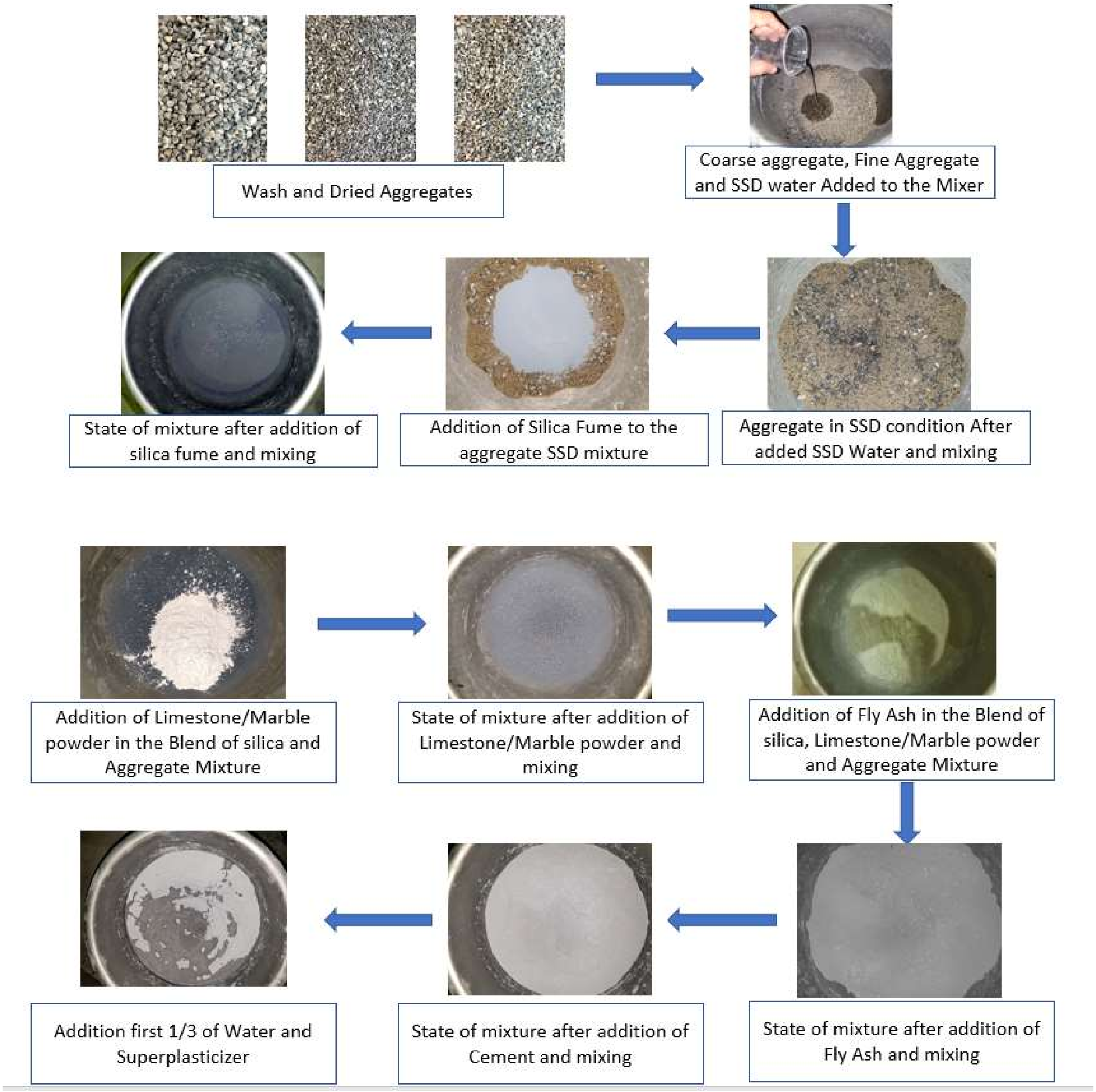


Figure 3.1 28 days compressive strength of UHPC and UHPFC


Wash and Dried Aggregates
Coarse aggregate, Fine Aggregate and SSD water Added to the Mixer
Aggregate in SSD condition After added SSD Water and mixing
Addition of Silica Fume to the aggregate SSD mixture
State of mixture after addition of silica fume and mixing
Addition of Limestone/Marble powder in the Blend of silica and Aggregate Mixture
State of mixture after addition of Limestone/Marble powder and mixing
Addition of Fly Ash in the Blend of silica, Limestone/Marble powder and Aggregate Mixture
State of mixture after addition of Fly Ash and mixing
State of mixture after addition of Cement and mixing
Addition first 1/3 of Water and Superplasticizer

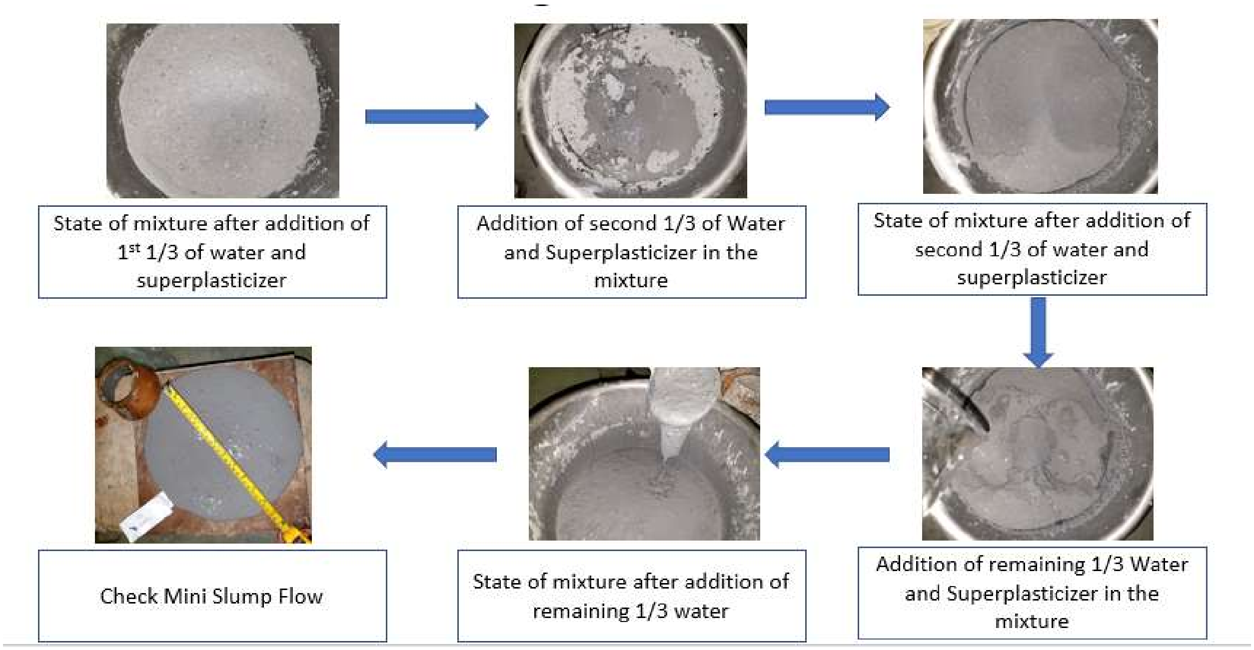


Figure 3.2 (a) UHPC Mixing Procedure

3.4 Normal Strength Concrete

As most of the RC structures built in later 20th century seeking rehabilitation are normal strength concrete. Therefore mix was designed to achieved a compressive strength greater than 3500 psi at 28 days NSC concrete cylinders were casted and tested Stress-strain response of which is shown in Figure 3.3.

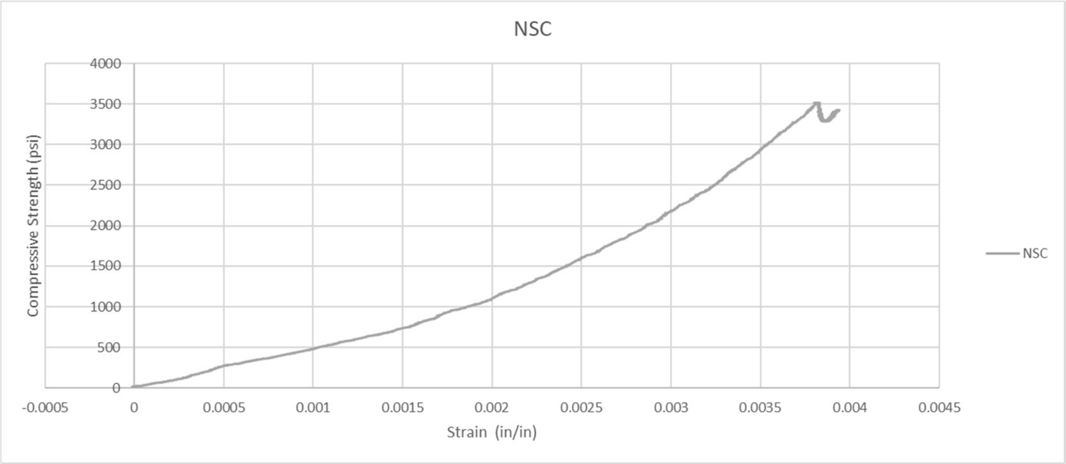


Figure 3.3 Stress Strain Curve of Normal Strength Concrete

3.5 Surface preparation of NSC substrate

The surface of the substrate was prepared as per the testing matrix. Surface of the specimen which were to be grooved and holes to be drilled were brushed using grinder. They were brushed to an extent that the cement layer is worn and aggregates can be clearly seen. This procedure was carried out for all three different types of tests and two different surface preparation to improve the bond performance. Figure 3.4 shows comparison of the NSC brushed and the one which was left as is.

Figure 3.4 Difference between smooth and roughened surface

Furthermore, surface preparation was carried out of the specimens. Grooves of the specimen were made with 10 mm x 10mm at spacing of 30 mm and drill holes of Φ 6 mm by 30 X 30 mm were made in slant shear, split tensile and cube specimen as shown in Figure 3.5

Figure 3.5 Surface preparation of specimen

Slant shear test

International standards have introduced the slant-shear test as one of the most widely accepted method for determining the strength of a bond between two distinct materials because of its realistic depiction of the stress states in real structures and its ease of use. Comprising two different materials bonded together along an interface at an angle to the applied load, the composite sample is subjected to compressive forces.

Cylinder having dimensions of 75 by 150-mm (3 by 6-in) was used for this cylinder as guided by (ASTMC882/C882M-05, 2005). Complete cylinder was cast with the substrate and later cured in water for 28 days. Later the NSC was cut at an angle of 60 degree (Figure 3.6) from horizontal using marble cutter and kept in open air for 90 days to depict old concrete.

Figure 3.6 shows dimensions of substrate at 30 degree from horizontal. The substrate cylinder was placed in molds again and UHPC was casted as an overlay in the cylinder which were demolded after 24 hours to be cured in water for 28 days. Compression test of the cylinders was carried out in accordance with (ASTM C39-01, 2003) on CTM with a loading rate of 0.1 kN/s. Shear stress (τ_n) and the normal compressive stress (σ_n) on the failure plane was calculated using the following formula.

$$\sigma_{\mathrm{n}}=\frac{P}{An}cos^2\alpha \qquad (1)$$

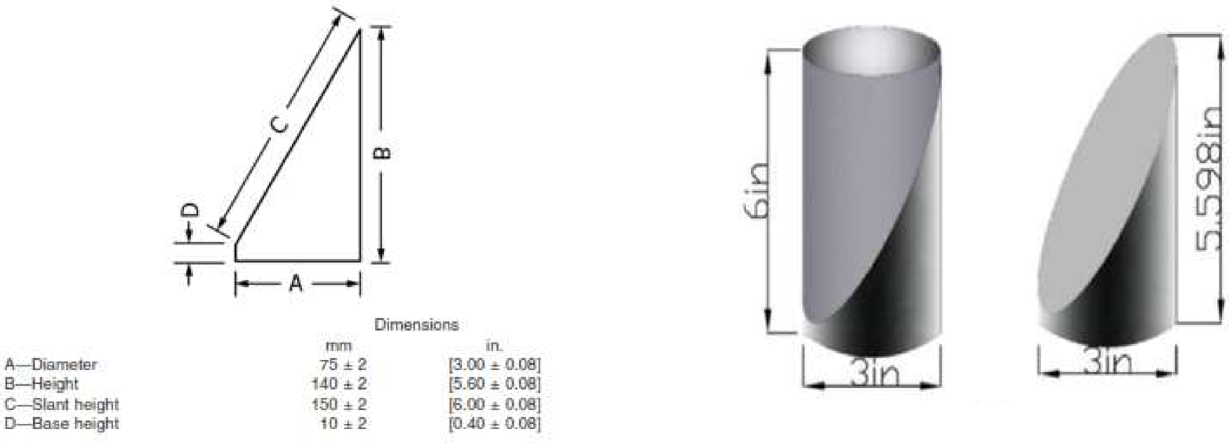
$$\tau_{\mathrm{n}}=\frac{P}{An}cos\alpha.sin\alpha \qquad (2)$$

Where,

P_n= Failure load

A_n=Inclined plain area

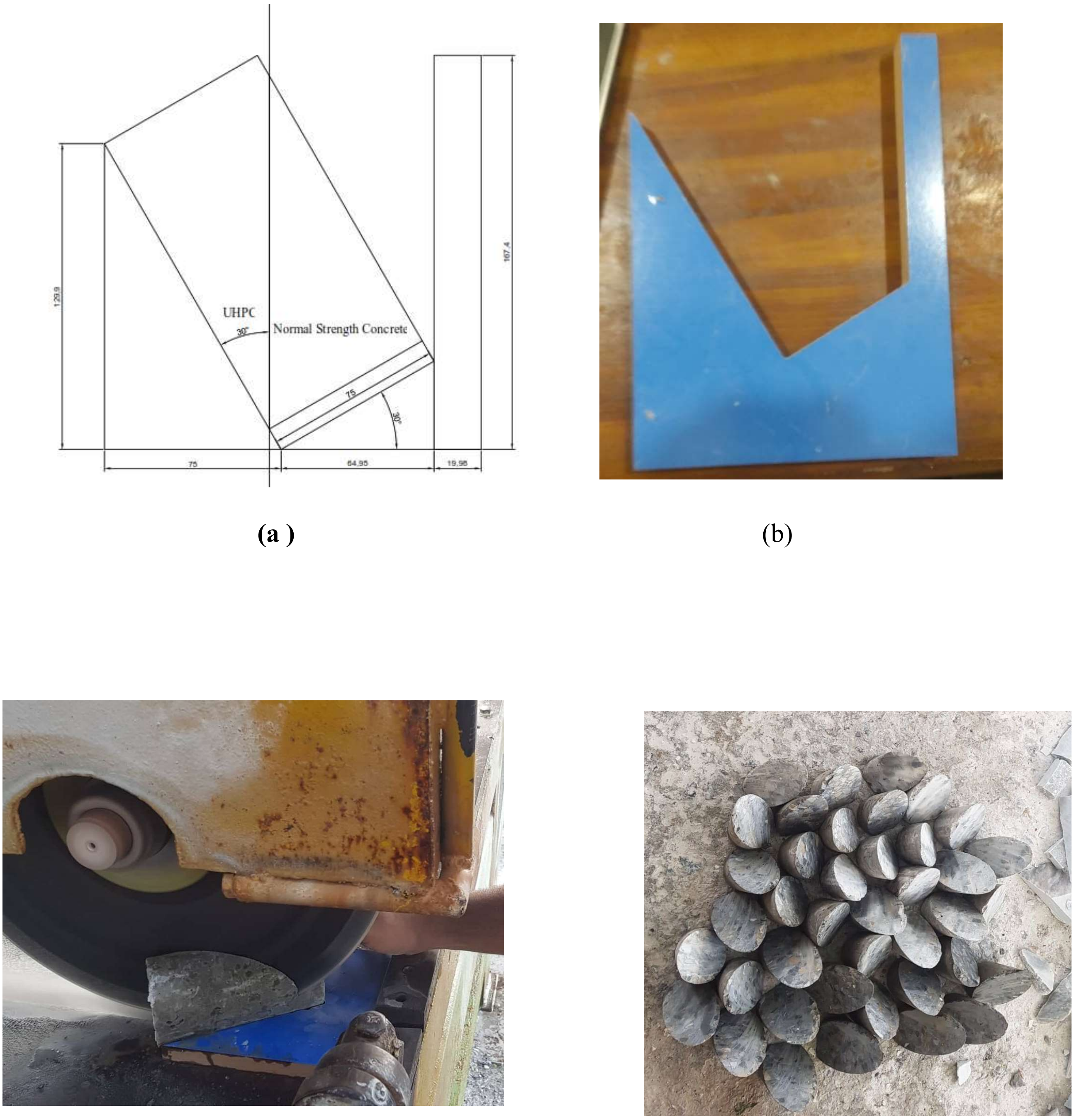
α = Bonded inclined surface angle= 30°



Dimensions

	mm	in.
A—Diameter	75 ± 2	[3.00 ± 0.08]
B—Height	140 ± 2	[5.60 ± 0.08]
C—Slant height	150 ± 2	[6.00 ± 0.08]
D—Base height	10 ± 2	[0.40 ± 0.08]

Figure 3.6 Slant shear test pictures taken from ASTM



(a)

(b)

(c)

(d)

Figure 3.7 Casting and cutting of NSC for slant shear test

3.6 Split tensile test

A common method for determining the tensile strength of prismatic concrete specimens is to use a test known as the split prism test. In some studies, it is also referred as as the splitting tensile test. We use two halves of a split prism in our experimental setup. One of the halves was cast with NSC, while the other was cast with UHPC. Both halves were cured with typical water curing for a period of 28 days. Each side of the specimen is 3 inches by 6 inches in dimension. ASTM C496 was used as the reference for the standards that were adhered to.(Drews, 2008) . Figure 3.8 shows NSC cylinders being cut with a marble cutter and then casted with UHPC. Compression Testing Machine of 3000 KN was used with split tensile assembly shown in Figure 3.9. The test was run at a loading rate of 0.5 kN/s and the bond strength in tension of the specimen was calculated using the formula given in the following equation.

$$fsp = \frac{2p}{\pi As}$$

Where,

f_{sp}= Bond strength in tension

p = Maximum applied load indicated by the machine

A_s= Bond plane area

``

(a) (b) (c)

Figure 3.8 NSC cylinders cut in half and casted with UHPC

Figure 3.9 Split tensile assembly

3.7 Bi surface shear test

According to investigation carried out by (Momayez et al , 2004.) a novel shear test for evaluating the strength of adhesives in concrete repairs. The specimen used in this technique is a 150-mm cube, and the volume of the repair material makes up one-third of the total. The repaired contact is subjected to shear stress with the application of three-point loads. This testing procedure can be quickly and easily executed both in the lab and in the field.

Concrete cube specimens were cast in two stages for the Bi-surface shear test. Styrofoam was used to fill one third of the molds as shown in Figure 3.10, and substrate concrete was used to fill the other two third. Substrate were cured in water for 28 days, and kept in open air for 90 days prior to casting of UHPC overlay. The test was run in accordance with (Al-osta et al., 2022), loading rate of 0.1 kN/s on compression testing machine was adopted, test setup is shown in Figure 3.11. The bond strength was calculated using the following equation

$$Vbs = \frac{P}{2bd}$$

Where;

V_{bs} = Bi-Surface shear bond strength

b= width of cube

d= depth of cube

Figure 3.10 Casting of cubes with NSC substrate

Figure 3.11 Bi-surface shear test setup

3.8 Heating at Elevated temperatures

Specimens' findings are greatly influenced by the sort of fire loading used. The outcome is dependent on two key factors: These are the temperature and heating rate that you desire. Due to a lack of high temperature testing standards, these two criteria were selected based on earlier concrete specimens that had been tested at extreme temperatures.

Temperatures of 23°C (room temperature) are among the most commonly utilized in elevated temperature testing of concrete, along with 200°C, 400°C, 600°C, and 800°C.

When a sample of concrete is heated, the temperature inside the furnace rises steadily i. The air temperature in the furnace may steadily increase, but the surface and center of the cylinder always heat up more slowly. Thus, until the core of the cylinder achieves the desired temperature, a period of time known as hold time must pass during which the furnace temperature must be maintained at the target temperature also known as dwell time.

The cylinder core was fitted with thermocouples (a collection of wires used to measure temperature) to keep track of the temperature history. This experiment used Type-K thermocouples. An opening was drilled to introduce an embedded thermocouple. Then, the cylinder was filled with cement paste and allowed to cure.

The Figure 3.12 illustrates how a thermocouple was put into the sample. The temperature was measured by connecting thermocouples to an 8-universal-channel strain smart data acquisition system. The cylinder that contained the thermocouple was then placed inside the chamber of furnace, and the temperature of the chamber was brought up to the necessary level. Through the process of heating in furnace, record over the course of time, the ideal hold duration for heated specimens was established.

Spalling behavior of specimens is intimately linked to the rate at which they are heated. Researchers often employ a heating rate of 2°C–10°C/min. We used a heating rate of 5 degrees Celsius per minute in this experiment.

Figure 3.12 Preparation of cylinders to determine rate of heating of core temperature of specimen

The temperature time graph of the specimen obtained from the thermocouples attached to the data logger is shown below in Figure 3.13.

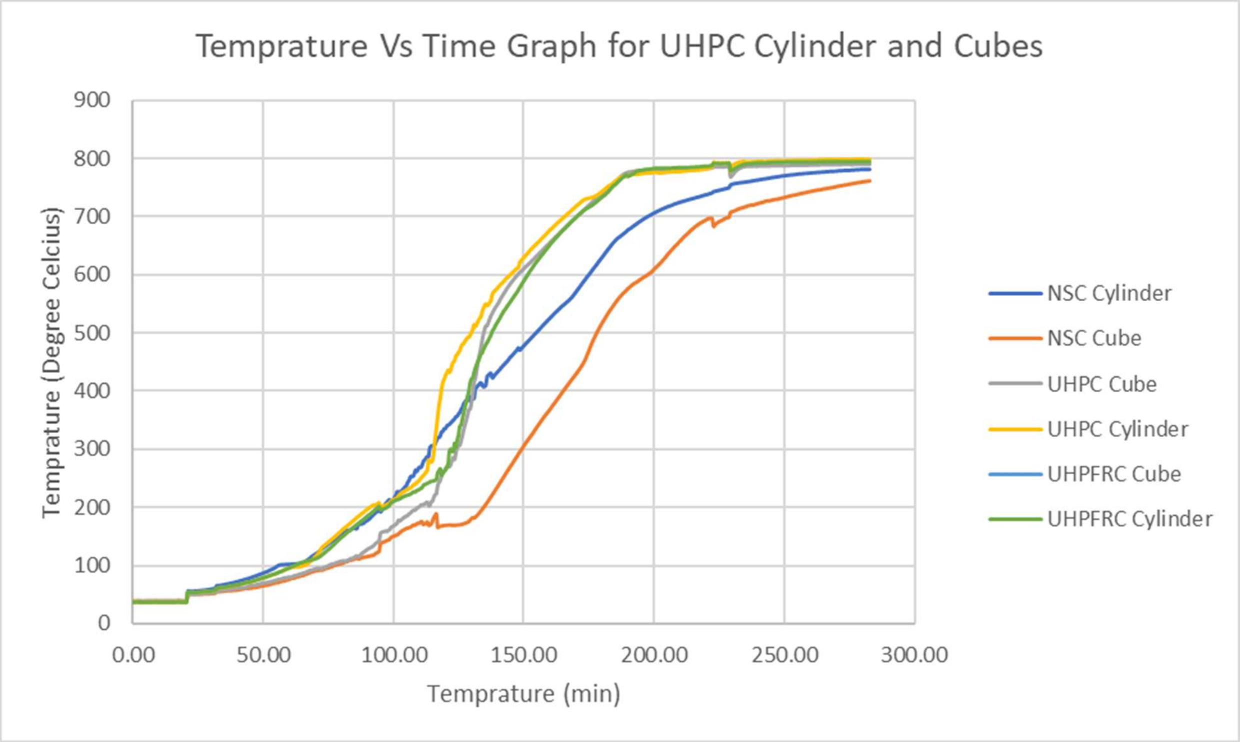


Figure 3.13 Temperature Vs Time Graph at 5 Degree Celsius Per Minute

CHAPTER 4

4. RESULTS

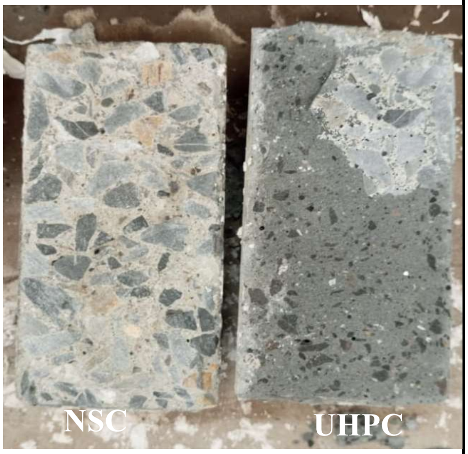
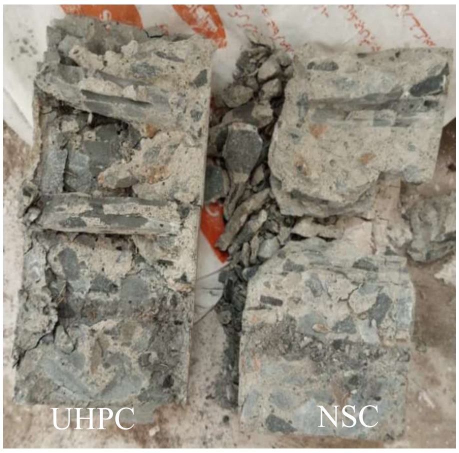
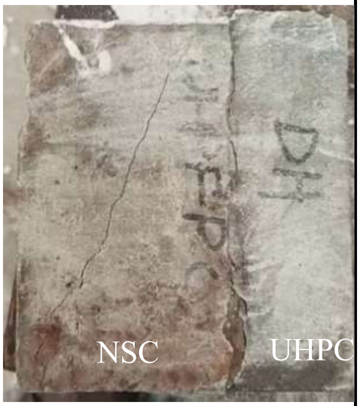
4.1 General

This chapter summarizes and analyses the results of tests done on specimens, including bi-surface shear, slant shear and split tensile test. Along with checking the mechanical qualities, visual observations were taken to determine how the color and spalling behavior of all samples changed after they were removed from the electric furnace. The resulting mechanical properties data for HSC and SS-HSC with and without plaster are used to construct relationships for various material properties as a function of temperature spanning from 23 to 600 °C.

4.2 Visual assessment

Three separate types of composite failure modes can be distinguished based on the qualities and location of the failure plane in the bi-surface shear test, slant shear test, and splitting tensile strength test. Three types of failures have been identified: (A) pure interface failure, (B) interface and partially substrate failure/crack, and (C) interface failure plus substrate failure following the procedure of (Al-osta et al., 2022). The pictorial distribution of failure type against each specimen is shown in Table 4.1 below.

Table 4.1 Visual Observation and Assessment of Failed Specimen

Description	Type A	Type B	Type C
Slant Shear			
Description	Type A	Type B	Type C
Split Tensile			
Bi-Surface Shear			

4.3 Bi-Surface shear Test

Bi-Surface shear test was carried out on the specimen which showed that all specimen have passed the minimum bond strength criteria of (ACI-Committee 546, 2001). The addition of fibers increased the bond strength by 20 percent on average owing to the bridging effect provided by the micro steel fibers. Specimen having drill holes performed the best with maximum bond strength of 1020 psi. The results of test carried out at room temperature are shown in Figure 4.1. Picture of the test being conducted is shown in

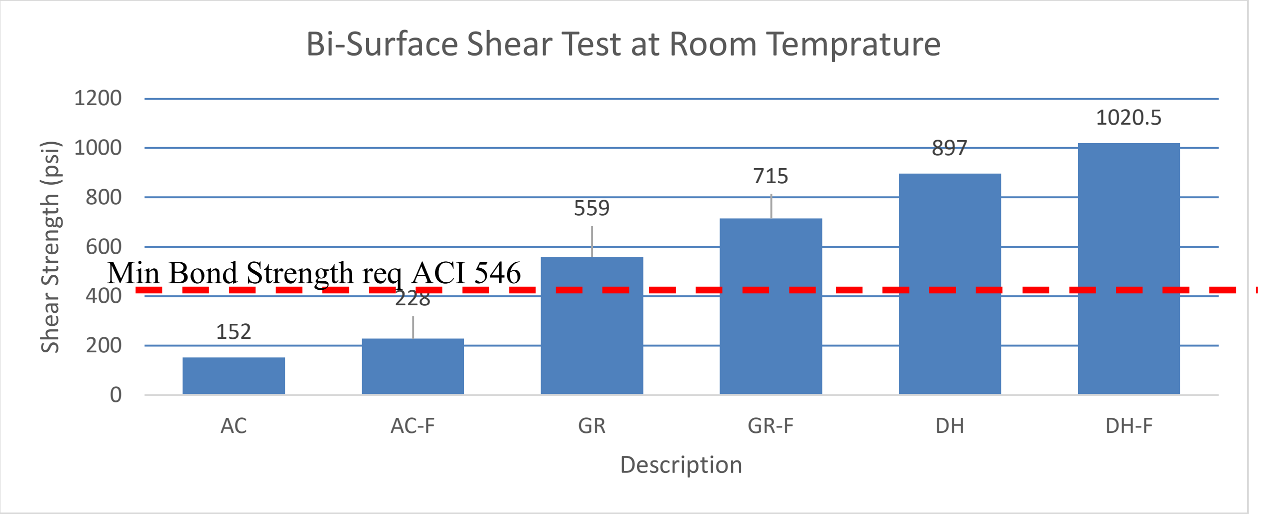


Figure 4.1 Bi-Surface Shear Test Conducted At Room Temperature

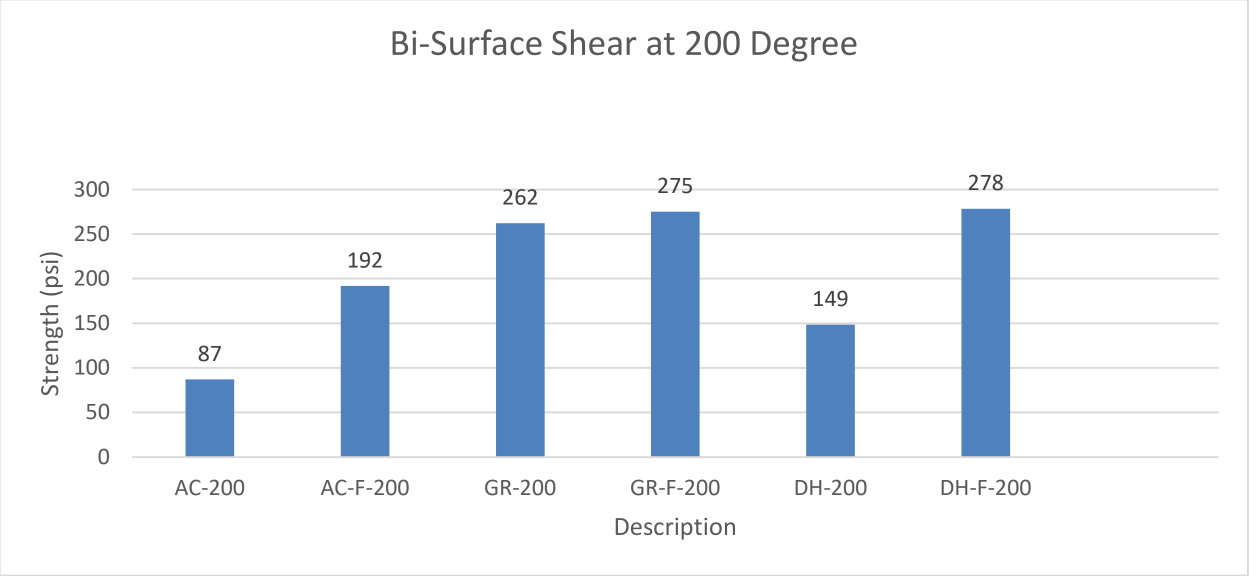


Figure 4.2 Bi-Surface Shear Test Conducted at 200 Degree

Figure 4.3 Bi-Surface Shear Test Assembly

4.4 Split tensile test

Indirect tensile test was carried out on the samples to predict the bond behavior of the overlay and substrate under tension. There is no quantitative criteria to accept the bond strength in tension but following the procedure of (Tayeh et al., 2013) was adopted as provided in Table 4.2. Specimen having grooves performed the best, followed by Drill Holes. Grooved surface with fibers enhanced the bond strength by 191% to that of as cast with addition of fibers and similar to bi-surface shear test, inclusion of fibers enhanced the bond strength by 98% on average. Bridging effect can be viewed in Figure 4.6 and the assembly is shown in Figure 4.7

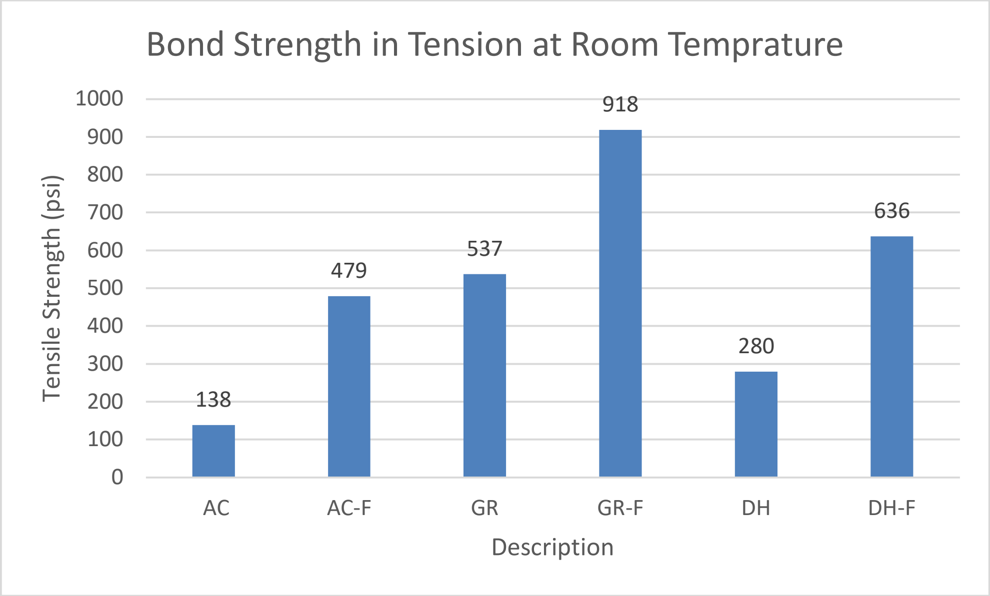


Figure 4.4 Split Tensile Bond Strength

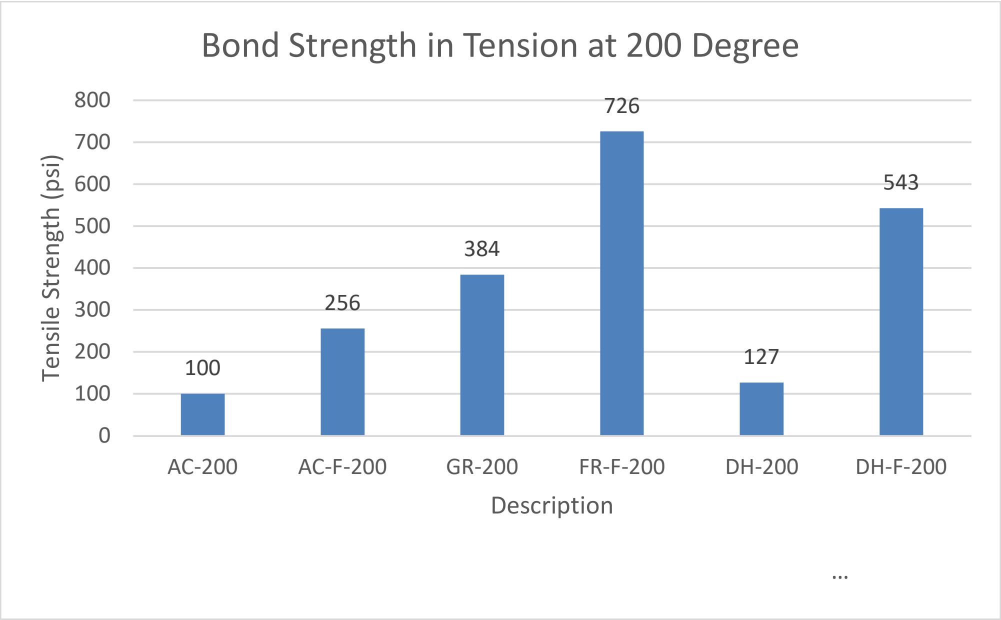


Figure 4.5 Split Tensile Bond Strength in Tension Heated at 200 Degree

Table 4.2 Bond Strength Criteria

Bond Quality	Bond Strength (Psi)
Excellent	≥ 304
Very Good	245-304
Good	203-245
Fair	102-202
Poor	0-101

Figure 4.6 Bridging Effect of Steel Fibers

Figure 4.7 Split Tensile Test Assembly

4.5 Slant shear test

Results of slant shear test are presented in Figure 4.8 which were conducted for an inclined plane of 30 degree. AC and DH samples without fibers fell below the acceptable criteria of (Clímaco & Regan, 2001), while substrate having grooves with fibers produced maximum bond strength .

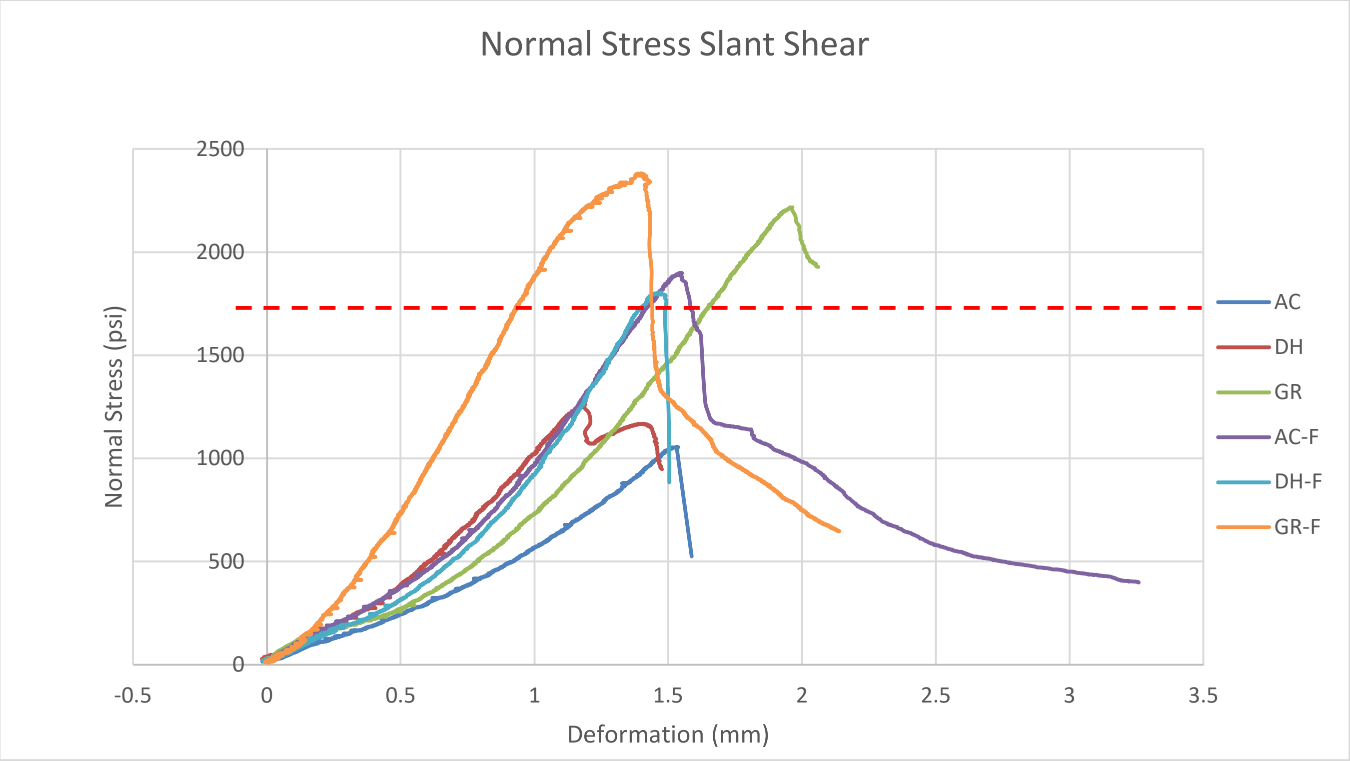


Figure 4.8 Slant Shear Test at Room Temperature

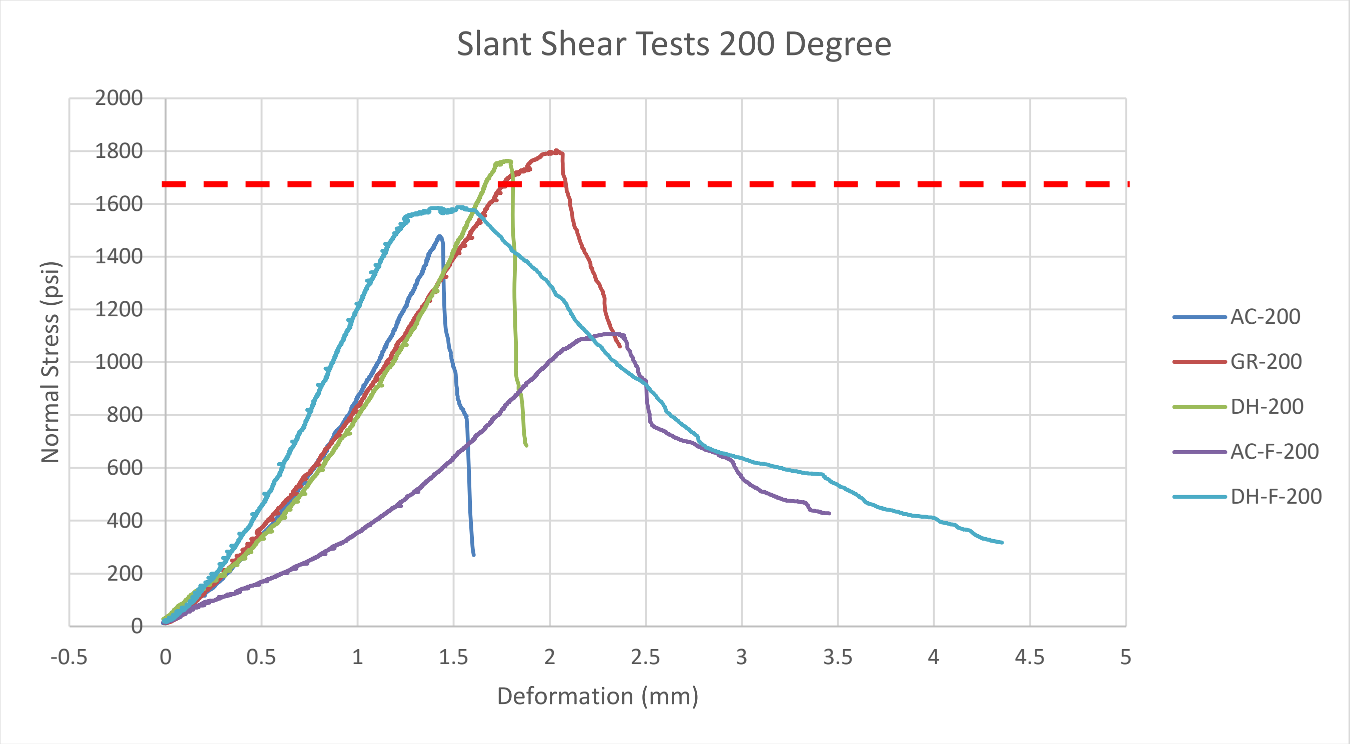


Figure 4.9 Slant Shear Test at 200 Degree

4.6 Heating effect on bond strength

Initially, the samples were supposed to be heated and test up to 800 Degree. When the specimens were placed inside the chamber furnace and heated until 800 Degree to find the rise in core temperature, it was observed that UHPC spalled at 400 Degree unlike Normal Strength Concrete which was intact till 600 Degree. Spalling of UHPC occurred because of having low porosity and high compaction results and increased pore water pressure at lower temperatures compared to normal strength concrete.

Therefore, composite specimen were heated to only 200 Degree and tested in residual unstressed condition in all three types of tests. Results for Bi-Surface shear, Split Tensile and Slant Shear are presented in

Figure **4.2** Bi-Surface Shear Test Conducted at 200 Degree

, Figure 4.5 and Figure 4.9 respectively.

The results show a decrease of 72% in the bond strength in bi-surface shear when the specimen is subjected to heat. 21% decrease in bond strength was observed under indirect tension and 22% decrease in slant shear was reported. Therefore, the bond strength is mostly affected in pure shear when subjected to elevated temperatures.

CHAPTER 5

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Following conclusion are presented on basis of analysis of results obtained from this experimental work:

- In visual assessment, most of the failure occurred in the substrate indicating higher bond performance of UHPC with NSC with preparation of surfaces
- UHPC is poor in heat resistance due to higher packing as compared to NSC. The UHPC spalled at temperature of 400 Degree Celsius
- The hypothesis of using lower percentage silica fume as SCM in the matrix is invalid as there was no positive impact on spalling sensitivity of UHPC with lowering silica fume content when compared with the literature
- Drill hole technique followed by wire brushing of the substrate has proven to give the best bond strength
- Steel fibers provide bridging effect between the substrate and overlay. Thus, increasing the bond strength between the two surfaces
- Bond strength is mostly affected in shear when subjected to elevated temperatures which falls below the acceptable criteria of MENDELEY CITATION PLACEHOLDER 1. Whereas, less decrease is recorded under slant shear an split tensile tests
- Samples casted without any surface treatment showed poor bond performance which are not acceptable as per ACI guidelines

5.2 Recommendations

As this study was focused on testing of UHPC and NSC bond under loading combinations pure shear, indirect tension and combination of both shear and compression with various surface treatments. In addition, the specimen were subjected to elevated temperatures and their response was recorded. UHPC is a novel technique which needs further research in this domain for the stakeholders to gain confidence while using it.

- Further study can be done to achieve the best performance with variation in size of drill holes, grooves and optimize the geometry.
- Comparison needs to be made with UHPC in which silica fume is not incorporated and subjected to heat. This may increase the heat resisting property of UHPC
- Flexural bond strength of this UHPC developed using locally available material, needs to be studied
- Further research can be conducted using the outcomes of this study on large scale models
- Variation in steel fibers can be made to see its affect on bond strength of concrete

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