

**EXPERIMENTAL AND NUMERICAL MODELING OF
THE BEHAVIOR OF ULTRA HIGH-PERFORMANCE
CONCRETE SLABS UNDER IMPACT LOADS**

BY

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Dedicated to

My respected parents,

Mr. & Mrs. Abdul Malik Khan

My beloved wife, lovely daughter and siblings

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LIST OF ABBREVIATIONS

UHPC :	Ultra-High Performance Concrete
HWUHPC :	Heavy Weight Ultra-High Performance Concrete
HWNC :	Heavy Weight Normal Concrete
OPC :	Ordinary Portlant Cement
SF :	Silica Fume
HP :	Hematite Powder
FEM :	Finite Element Modeling
FESEM :	Field Emission Scanning Electron Microscope
EDS :	Energy-Dispersive X-ray Spectroscopy
XRD :	X-Ray Diffraction

ABSTRACT

Full Name : Muhammad Umar Khan

Thesis Title : Experimental and Numerical Modeling of the Behavior of Ultra High-Performance Concrete Slabs Under Impact Loads

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Ultra-High-Performance Concrete (UHPC) has recently evolved as a revolutionary structural material with potential of applications in special conditions. It possesses excellent mechanical and durability properties owing to its highly dense microstructure achieved through the proper selection of its ingredients (high amount of cement and ultra-fine mineral admixtures, fine quartz sand, steel fibers, and no coarse aggregate), optimum mixture design, special mixing and curing practices. The stress-strain behavior of UHPC is characterized by strain hardening in tension, accompanied by multiple cracking, which allows it to undergo high strain before failure resulting into its very high resistance against impact and crack propagation (i.e., fracture toughness). Furthermore, the capability of UHPC to absorb higher energy during impact loading due to greater fracture toughness makes it a promising smart material for the construction of the protective engineering structures subjected to impact and dynamic loadings for safety against explosion, tornado-generated projectiles and accidental loads. The UHPC can be used for construction of structural elements in nuclear power plants to offer resistance against high intensity accidental loads as well as to provide resistance against nuclear radiations, if the dry density of UHPC is increased to fall under the category of heavy-weight ultra-high-performance concrete (HWUHPC) by partially replacing the sand by a heavy-weight powder material.

In this study, firstly, three mixtures of UHPC containing 10% hematite powder, by partially replacing sand with hematite powder having very high fineness (thirty times

higher than cement) and density (two times heavier than sand), and three different dosages of fiber (2, 4 and 6%) were considered to examine the effect of fiber content on the mechanical properties. As expected, higher fiber content significantly improved the mechanical properties. An optimum dosage of fiber was taken as 6%, by mass of concrete, based on the test results showing variations of the mechanical properties with fiber content.

After the completion of first phase, an attempt was made to first develop HWUHPC mixtures containing 0, 10, 20, 30, 40, and 50% of hematite powder (partially replacing the sand) and 6% fiber content (taken as an optimum dosage) and then to evaluate their performance in terms of mechanical properties and radiation shielding. The mechanical properties of the HWUHPC mixtures studied in the present work included compressive strength, modulus of elasticity, flexural strength, fracture toughness and resistance against impact loading. All the HWUHPC mixtures satisfied the flow requirements and their dry densities varied in the range of about 2600 kg/m³ to 2900 kg/m³ meeting the requirements of heavy-weight concrete mixtures. Although the HWUHPC mixtures had different dry densities, their mechanical properties did not vary significantly and showed no adverse effect of the replacement of sand by the hematite powder. This is due to the role of hematite powder in making the microstructure of the mixtures highly dense owing to its very high fineness and its non-interference with the hydration of the cementitious materials, as evident from the analysis of SEM, EDS and XRD test results obtained by testing the mixtures of HWUHPC.

In order to study the resistance of the developed mixtures against impact loading, slab specimens (750 mm × 750 mm × 50 mm) were cast for all nine mixtures (1 conventional high-performance concrete with aggregates, 1 conventional UHPC, and 7 HWUHPCs). The slab specimens were tested under low-velocity impact loading using tailor-made drop-weight impact test set-up. The analysis of the experimental data indicates that the impact resistance of conventional high-performance concrete was far less as compared to UHPC and HWUHPC mixtures. Moreover, the impact resistance of the mixtures increased

exponentially with increasing the fiber content. However, the impact resistance did not vary significantly with increase in hematite powder content and showed no adverse effect of the replacement of sand by the hematite powder. Utilizing the experimental data generated under the present study, the correlations between the applied impact energy and resulting deflection in slabs were obtained through regression analysis. Furthermore, finite element modeling (FEM) was performed in ABAQUS[®] using concrete damaged plasticity model, to simulate the behavior of slabs under low-velocity impact loading. The FEM results were found to be in good agreement with their corresponding experimentally generated results.

The performance of the developed HWUHPC mixtures against nuclear radiation was evaluated by exposing the concrete specimens to gamma radiation. As expected, it was observed through the analysis of the experimental data that the radiation shielding increased with increase in the dry density of the HWUHPC mixtures. However, an important observation made through this study is worth noting. That is, at a same dry density, the radiation shielding of the HWUHPC mixtures was found to be around 40% higher as compared to that of the heavy-weight conventional concrete, indicating that the denseness of the microstructure also improves the radiation shielding besides the dry density of concrete, which has not been reported yet in context to the HWUHPC. Empirical correlations between the dry density of the HWUHPC and different indicators of the radiation shielding were obtained through regression analysis utilizing the experimental data.

The outcomes of the present study would be very useful for optimal design of the mixtures of HWUHPC for meeting the structural as well as radiation shielding requirements of the special structures, for example, for structural members of a nuclear power plant where the structural members are susceptible to both, accidental loads and nuclear radiation.

ملخص الرسالة

الاسم الكامل: محمد عمر خان

عنوان الرسالة: التحقيق التجريبي والنمذجة العددية لسلوك بلاطات الخرسانة فائقة الأداء تحت تأثير قوى الصدمة

التخصص: الهندسة المدنية

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الخرسانة فائقة الأداء (UHPC) والتي تم تطويرها مؤخراً تعتبر أحد المواد الإنشائية تقدماً ويمكن تطبيقها في ظروف خاصة. وتكمن خواصها الميكانيكية وديمومتها العالية والمتمثلة في بنيتها الكثيفة من خلال المواد المستخدمة (بدءً من كمية الأسمنت العالية والمواد ذات الحجم الصغير جداً بالإضافة إلى الرمل وألياف الحديد وكما أنها لا يدخل في تكوينها الركام الكبير) وبالإضافة إلى تصميم الخلطة المثالي وآلية الصب والمعالجة. وكما أن سلوك الإجهاد لهذه الخرسانة يتميز بأنه أكثر تصلداً في الشد ويرافقه تصدعات متعددة والتي تسمح للخرسانة بأن تمتص إجهاد عالي قبل الإنهيار وهذا ينتج عنه مقاومة عالية لقوى الصدمة وتوسع التشققات (يعني أنها تمتلك متانة ضد الكسر). أيضاً قدرة هذه الخرسانة في إمتصاص طاقة عالية خلال تعرضها لقوى الصدمة ومتانتها العالية جعل منها مادة واعدة في مجال البناء والإنشاءات الهندسية وخاصة تلك المعرضة لأحمال الصدمة والأحمال الديناميكية من أجل معاملات الأمان ضد الانفجارات والمفدوفات المتولدة خلال الأعاصير والأحمال العرضية. وكما أن الخرسانة فائقة الأداء يمكن إستخدامها في العناصر الإنشائية في محطات الطاقة النووية من أجل توفير مقاومة عالية ضد الأحمال العرضية وأيضاً توفير وقاية ضد الإشعاعات النووية وهذا يعتمد على ما إذا كانت الخرسانة المستخدمة تدرج تحت تصنيف الخرسانة فائقة الإداء الثقيلة (HWUHPC) حيث يتم إستبدال الرمل جزئياً بمواد أكثر كثافة.

في هذه الدراسة، أولاً تم إستخدام ثلاثة خلطات من الخرسانة فائقة الأداء وهي تحتوي على 10% من مادة الهيماتيت حيث أنه إستخدم كبديل جزئي عن الرمل، وتمتاز مادة الهيماتيت بأنها مسحوق ذو درجة نعومة عالية (حوالي ثلاثين مرة أنعم من الإسمنت) وذات كثافة (حوالي مرتين أثقل من الرمل). وأيضاً تم

إستخدام ثلاث نسب من ألياف الحديد (وهي 2% و 4% و 6%) من أجل دراسة تأثير محتوى تلك الألياف على الخواص الميكانيكية. وكما هو متوقع، فإن إستخدام كمية أكبر من ألياف الحديد نتج عنه تحسن كبير في الخواص الميكانيكية. وبناءً على نتائج الإختبارات المعملية فإن المحتوى المثالي لألياف الحديد هو 6% من وزن الخرسانة.

بعد الإنتهاء من المرحلة الأولى، جرت محاولة إنتاج خرسانة فائقة الأداء وذات وزن ثقيل حيث تم إستبدال الرمل جزئياً بمادة الهيماتيت بنسب متفاوتة من 0% إلى 50%. وأيضاً محتوى ألياف حديد بنسبة 6% (وهي النسبة المثالية)، ومن ثم تم تقييم أداء هذه الخرسانة من حيث الخواص الميكانيكية والقدرة على إمتصاص الإشعاع. حيث أن الخواص الميكانيكية تشمل على مقاومة الضغط و معامل المرونة ومقاومة الإنحناء ومتانة الإنكسار والمقامة ضد قوى الصدمة. كل الخلطات المستخدمة في إنتاج الخرسانة أظهرت نتائج مرضية بخصوص متطلبات الإنسيابية و حيث أن الكثافة الجافة كانت في حدود 2600 كجم/سم³ إلى 2900 كجم/سم³ وهي تلي متطلبات الخرسانة الثقيلة. وتجدر الإشارة إلى أنه بالرغم من أن الخلطات المستخدمة لديها كثافات مختلفة إلا أن الخواص الميكانيكية لم تتباين كثيراً ولم يظهر أي تأثير عكسي للإستبدال الجزئي للرمل. وهذا يعزو إلى دور مادة الهيماتيت في جعل بنية الخرسانة أكثر كثافة نتيجة دقة نوعيته وعدم تداخله مع تفاعلات تموه المواد الإسمنتية وهذا ما تم إستنتاجه من تحاليل SEM, EDS and XRD التي جرت على أنواع الخلطات المستخدمة.

ومن أجل دراسة مقاومة الخرسانة المطورة في هذه البحث ضد قوى الصدمة، فإنه تم صب بلاطة بأبعاد (750 ملم x 750 ملم x 50 ملم) لعدد تسع خلطات مختلفة (تشمل واحدة خرسانة عالية الأداء التقليدية مع الركام وواحدة خرسانة فائقة الأداء بدون ركام وسبع خلطات للخرسانة فائقة الأداء الثقيلة). تم إختبار البلاطات الخرسانية تحت قوى الصدمة بمعدل سرعة منخفض بإستخدام إختبار مصمم لمحاكاة سقوط الوزن. تحليل نتائج الإختبارات المعملية أوضح أن مقاومة الصدمة للخرسانة عالية الأداء أقل بكثير من الخرسانة فائقة الأداء والخرسانة الأخرى الثقيلة. أيضاً، وجد أن مقاومة الصدمة للخلطات يتزايد تصاعدياً بإزدياد محتوى ألياف الحديد. غير أن مقاومة الصدمة لم تتأثر كثيراً بزيادة محتوى مادة الهيماتيت

ولم يظهر أي تأثير عكسي للإستبدال الجزئي للرمل. بالإستفادة من نتائج هذه الدراسة، فإنه تم الحصول على علاقة تجريبية تربط بين شدة طاقة الصدمة والانحناء الناتج عنها من خلال تحليل الإنحدار. إضافة إلى ذلك، فقد تم نمذجة سلوك البلاطات الخرسانية تحت تأثير قوى الصدمة بمعدل سرعة منخفض بإستخدام طريقة العناصر المحدودة عبر برنامج ABAQUS. حيث أظهرت النتائج تطابق مع النتائج العملية.

أما قياس مدى فعالية الخرسانة فائقة الأداء المطورة في هذا البحث ضد الاشعاعات النووية، فقد تم من خلال تعريض عينات الخرسانة لأشعة جاما. وكما هو متوقع، فإن نتائج التحليل المعملية أثبتت أن قدرة الخرسانة لإمتصاص الإشعاع تزداد بزيادة كثافة الخرسانة. ومع ذلك فإن ملاحظة هامة يجدر ذكرها هنا وهي أنه عند نفس الكثافة فإن قدرة إمتصاص الإشعاع كانت حوالي 40% أعلى مقارنة بالخرسانة الثقيلة التقليدية، وهذا يدل على أن كثافة البنية أيضاً ساعدت في تحسين قدرة إمتصاص الإشعاع إضافة إلى كثافة الخرسانة وهو ما لم يتم الإشارة إليه في الأبحاث المتعلقة بالخرسانة فائقة الأداء الثقيلة. أيضاً بإستخدام النتائج العملية، ومن خلال تحليل الإنحدار فقد تم التوصل إلى علاقة تجريبية بين كثافة الخرسانة فائقة الأداء الثقيلة وبين المقاييس المختلفة لقدرة إمتصاص الإشعاع.

حصيلة نتائج هذه الدراسة ستكون مفيدة جداً في التصميم المثالي لخلطات الخرسانة فائقة الأداء الثقيلة والتي تحقق المتطلبات الإنشائية وتلك المتعلقة بإمتصاص الإشعاع في المنشآت الخاصة. وكمثال فإن محطات الطاقة النووية تتطلب ذلك النوع من الخرسانة حيث أن العناصر الإنشائية معرضة لكلٍ من الأحمال العرضية والإشعاعات النووية.

CHAPTER 1

INTRODUCTION

The increasing requirement of strength, durability, safety and security of structures is leading to the development of new materials. Ultra-high performance concrete (UHPC) is a revolutionary material, developed in France two decades ago using fine quartz sand, steel fibers, and high amounts of cement, silica fume and superplasticizer [1][2]. This breakthrough in the technology was made by Richard and Cheyrezy, 1994 [3], when they first developed Reactive Powder Concrete (RPC) having compressive strength more than 200 MPa and tensile strength over 40 MPa. It is distinguished due to its excellent mechanical and durability properties owing to its very dense microstructure [4]. The features that differentiates UHPC to normal concrete and provides it much superior properties are; low water to cementitious material ratio, coarse aggregate elimination, more efficient and optimized particle packing and addition of randomly dispersed short fibers which enhance the flexural strength, ductility and toughness of the material [5]–[9]. The stress-strain behavior of UHPC in tension experiences strain hardening accompanied by multiple cracking that allows it to undergo high strain before failure [10]. The ability of UHPC to absorb higher energy during impact loading due to its excellent fracture toughness allow us to design strong yet slim structures [11]. Presently, the UHPC is being used globally as a smart construction material, particularly in special structures such as bridges, utility towers in oil and gas industries, and off-shore structures etc. [12], [13].

A reinforced concrete structure undergoes several types of loading phenomenon during its lifetime, from gravity loadings to accidental impact loads, earthquake forces, impact forces from tornado generated projectiles, and in recent years an increased threat of blast loads from terrorists' attacks [14]. Due to these extreme loadings, flexural damage, shear damage and concrete spalling may occur [15]. Strategic buildings such as military structures, nuclear power plants are designed to resist blast and impact loads. In actual design of nuclear power plants, the containment building should prevent scabbing and perforation under the impact of a Boeing 747 aircraft crash [16]. Over the years, the researchers have been developing the understanding of the behavior of reinforced concrete members under impact loads [17][18]. Concrete being a brittle material have always exposed its limitation when it comes to the tensile strength and fracture toughness [7]. Therefore in order to improve the tensile and flexural strength; ductility and fracture toughness; short length fibers have been used in concrete matrix [5]. In normal concrete construction, compressive strength is considered as an index property and the indicator of the quality, whereas in UHPC; impact resistance and fracture toughness are also to be evaluated along with the other strength and durability parameters [18]. Furthermore, in order to prevent structural collapse and occupant injuries, structures should possess greater resistance to impact loading [19].

In many applications the concrete is subjected to gamma radiations, such as nuclear reactors, nuclear research laboratories, medical facilities and nuclear waste storage casks [20], [21]. The gamma ray photons do not possess charge and can easily penetrate the matter due to its wave like pattern, which makes it very difficult for shielding [22]. Higher atomic number elements and high density material helps in attenuation of photons [23].

Effectiveness of radiation shielding depend on the utilization of appropriate materials [24]. Plenty of materials are used for radiation shielding, for example, normal concrete, heavy weight concrete, iron, lead and water etc. Every material has its own characteristics. For example, lead is the best shielding material but it's expensive and harmful to human health, whereas, concrete has good structural and functional properties [25], [26]. Concrete used in the construction of nuclear power plants should have enough shielding against exposure to nuclear radiation, besides its strength and durability [27]. Conventionally, the resistance against gamma radiation is provided by heavy weight concretes (HWC). These HWC's are produced by incorporating high-density coarse aggregates. Various researchers have produced and reported heavy weight concrete by using barite, magnetite, hematite, heavy metal oxide and colemanite [24], [28]–[35]. However, the mechanical properties and impact resistance of these HWC's are similar to the normal concrete.

With the wonderful durability properties, UHPC becomes a strong candidate for the construction of containment buildings in nuclear power plants specifically, and for fortification structures in military and other structural applications generally. The higher fracture toughness and greater energy absorption of UHPC gives a greater resistance to impact loading and spalling of concrete, and the dense microstructure and very low porosity resists the ingress of harmful species to give better performance in durability [36]–[39]. The application of UHPC in the construction of nuclear power plants for the protection from nuclear irradiation seems feasible [40]. A thorough literature search indicate that a very few studies are reported on the development of HWUHPC that can offer radiation shielding along with an excellent performance in terms of the mechanical properties and the durability characteristics.

Keeping in view the superior performance of UHPC over normal concrete in strength and durability properties, the conventional UHPC can be modified by incorporating high density materials such as “hematite” into the mix design to develop HWUHPC. This proposed material will be useful in the applications such as nuclear power plants where high radiation shielding is desired with improved strength, durability and toughness.

1.1 NEED FOR RESEARCH

In order to meet its ever increasing energy demands, Kingdom of Saudi Arabia (KSA) have announced its energy diversification plan by considering alternative sustainable and reliable sources of energy for generating power and production of desalinated water [12]. For this purpose, Kingdom of Saudi Arabia (KSA) has planned the construction of nuclear power plants. In June 2011, the coordinator of scientific collaboration at King Abdullah City for Atomic and Renewable Energy (KA-CARE), announced the plan to construct 16 nuclear power reactors over next 20 years with an estimated cost of \$80 billion. Following this development a National Saudi Arabian Atomic Regulatory Authority (SAARA) was set up, which commenced its activities early in 2014 [41].

The feature that makes the concrete used in nuclear structure different than conventional structure is the safety aspect. As per ACI 349-10 [42], “these structures are integrally designed with the various systems and components they support and protect, in order to restrict the spread of radiation and radioactive contamination to the general public”. Keeping in view the well documented superior performance of UHPC over normal concrete in strength and durability properties, the conventional UHPC is modified by incorporating high density materials such as “hematite powder” as a partial replacement of

sand to develop HWUHPC mixtures. This new material possessing very high impact resistance, fracture toughness and radiation shielding would provide safety to the structural members of a nuclear power plant in the case of earthquakes or any other accidental event. Hence, the proposed material can be used in future for the construction of proposed nuclear power plants for meeting increasing energy demands.

1.2 OBJECTIVES

The primary objective of this research work is to develop and evaluate the performance of HWUHPC mixtures in terms of mechanical properties (with focus on the resistance against impact loading) and gamma radiation shielding.

The specific objectives of this study are the following:

1. To investigate the effect of hematite content on the dry density, microstructure, and mechanical properties of the HWUHPC mixtures.
2. To investigate the effect of fiber content on the mechanical properties of the HWUHPC leading to the selection of an optimum dosage of the fiber to produce HWUHPC mixtures.
3. To perform finite element modelling (FEM) of the slabs subjected to impact loading, and to calibrate the models using experimental data enabling prediction of the behavior of HWUHPC slabs under impact loadings.
4. To evaluate the performance HWUHPC against nuclear radiation and compare it with the heavy-weight normal concrete (HWNC)

CHAPTER 2

LITERATURE REVIEW

A detailed literature survey was conducted to review the work done before related to this study. For the clarity of presentation, the literature review is divided into the following aspects.

- UHPC mix design; advantages and applications
- Effect of varying fiber content on mechanical properties of UHPC
- Experimental investigation and finite element modeling of impact tests on UHPC slabs and the effect of fiber content on impact resistance
- Nuclear radiation shielding of concrete

2.1 UHPC Mix design, advantages and applications

UHPC is a revolutionary material that was first developed in France two decades ago [2]. This breakthrough in the technology was made by Richard and Cheyrezy, 1994 [3], when they first developed Reactive Powder Concrete (RPC) having compressive strength more than 200 MPa and tensile strength over 40 MPa. Following this work, three companies in France; LAFARGE, BOUYGUES and RHODIA (construction material manufacturer; Civil and structural engineering contractor; and chemicals manufacturer, respectively) developed a material with the proprietary name of “DUCTAL[®]”, which was patented, industrialized and commercialized. This promising material outperformed not only normal concrete but as well the High-Performance Concrete (HPC). The improvement

in the various characteristics of UHPC in comparison to HPC, has been reported by Lubber, 2003 [43] as shown in Table 2.1:

Table 2.1: Comparison of properties of UHPC and HPC (Lubbers, 2003)

Material Characteristics	UHPC compared with HPC
Compressive Strength	2–3 times greater
Flexural Strength	2–6 times greater
Elastic Modulus	1.5 times greater
Total Porosity	4–6 times lower
Micro-porosity	10–50 times lower
Permeability	50 times lower
Water Absorption	7 times lower
Chlorine Ion Diffusion	25 times lower
Abrasive Wear	2.5 times lower
Corrosion Rate	8 times lower

Table 2.2: DUCTAL[®] mixture proportions (Jun Li et al. 2015)

Constituents	Quantity (per m³)
Cement	680 kg
Silica fume	204 kg
Silica flour	204 kg
Sand	974 kg
Steel fibers	156 kg
Superplasticizer	441 lit
Water	150 lit

Jun Li et al. [44], reported the mixture proportion of DUCTAL[®], which are very close to the other UHPC mixture proportions employed and reported by various researchers. The mixture proportions reported by Jun Li et.al. [44], are given in Table 2.2.

The features that differentiates UHPC to normal concrete and provides it much superior properties are; low water to cementitious material ratio, coarse aggregate elimination, more efficient and optimized particle packing and randomly dispersed short fibers which are added to enhance the tensile and flexural strength and improves the ductility and toughness of the material [5]. The key factor in producing UHPC is to achieve a highly densified microstructure by enhancing homogeneity, improving particle packing and minimizing size of flaws [45]. The optimization of particle packing is one of the major aspects and challenges in the production of UHPC. It is extremely important to ensure the grading requirement of fine quartz sand in the size range of 150-600 μm [46]. In the absence of the required optimum grading, fine quartz sand is obtained through crushing, which is time consuming, costly and environmentally hazardous due to the generation of dust during crushing [45]. Ahmad et al. [47] conducted a comprehensive study to develop an optimum UHPC mixture using fine dune sand, which is naturally available meeting the optimum grading requirements. The UHPC mixture developed by Ahmad et al. [47] satisfied all the requirements of an UHPC pertaining to its mechanical properties and durability characteristics. In the literature, following characteristics of UHPC are generally agreed upon [9]:

- Compressive strength greater than 150 MPa
- Tensile matrix strength (without fibers) greater than 7 MPa
- Higher binder content to reduce capillary porosity

- Elimination of coarse aggregates for homogeneity
- Low water-cementitious ratio
- Use of fibers (typically steel) for achieving ductility and toughness

The first application of UHPC in Civil construction was for an Innovative Train Station Canopy in Canada [12]. Following it, in Germany and New Zealand, UHPC material was used in the construction of pedestrian bridges and it was also used in the construction of a cable stayed bridge in Korea [12]. UHPC in recent years have been used in structural elements to resist extreme loadings such as earthquake effects, impact and explosive loads.

2.2 Effect of varying fiber content on mechanical properties of UHPC

Concrete being a brittle material have always exposed its limitation when it comes to the tensile strength and fracture toughness [7]. Researchers have been investigating the use of fiber reinforcement in concrete to cater with its low tensile strength and energy dissipation characteristics. Therefore, in order to improve the tensile/flexural strength; ductility and fracture toughness; short length fibers have been used in concrete matrix [5]. In normal concrete construction, compressive strength is considered as an index property and the indicator of the quality, whereas in UHPC; impact resistance and fracture toughness are to be evaluated along with the other strength and durability parameters [18]. Furthermore, to prevent structural collapse and occupant injuries, structures should possess greater resistance to impact loading [19]. Ahmad et al. [6], performed a study to evaluate the performance of UHPC with varying fiber content (0, 3.1% and 6.2% by weight) and curing regimes (water cured and air cured) on the compressive strength and modulus of elasticity. It was concluded that, with an increase in fiber content, there was improvement

in compressive strength and modulus of elasticity to an extent, and this increment is not proportionally beneficial to the increase in fiber content. And the water cured specimen performed better than the air cured specimens as expected. Similarly, Azad et al. [7], reported the tensile properties of UHPC with varying fiber content (0, 3.1% and 6.2%) and wet-dry and heating-cooling cycles to simulate the local harsh environmental conditions. Split tensile and flexural properties were investigated. Prisms were used for the determination of flexural toughness, modulus of rupture and post-cracking flexural strength. UHPC with fiber content exhibited significant post-cracking strength and ductility and the tensile strength at peak load doubled with 6.2% fiber content than that of without fibers.

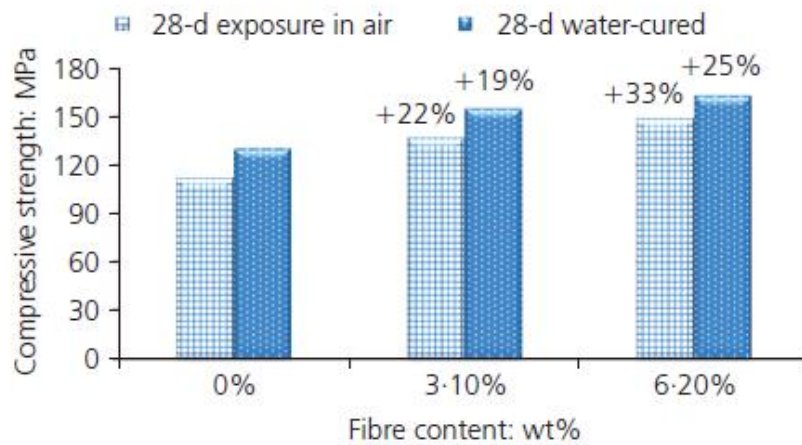


Figure 2.1: Effect of fiber content on 28-d compressive strength of UHPC (Ahmad et al. 2015)

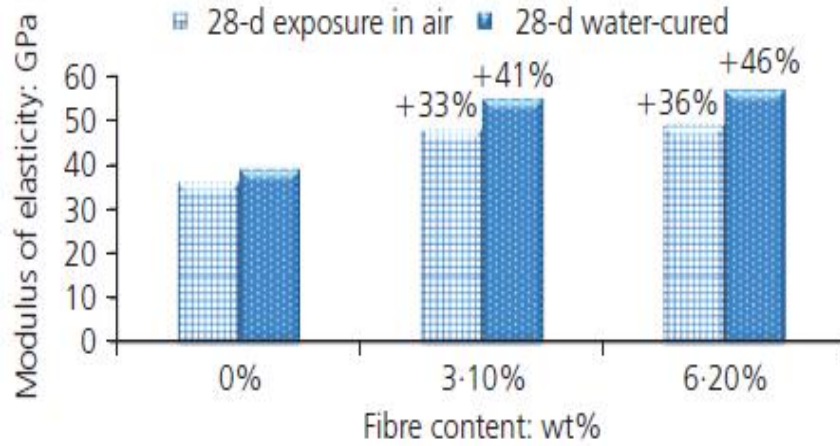


Figure 2.2: Effect of fiber content on 28-d modulus of elasticity of UHPC (Ahmad et al. 2015)

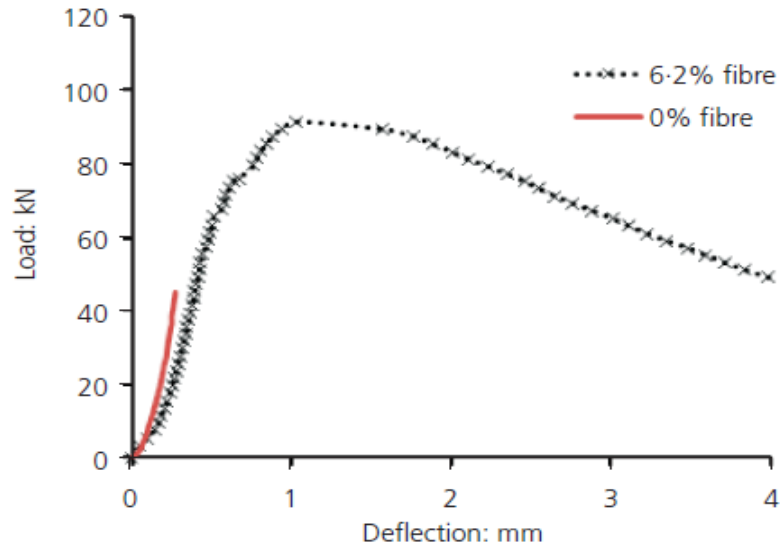


Figure 2.3: Typical load-deflection curve after 28 days of water curing (Azad et al. 2012)

Hakeem et al. [1], studied the fracture properties of UHPC with varying steel fiber content (0, 3.1% and 6.2% by weight) and thermal cycles. They performed tests on $100 \times 100 \times 400$ mm standard specimen with central notch and tested it in three-point bending test for determining critical intensity factor (K_{IC}), critical crack tip opening displacement (CTOD_c), energy release rate and total fracture energy. Two-parameter fracture model was used for the determination of fracture energy and procedure followed is given in RILEM

Committee on fracture mechanics. It was reported that there was a significant enhancement in the fracture energy and toughness with the addition of steel fibers. The critical energy release rate (G_f) was calculated to be 48 N/m for 0% fibers and 1755 and 5786 N/m for 3.1% and 6.2% fiber content respectively. As it can be observed that the fracture resistance increased in fold of orders with the addition of steel fibers. The fracture behavior of UHPC was described as the attainment of peak load by concrete matrix cracking, after which the steel fiber gets activated and the composite undergoes prolonged softening. During this period, it can carry decreased load without brittle failure, this phenomenon is commonly known as “crack bridging” as shown in Figure 2.4:

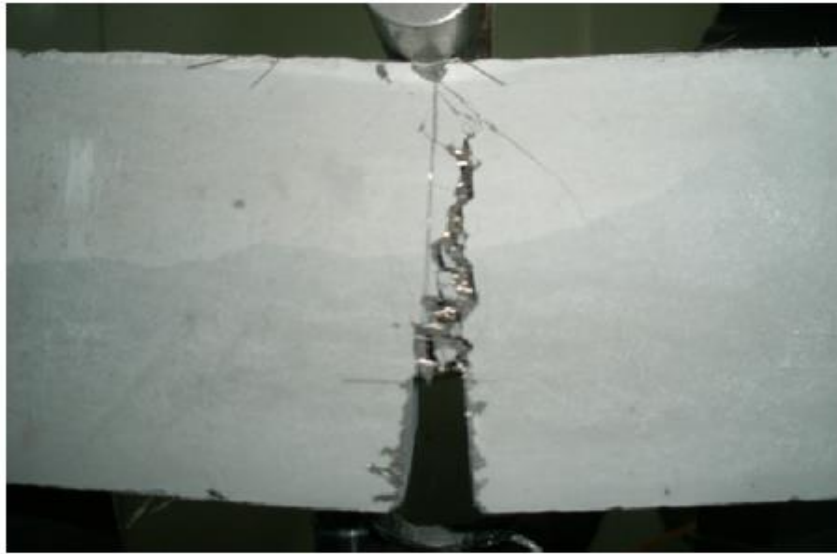


Figure 2.4: Bridging effect of fibers during fracture test (Hakeem et al. 2013)

Similar observations were reported by Yu Su et al. (2016) [48], where they considered varying fiber content (0.5%, 1% and 2.5% by volume) and different shapes and aspect ratios of steel fibers.

2.3 Experimental investigation and finite element modeling of slabs under impact loading

Researchers have been investigating the use of fiber reinforcement in concrete to cater with its low tensile strength and energy dissipation characteristics. Concrete structures are often subjected to short term dynamic loads and because of its poor impact resistance leads to the potential problems [18]. Different tests have been employed by the researchers to assess the impact resistance of fiber reinforced concrete. Following are four methods reported in the literature [18]:

- Explosive test
- Projectile impact test
- Drop weight impact test
- Charpy impact test

There is no standardized test to assess the impact resistance but ACI has suggested the drop weight impact testing for fiber reinforced concrete [18].

S. Elavenil et al. [18], investigated the dynamic behavior of steel fiber reinforced UHPC plates under impact loading. They considered 3 thicknesses (20, 25 and 30mm) with 3 different steel fiber contents (0.5, 0.75 and 1% by volume) and three aspect ratios of steel fibers (50, 75 and 100). The impact was generated using a mass of 4.3 kg dropped from a height of 4 m. the comparison was made between the energy absorbed at first and final crack, for varying steel fibers and aspect ratios. It was reported that the crack width in steel fiber reinforced concrete plates was significantly less, compared with the plates without

fibers, and the rate of decrement in crack width was higher in greater aspect ratios of steel fibers.

Petr Máca et.al. [19], performed impact test on slabs ($300 \times 400 \times 50$ mm) with deformable and non-deformable projectiles. From the mechanical testing, they concluded that 2% fiber content by volume (approx. 6.4% by weight) is optimum. The parameters for damage assessment were penetration depth, crater diameter, and loss of mass on impact. The weight of the projectile was 8.04 g and it was shot at an average velocity of 710 m/s. It was reported, that the perforation occurred in the specimens without fibers, whereas, the specimens with steel fibers did not experienced any perforation. Moreover, due to the incorporation of the fibers, the crater diameter also reduced significantly. However, very little effect was added for fiber contents beyond 2%, hence 2% fiber content (by volume) was reported to be optimal.

Ngo et.al. [49], performed experimental investigation on the blast resistance of reinforced concrete and prestressed UHPC panels. Four panels of $2\text{m} \times 1\text{m}$ with various thicknesses were subjected to 6t TNT equivalent explosion ($1\text{t TNT} = 4,184,000$ kJ of energy). Blast pressure and panel deflections were recorded for each specimen. It was reported that, 100 mm UHPC panel performed extremely well with minor cracking and 75 mm thick UHPC panel suffered moderate damage, whereas, 100 mm thick normal concrete panel was breached. The authors also developed constitutive model for concrete structures subjected to high strain rates. The numerical results were showing fair agreement with the experimentally obtained data.

Jun li et.al. [44], performed experimental program on 5 UHPC and one normal concrete slabs. The specimen size was $2000 \times 1000 \times 100$ mm. UHPC slabs were cast with 2 different reinforcement ratios (0.8 and 1.4 %). Whereas, the normal concrete slab was cast having reinforcement ratio of 0.8%. The details of the specimen and their performance under blast load is shown in the Table 2.3, reproduced by the data presented in the literature [44]. The authors, presented several comparisons, out of which our interest is between the behavior of UHPC slab and normal concrete slab. At similar reinforcement ratio (UHPC-D1 and NSC-1), it has been reported, that the slab with normal concrete failed completely when subjected to blast loading whereas, the UHPC slab with similar reinforcement ratio experienced plastic deformations but kept intact, even though when subjected to higher blast intensity.

Table 2.3: Response of slabs to blast load (Reproduced from Jun Li et.al. 2015)

Slab No.	Steel ratio (%)	Steel strength (MPa)	Charge weight (kg in TNT)	Response	Maximum Deflection (mm)	Permanent Deflection (mm)
UHPC-D1	0.8	600	14	Plastic	---	53
UHPC-D2	1.4	1750	8	Elastic	41	0
UHPC-D3A	0.8	300	1	Elastic	1	0
UHPC-D3B	0.8	300	14	Fail	---	---
UHPC-D4	0.8	300	8	Plastic	72	40
NSC-1	0.8	600	8	Fail	---	---

Duc-Kien Thai et.al. [16], performed finite element analysis to model the local damage of fiber reinforced UHPC wall caused by the impact of aircraft engine missile. Concrete

Damage Plasticity (CDP) model been used to model the complete behavior of UHPC materials. CDP was initially introduced for monotonic loading by Lubliner et al. [50]. Afterwards, Lee and Fenves [51] adopted it for cyclic and dynamic loadings. The complete mathematical formulation of CDP can be found in [50]–[52]. CDP can be used to model various types of concrete, by inputting the experimentally measured parameters. These parameters are well defined for normal concrete but the performance of UHPC is a topic of research. According to Nuclear Energy Institute (NEI), nuclear building structures are designed practically to resist aircraft crash without scabbing and perforation. NEI 07-13 [53], provides the formula for the minimum thickness of RC wall to prevent the local damage. The authors fully modelled the UHPC panel, aircraft engine model and their contact attributes. The numerical results were then compared with the experimental data produced by W. Riedel et.al. [11], based on the parametric studies performed numerically with varying panel thickness, fiber content and impact velocities. A modified equation was proposed for the minimum wall thickness to prevent perforation and scabbing of UHPC structures. The numerical results were showing fair agreement with the experimentally obtained data.

2.4 Nuclear radiation shielding of concrete

Radiation shielding ability depends upon three factors: radiation energy; density of absorbent material; and the atomic number of the elements in the protective material. The attenuation decreases with increasing radiation energy, however, the attenuation is enhanced by increasing the density of absorbent material as well as the atomic number of the elements in the absorbent material [54]. Gencel et al. [55] and Zhen et al. [56] have

concluded that, the shielding properties of the concrete can be improved by utilizing suitable materials (heavy aggregates comprising of higher atomic number) and densifying the concrete matrix by reducing the number and sizes of pores. The filler materials fill the voids in the concrete due to the fineness, and enhances the interaction between radiations and absorbent materials due to high specific surface area [56].

Conventionally, heavy weight concretes provide the resistance against nuclear radiation. Heavy weight concrete is characterized in the literature as a concrete having a dry density of 2600 kg/m^3 and higher [57]. These HWC's are produced by incorporating high-density coarse aggregates like barite, magnetite, hematite, heavy metal oxide and colemanite [24], [28]–[35]. However, The mechanical properties of these HWC's are almost similar to the normal concrete. Therefore, there is clear need to develop heavy weight concrete with enhanced mechanical, toughness and radiation shielding properties. UHPC is a promising material with very high strength and toughness properties. The durability properties of UHPC have been reported to be excellent due to its dense microstructure. It shows negligible porosity and extremely low diffusion co-efficient [58]. Apart from strength and durability performance, concrete used in the construction of nuclear power plants should have enough shielding against exposure to nuclear radiation, besides its strength and durability [27].

A thorough literature search indicate that a very few studies are reported on the development of HWUHPC that can offer radiation shielding along with an excellent performance in terms of the mechanical properties and the durability characteristics [40]. Akanshu et.al. [59] investigated the mechanical and radiation shielding properties of hybrid lead-steel reinforced concrete and reported a significant improvement in both mechanical

and radiation shielding properties. Similarly, Tufekci and Gokce [32] developed heavyweight high-performance fiber reinforced cementitious composite (HPFRCC) by using barite and granulated ferrous waste (GFW) as fine aggregates and compared the mechanical properties with the reference UHPC consist of silica sand-quartz powder blend as fine aggregates. They reported that the GFW aggregate in HPFRCC resulted in improved rheological and mechanical properties, however, the use of barite as fine aggregate reduced the mechanical properties. Moreover, Azreen et al. [60] produced UHPC for radiation shielding by incorporating high-density fine aggregates that included Amang (rich in Fe_2O_3 and TiO_2) and lead glass (rich in SiO_2 and PbO). They reported a significant increase in dry density and radiation shielding properties of modified UHPC, however, the mechanical properties were adversely affected to some extent.

As mentioned above, Tufekci and Gokce [32] and Azreen et al. [60] have attempted to produce the UHPC mixtures using high-density fine aggregates to offer the radiation shielding, however, they reported an adverse effect of the materials used as fine aggregate on the mechanical properties. In the present work, the UHPC mixture developed by the Ahmad et al. [47], was used as a basis for developing the HWUHPC mixtures incorporating hematite powder as a partial replacement of sand. Hematite powder (having Fe_2O_3 more than 90%) used in this study was selected due to its high density and very high fineness so that the dry density of the HWUHPC would be higher increasing its radiation shielding on one side and the microstructure would be densified so that the mechanical properties will remain unaffected. Several mixtures of HWUHPC were prepared to study mainly the effect of hematite content on the microstructure, dry density, the mechanical properties (compressive and tensile strengths, modulus of elasticity, and fracture toughness), radiation shielding, and impact resistance.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Methodolgy

The experimental procedures adopted during the course of this study for mechanical testing, material characterization, impact loading and radiation shielding are addressed in this chapter. In the experimental program, the performance of 9 different mixtures (1 normal concrete, 1 UHPC and 7 HWUHPC) was investigated in terms of compressive strength, flexural strength, modulus of elasticity, fracture toughness, SEM, EDS and XRD and resistance against nuclear radiation. After characterizing the concrete mixtures, slab specimens were prepared for each mixture for drop weight impact testing. Details of the specimen sizes are given in Table 3.1:

Table 3.1: Details of the specimens for testing

Test	Testing Standard	Specimen detail
Compressive strength	ASTM C39	75 × 150 mm cylinder
Flexural strength and flexural toughness (four-point bending test)	ASTM C78 and ASTM C1609	40 × 40 × 160 mm prism
Fracture toughness	RILEM Committee on Fracture Mechanics	40 × 40 × 160 mm prism (notched)
Modulus of Elasticity	ASTM C469	75 × 150 mm cylinder
Impact resistance	Drop weight Impact test	750 × 750 × 50 mm
Gamma radiation shielding	Radiation test setup	100 mm cube

3.2 Materials

3.2.1 Cement, silica fume and hematite powder

ASTM C150 Type I ordinary Portland cement (OPC) was used in all the mixtures. Silica fume (SF) with a propriety name of ELKEM[®] micro silica, a byproduct of silicon and ferrosilicon alloys was used as mineral admixture. Hematite powder (HP), a patented product of HALIBURTON with propriety name of DENSE 4[®], was used to partially replace the sand for increasing the dry density of the mixtures for satisfying the criteria of HWUHPC. Tests were conducted to determine the chemical composition, specific gravity and physical properties of OPC, SF, and HP. X-ray fluorescence (XRF) test was used to determine the chemical composition of OPC, SF and HP. Specific gravity of these ingredients was measured using Pycnometer test. BET (Brunauer, Emmett and Teller) analysis was performed to determine the specific surface area and average particle size of OPC, SF and HP. The test results pertaining to physical properties and chemical composition of OPC, SF, and HP are presented in Table 3.2 and Table 3.3, respectively.

Table 3.2: Physical properties of OPC, SF and HP

Material	Specific gravity	BJH adsorption Pore volume (cm³/g)	BJH adsorption average pore diameter (nm)	BET surface area (m²/g)	Average particle size (μm)
Cement	3.14	0.0048	9.03	1.28	8.65
SF	2.33	0.0064	14.09	2.45	2.45
Hematite	4.98	0.173	38.11	20.74	0.289

Table 3.3: Chemical composition of OPC, SF and HP

Compound	Weight (%)		
	OPC	SF	Hematite
CaO	66.78	1.24	0.96
SiO ₂	17.34	92.13	3.72
Fe ₂ O ₃	3.76	2.03	91.49
Al ₂ O ₃	4.55	0.51	1.78
K ₂ O	0.56	1.67	0.21
MgO	1.94	1.11	0.35
SO ₃	4.01	0.25	-
P ₂ O ₅	0.29	0.713	1.04
TiO ₂	0.40	-	-
Traces	0.296	0.353	0.447

It can be observed from the data in Table 3.3, that the HP has a very high Fe₂O₃ content (91.49%), as expected. Due to the presence of very high amount of Fe₂O₃ in the HP its specific gravity (around 5) is found to be about two times higher than that of the sand used in the mixtures. Furthermore, the HP is highly fine as compared to the other granular ingredients of the mixture. For example, the physical properties listed in Table 3.2, indicate that the specific surface area of HP is 16 and 8 times higher and average particle size of HP is 30 and 8 times smaller than that of OPC and SF, respectively. Due to the advantageous physical properties of the HP, when the sand will be partially replaced by HP, there will be increase in the dry density of HWUHPC mixtures (owing to higher specific gravity of the HP) and the microstructure of the HWUHPC will be densified (owing to very high fineness of HP) resulting into an enhancement of the mechanical

properties and durability characteristics. However, the higher specific surface area of the HP will slightly increase the water demand. The adverse effect of slightly increased water/binder of the HWUHPC mixtures prepared using higher dosages of HP will be compensated by the denser microstructure with higher HP content.

3.2.2 Aggregates

Coarse aggregates confirming to ASTM C33 [61], No. 7, were used for the conventional high performance concrete mixture only, whereas dune sand (characterized as fine quartz sand), was used as fine aggregate for all types of concrete mixtures. The sand was used in the natural form as aggregate due to its fine particle size, eliminating any requirement of quartz powder, mostly used along with sand, for producing UHPC mixtures. Both coarse and fine aggregates are locally available in Kingdom of Saudi Arabia in abundance. The particle size distribution of coarse aggregates and fine aggregates are given below in Table 3.4 and Table 3.5, respectively. Whereas, the specific gravity and water absorption of the aggregates are given in Table 3.6.

Table 3.4: Particle size distribution of coarse aggregates

Size (mm)	% Retained	Cumulative (% Retained)	Cumulative (% Passing)	ASTM C33 (No.7 Grading)
19	0	0	100	100
12.5	10	10	90	90-100
9.5	40	50	50	40-70
4.75	40	90	10	0-15
2.36	10	100	0	0-5

Table 3.5: Particle size distribution of fine aggregates

ASTM sieve no.	Size (mm)	Percentage passing
4	4.75	100
8	2.36	100
16	1.18	100
30	0.6	75
50	0.3	10
100	0.15	5

Table 3.6: Properties of aggregates

Aggregates	Absorption (%)	Bulk specific gravity
Coarse aggregates (Riyadh road)	2.05	2.45
Fine aggregates (dune sand)	0.6	2.65

3.2.3 Superplasticizer

A polycarboxylic-based hyper-plasticizer manufactured by BASF[®], named as Glenium 51, complying with ASTM C495 Type A and F was used to achieve the required flow (200mm $\pm$ 20mm) of the mixtures. It is available in the brownish liquid form having specific gravity just higher than that of water. Glenium 51 was acquired from a local supplier. Properties of Glenium 51, as specified by the manufacturer, are shown in the Table 3.7.

Table 3.7: Properties of Glenium 51

Property	Description
Specific gravity	$1.08 \pm 0.02 \text{ g/cm}^3$
pH at 20°C	7.0 ± 1.0
Alkali content, %	≤ 5.0
Chloride Content, %	0.6

3.2.4 Fibers

Copper-coated plain steel fibers were used as micro-reinforcement in all UHPC and HWUHPC mixtures. These fibers were imported from China. The properties of the steel fibers provided by the manufacturer are given below in Table 3.8:

Table 3.8: Properties of steel fibers

Property	Description
Tensile Strength	2500 MPa
Length	12.7 mm
Diameter	0.15 mm
Aspect ratio	65

All the ingredients of the mixtures are shown in Figure 3.1.



Figure 3.1: a) OPC, b) SF, c) HP, d) Dune sand, e) Steel fibers, f) Superplasticizer

3.3 Mix design details

As mentioned earlier, an optimum mixture of UHPC developed by the Ahmad et al. [47], was considered as the control mixture for examining the effect of fiber content as well as the effect of HP content. The mixture proportions (by weight) of the selected control UHPC mixture is as follows: OPC (1): SF (0.244): water (0.174): SP (0.045): sand (1.112): fiber (0.167 corresponding to a 6% fiber content).

In order to study the effect of fiber content on the mechanical properties of the UHPC having a HP content of 10% (that just satisfies the dry density requirement of a HWUHPC mixture), three dosages of fiber (2, 4, and 6%) were considered. Furthermore, for observing the effect of HP content on the dry density and mechanical properties of HWUHPC, five dosages of HP (10, 20, 30, 40, and 50%) were considered partially replacing the sand. All these five mixtures and the control mixture had a constant superplasticizer and fiber contents of 3.6% (by the weight of binder) and 6%, respectively. The water/binder ratio of

the HWUHPC having HP content more than 10% was slightly increased to satisfy the targeted flow (i.e., a flow value of 200 ± 20 mm obtained using flow table test) without increasing SP content.

The mixture IDs and their corresponding descriptions are given in Table 3.9.

Table 3.9: IDs and description of the mixtures

Mixture ID	Replacement of sand by HP	Fiber content	Remarks
NC	-	-	Conventional high-performance concrete with coarse aggregates
H10-2	10	2	To examine the effect of fiber content at a minimum dosage of HP
H10-4	10	4	
H10-6	10	6	
H0-6 (UHPC)	0	6	To study the effect of HP content at an optimum fiber content
H10-6	10	6	
H20-6	20	6	
H30-6	30	6	
H40-6	40	6	
H50-6	50	6	

Design of the mixtures of UHPC and HWUHPC was carried out using absolute volume equation. The conventional high-performance concrete mixture contained an OPC of 375 kg/m³, w/c ratio of 0.4, 728.2 kg of sand, 1092.3 kg of coarse aggregates, and 1.4 % superplasticizer (by weight of cement). The calculated weights of the ingredients for producing one cubic meter of UHPC and HWUHPC mixture are presented in Table 3.10.

Table 3.10: Weight of ingredients for one cubic meter of UHPC/HWUHPC

Mixture ID	Binder		Water (kg)	water/binder ratio	SP (kg)	Sand (kg)	Hematite (kg)	Fiber (kg)
	Cement (kg)	SF (kg)						
H0-6	900	220	156.8	0.14	40.32	1001.2	0	150
H10-2	900	220	156.8	0.14	40.32	929.4	207.59	50
H10-4	900	220	156.8	0.14	40.32	915.2	204.42	100
H10-6	900	220	156.8	0.14	40.32	901.0	201.24	150
H20-6	900	220	162.4	0.145	40.32	789.8	396.9	150
H30-6	900	220	173.6	0.155	40.32	671.6	578.61	150
H40-6	900	220	184.8	0.165	40.32	559.1	749.15	150
H50-6	900	220	190.4	0.17	40.32	458.9	922.48	150

3.4 Mixing procedure

Conventional concrete was mixed in a revolving drum mixer. Whereas, the mixtures of UHPC and HWUHPC were prepared in a planetary mixer, as shown in Figure 3.2. Soon after the mixture is prepared, it is tested for measuring the flow using flow table test, as shown in Figure 3.2.



Figure 3.2: Planetary mixer (left), UHPC mixture (center), flow table test (right)

Following steps were adopted for the preparation of UHPC and HWUHPC mixtures:

- Weigh the water and super-plasticizer at the start and mix them. Leave this solution for around 15 minutes.
- Start weighing the materials in the order of lighter material first followed by heavier materials. This precaution is taken in order to minimize the loss of material due to spilling of material in dry mixing.
- Put these materials one after the other into the mixing drum except fibers.
- Run the mixer for around 2 minutes for dry mixing.
- Put two-third of water with small discharge so that water can be thoroughly mixed rather than being concentrated at locations and forming lumps.
- Note the time when water is mixed.
- Keep monitoring the mixture for observing the signs of cohesiveness.
- After 8-10 minutes of first pouring of water, add half of the remaining water.

- While pouring the water in cylinder (through which water is poured into the mixing drum), use funnel and place your cylinder in a container so that the spilled water can also be utilized
- Around 15 minutes after first pour, signs of cohesive mix will be prominent and moisture traces will be visible in mixture. Then pour the remaining water and mix for another 2 minutes. The mixture will start to flow at this stage
- Dispense the steel fibers in the mixing drum and keep mixing for another 2 minutes until all fibers seems to be evenly mixed in the matrix

3.5 Casting and curing of specimen

After completion of mixing and flow test, each concrete mixture was poured into the molds within half an hour of casting to avoid excessive loss of moisture. The molds were filled with scoops and vibrated on vibrating table for achieving proper compaction, as shown in Figure 3.3. Afterwards, the specimens were covered using a plastic sheet for 24 h and then the specimens were demolded and immersed in water tank for curing.



Figure 3.3: Concrete pouring into the moulds

3.6 Testing age and representative values of the test results

All tests on hardened concrete were conducted after the water curing for a period of 28 days. The averages of the test results obtained for three replicate specimens were considered as the representative values of the test results.

3.7 Laboratory testing

Following tests were carried out on hardened concrete for characterizing the mechanical and radiation shielding properties:

- Dry unit weight
- Compressive strength
- Modulus of elasticity
- Flexural strength
- Direct tension test
- Fracture toughness
- FESEM, EDS and XRD tests
- Drop weight impact test
- Gamma radiation shielding

3.7.1 Dry unit weight test

Dry unit weight was determined using 100 mm cube specimens in accordance with ASTM C642 [62].

3.7.2 Compressive strength and modulus of elasticity tests

The compressive strength and modulus of elasticity tests were carried out as per ASTM C39 [63] and ASTM C469 [64], respectively, using the cylindrical specimens. For all the specimens, the standard size was 75 mm diameter and pre-end preparation length of 150 mm. Since the top surface of the cylinder (as cast) was not smooth and sulfur capping could not work due to the lower strength of sulfur as compared to that of the strength of UHPC/HWUHPC, top surfaces of all the specimens were ground to achieve a smooth surface for ensuring an even distribution of loading, as shown in Figure 3.4:



Figure 3.4: Mechanical grinder for smoothening the concrete casting surface

A digital compression-testing machine with a loading capacity of 3000 kN was used to apply the load at a rate of 1.5 kN/s. A load cell having a maximum capacity of 1000 kN was used to record the applied load. For recording the deformation of the specimens at an applied load, two linear variable displacement transducers (LVDTs) were installed on a frame having 87 mm gauge length that was attached to the specimens. Load cell and LVDTs were electronically attached to a digital data logger to record the load-deformation

data. The setup used for conducting compressive strength and modulus of elasticity tests is shown in Figure 3.5. A typical stress versus strain curve obtained through the compression test is also shown in Figure 3.6. The peak stresses, as indicated by the stress versus strain curves were taken as the compressive strength. The modulus of elasticity was determined using secant modulus method considering the initial straight line portion of the stress-strain curves, as shown below:

$$E = \frac{(S_2 - S_1)}{(\epsilon_2 - 0.00005)}$$

where,

E = chord modulus of elasticity, MPa,

S_2 = stress corresponding to 40 % of ultimate load (i.e. 40% of f_c'),

S_1 = stress corresponding to a longitudinal strain, ϵ_1 , of 50 millionths, MPa, and

ϵ_2 = longitudinal strain produced by stress S_2



Figure 3.5: Testing setup for compressive strength and modulus of elasticity tests

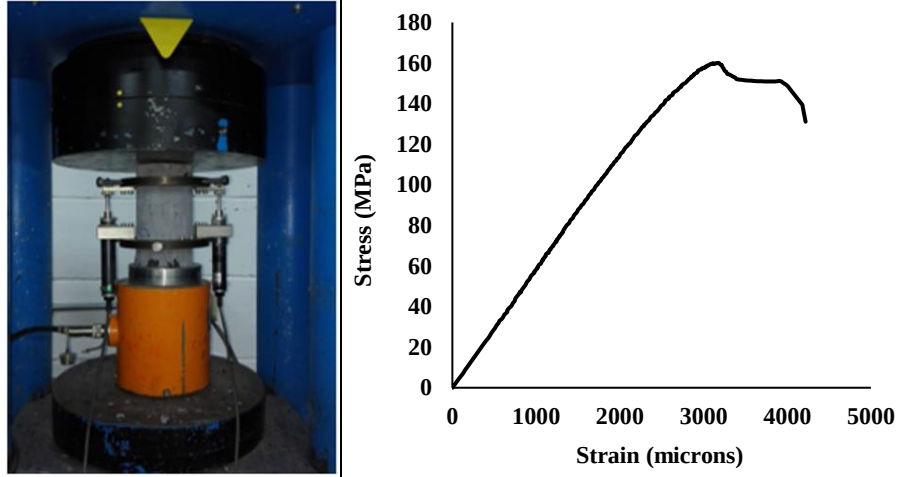


Figure 3.6: Compressive strength and modulus of elasticity test (left), typical stress-strain curve (right)

3.7.3 Flexural strength

Four-point flexural loading was applied on the prism specimens having 40×40×160 mm size in accordance with ASTM C78 [65]. The test was performed using INSTRON universal testing machine having a maximum capacity of 600 kN. LVDT was placed under the prism at the mid-span point to measure deflection corresponding to each loading interval, as shown in Figure 3.7. Loading rate was kept as 0.5 mm/min. Load-deflection data was recorded by using a digital data logger. A typical load versus deflection curve obtained through the flexural test is shown in Figure 3.7. The flexural strengths of the concrete mixtures were determined using the flexural formula considering the peak loads obtained from the load-deflection curves. Following equation was used to calculate modulus of rupture:

$$R = \frac{PL}{bd^2}$$

where,

R = modulus of rupture, MPa,

P = maximum applied load indicated by the testing machine, N,

L = span length, mm,

b = average width of specimen, mm

d = average depth of specimen, mm

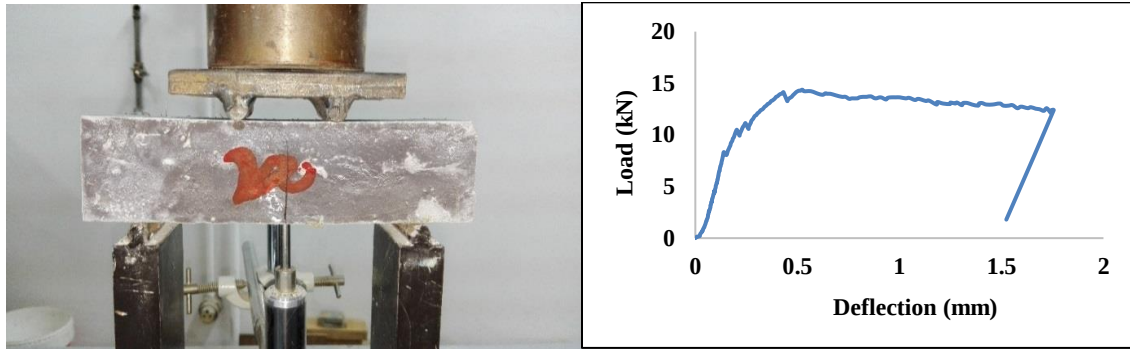


Figure 3.7: Testing setup of flexural strength (left), typical load-deflection curve obtained from data logger (right)

3.7.4 Direct tension test

Dog-bone shaped specimens were prepared for evaluating direct tensile strength and the tension damage parameters. These parameters were used in concrete damaged plasticity model in FEM. The test was performed using direct tension testing machine having a maximum capacity of 600 kN. Extensometers were placed at the locations where crack was expected to be initiated (at center of the specimen, and at the interface of the sample and CFRP wrap. Very slow loading rate(0.1 mm/min) was applied, to capture the post crack behavior. Load-deflection data was recorded by using a digital data logger. The test setup for evaluating the direct tensile strength is shown in Figure 3.8.



Figure 3.8: Testing setup of direct tensile strength

3.7.5 Fracture toughness

Fracture properties were determined using fracture toughness test developed by Jenq and Shah (1985) [66] and given in RILEM Committee on Fracture Mechanics [67]. The actual specimen size used by Jenq and Shah was $100 \times 100 \times 400$ mm with a notch created at center point, but recently smaller size single edge notch (SEN) specimens are adopted. For this reason, the specimen size used for the current study was $40 \times 40 \times 160$ mm with a 13 mm deep and 4 mm notch created at the mid of the specimen as shown in Figure 3.9:

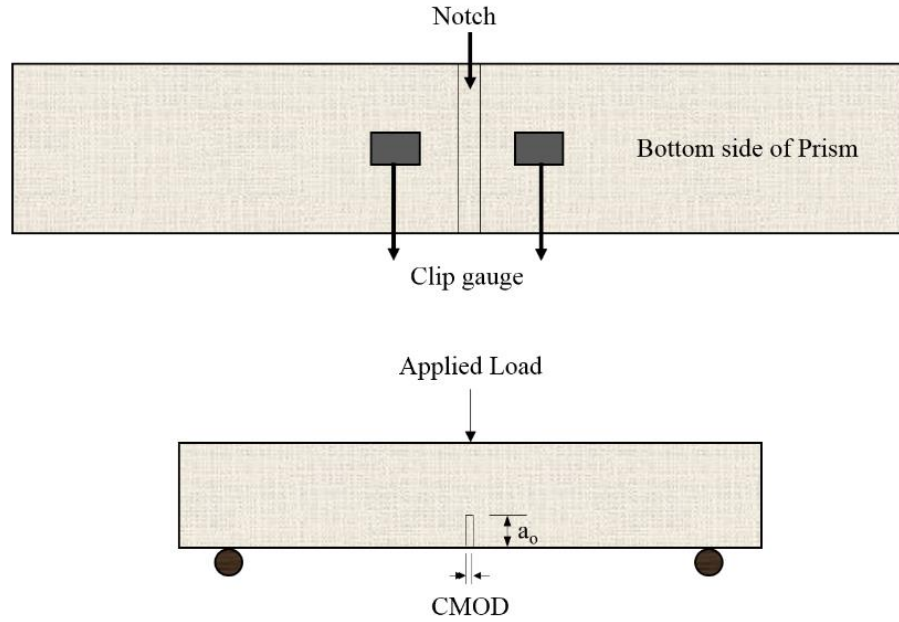


Figure 3.9: Details of SEN specimen used in fracture toughness test

For conducting this test, specimens having 40×40×160 mm dimensions were subjected to three point bending cyclic loading and the crack opening values were measured by extensometers attached to the data logger. The test was performed using INSTRON machine with a capacity of 600 kN maintaining a loading rate of 0.5 mm/min. The specimen was loaded until the peak load reached and the loading became almost constant followed by unloading the specimen. This cyclic loading and unloading were continued until a significant reduction in the peak load was observed. The applied loads and corresponding crack mouth opening displacements (CMODs) were recorded using a data logger. The experimental setup and a typical load versus CMOD curve, obtained from fracture toughness test, are shown in Figure 3.10:

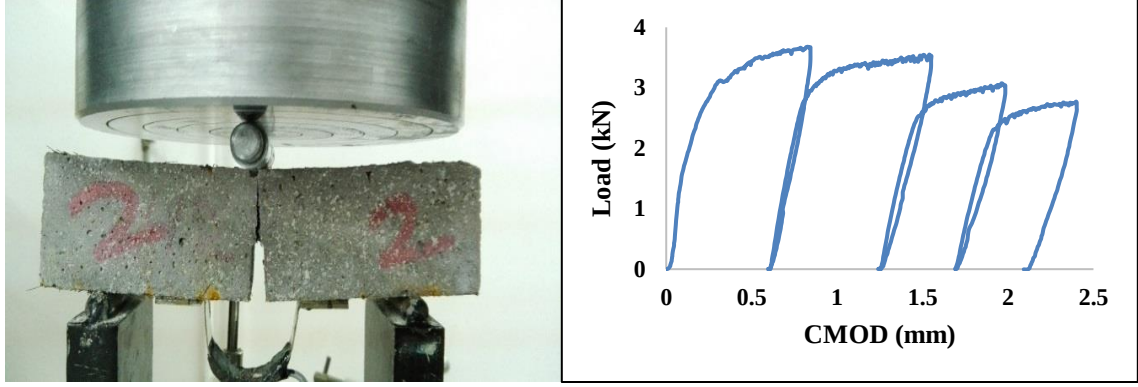


Figure 3.10: Testing setup for fracture toughness test (left), typical load versus CMOD curve (right)

Two parameter fracture model (TPFM) was used to determine the critical stress intensity factor (K_{Ic}) and critical Crack Tip Opening Displacement ($CTOD_c$). For the calculation of K_{Ic} and $CTOD_c$; critical effective length (a_c) value is to be obtained. The value of a_c was obtained by equating the concrete's modulus of elasticity in loading and unloading curve ($E = E_i = E_u$) as follows:

$$E_i = \frac{6Sa_o g_2(\alpha_o)}{C_i d^2 b} \quad \text{and} \quad E_u = \frac{6Sa_c g_2(\alpha_c)}{C_u d^2 b}$$

where,

$$\alpha_o = \frac{(a_o + HO)}{(d + HO)} \quad \text{and} \quad \alpha_c = \frac{(a_c + HO)}{(d + HO)}$$

$$g_2(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1 - \alpha^2)}$$

Where S is the span length, d and b are depth and width of prism respectively ($d=b$ as the cross section is square), α_o and α_c are initial and critical ratios of notch to depth respectively, C_i and C_u are loading and unloading compliances respectively and $g_2(\alpha)$ is the opening displacement geometric factor for SEN specimen subjected to three-point

bending loading. The C_i is the inverse of the slope of the point from 10% to 50% of the peak load. Similarly, C_u is the inverse of slope of the unloading curve between 10% and 80% of the peak load [68]. Microsoft Excel[®] solver was used to obtain the value of a_c numerically. Once the value of a_c is obtained, then the value of K_{Ic} can be calculated by the following equation:

$$K_{Ic} = 3(P_c + \frac{0.5W_oS}{L}) \frac{S \sqrt{\pi a_c g_1(\frac{a_c}{d})}}{2d^2b}$$

Where, P_c = peak load, W_o = weight of the specimen, L = length of the specimen and $g_1(a_c/d)$ = stress-intensity geometric function for SEN specimen subjected to three-point bending loading defined as follows.

$$g_1\left(\frac{a_c}{d}\right) = \frac{1.99 - \left(\frac{a_c}{d}\right)\left(1 - \frac{a_c}{d}\right)\left[2.15 - 3.93\left(\frac{a_c}{d}\right) + 2.70\left(\frac{a_c}{d}\right)^2\right]}{\sqrt{\pi}\left[1 + 2\left(\frac{a_c}{d}\right)\right]\left[1 - \left(\frac{a_c}{d}\right)\right]^{\frac{3}{2}}}$$

Moreover, the $CTOD_c$ can now be computed as follows:

$$CTOD_c = 6(P_c + \frac{0.5W_oS}{L}) \times \frac{S a_c g_2(\frac{a_c}{d})}{E d^2 b} \times \left[\left(1 - \left(\frac{a_c}{d}\right)^2\right) + \left[1.081 - 1.149\left(\frac{a_c}{d}\right)\right] \times \left[\left(\frac{a_c}{a_o}\right) - \left(\frac{a_c}{a_o}\right)^2\right] \right]^{\frac{1}{2}}$$

Finally, the relationship between K_{Ic} and critical energy release rate (G_f) is given by the following equation:

$$G_f = K_{Ic}^2 \left(\frac{1 - \nu^2}{E} \right)$$

By assuming plain strain condition and that the crack will extend along the direction of the initial crack, the above equation can be re-written as.

$$G_f = \frac{K_{1c}^2}{E}$$

3.7.6 FESEM, EDS and XRD tests

Field Emission Scanning Electron Microscope (FESEM) and Energy-Dispersive X-ray Spectroscopy (EDS) were performed to examine the microstructure and elemental composition of the mixtures, respectively. The FESEM was performed using Tescan Lyra3. LINK INCA programing system attached to Tescan Lyra3 was used for elemental analysis using EDS. A voltage of 20 kV was adopted for all the FESEM imaging and EDS analysis. Fractured samples were obtained for all mixtures and gold coating was applied in order to make them sufficiently conductive for the observations. The samples used for FESEM and EDS analysis are shown in Figure 3.11.

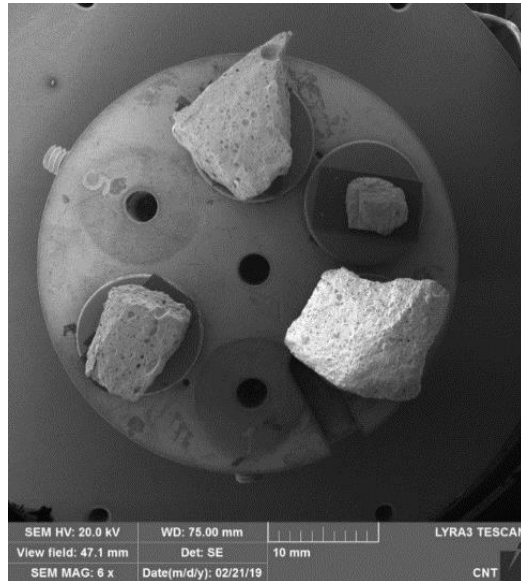


Figure 3.11: Fractured concrete samples coated with gold for FESEM and EDS analysis

The X-Ray Diffraction (XRD) test was performed to investigate the crystalline phases. Powdered samples were obtained by mechanical grinding for the XRD analysis. The XRD data were recorded on a Rigaku SmartLab machine at a scanning rate of 2°/min from 10° to 70° in the 2θ mode

3.7.7 Drop weight impact test

There is a lack of standardized method of testing and analysis, which can be used for evaluating the performance of UHPC structural members under impact loading. ACI suggests drop weight impact test to be the most appropriate method for evaluating the response of slabs under impact loads. Researchers have adopted different test setups with varying drop heights and masses based upon the size of the specimen and feasibility of testing setup.

An indigenous testing setup was designed and developed for testing slabs under impact loads. The slabs were clamped (clear span 610 mm square) over a steel frame raised above the ground such that LVDT's can be placed to monitor the deflection. LVDT's were placed under the slab at the pre-determined critical locations to monitor the deflections induced by the impact forces as shown in Figure 3.12 and Figure 3.13.

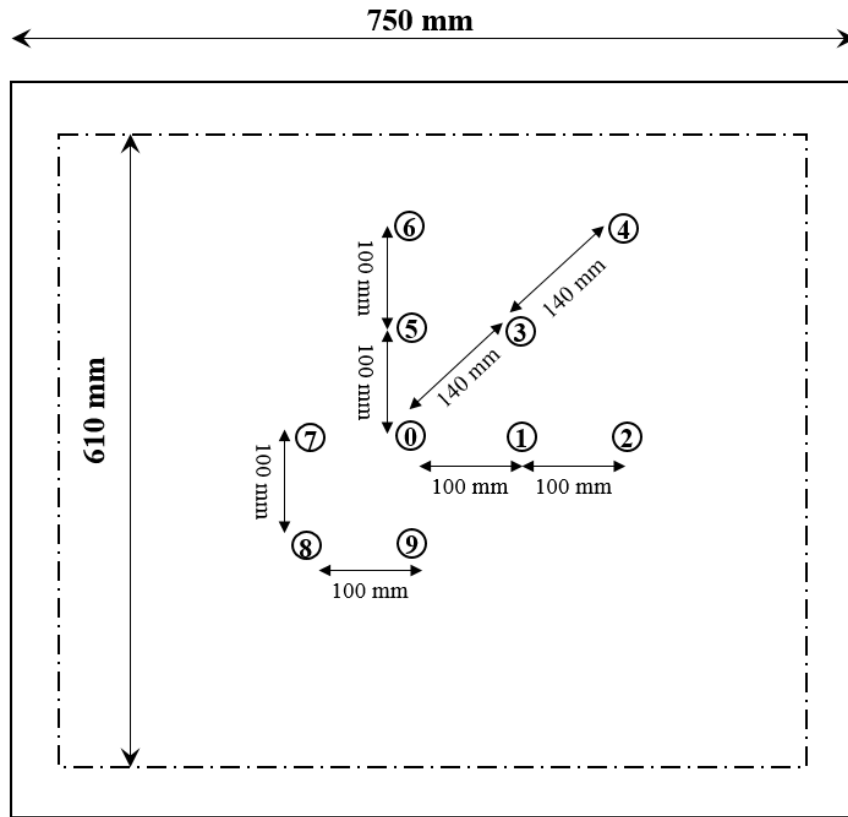


Figure 3.12: LVDT locations for measuring the deflection of slab



Figure 3.13: LVDT's under the slab for measurement of deflections

Cast iron cylindrical was used as an impact mass, and dropped at the center of $750 \times 750 \times 50$ mm slab from various pre-determined heights. Each blow height was greater than

the previous one and the test continued until the specimen showed the signs of major damage or the total 19 no. of blows were applied. (maximum number of blows of the impact test setup). The details of impactor are given in Table 3.11, and the details of drop heights and impact energy are given in Table 3.12.

Table 3.11: Impact mass details

Size of impactor	
Diameter (mm)	75
Length (mm)	600
Weight (kg)	21

Table 3.12: Loading protocols of drop weight impact test

Drop no.	Drop height (mm)	Cumulative impact energy (J)
1	600	124
2	700	268
3	800	433
4	900	618
5	1000	824
6	1100	1051
7	1200	1298
8	1300	1566
9	1400	1854
10	1500	2163
11	1600	2493

12	1750	2853
13	1900	3245
14	2050	3667
15	2350	4151
16	2500	4666
17	2650	5212
18	2800	5789
19	2950	6397

A steel guide pipe with holes at specified points was used to ensure the alignment of the impactor and to control the impact height. The guide pipe was clamped to a steel frame to keep it steady during the testing elevations. The schematic diagram of the test setup is shown in Figure 3.14.

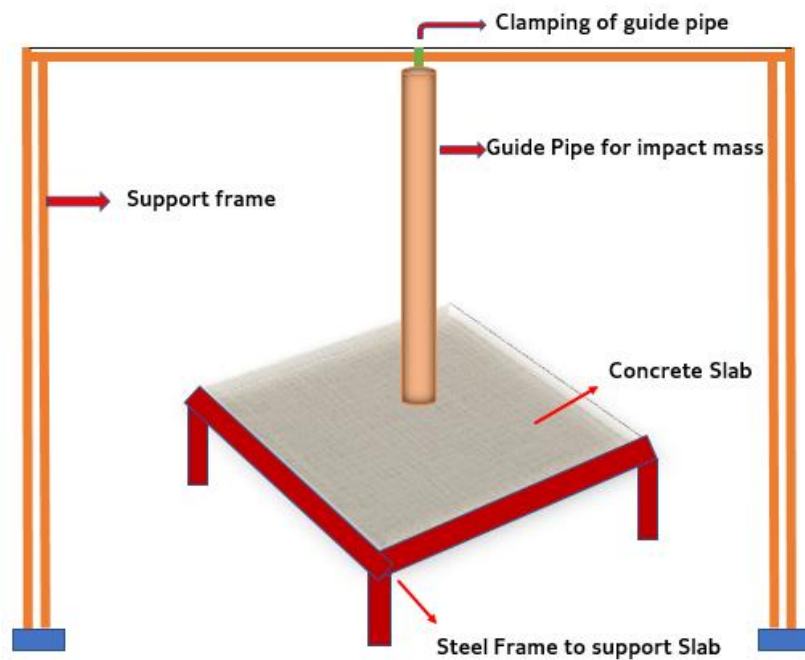


Figure 3.14: Schematic diagram of indigenous test setup for impact loading

3.7.8 Gamma radiation shielding

Concrete cube specimens of 100 mm dimension were used to evaluate the radiation shielding resistance of the concrete mixtures. The specimens were irradiated by ^{137}Cs source using the experimental setup available at Nuclear Radiation Lab at KFUPM as shown in Figure 3.15. The setup consisted of a ^{137}Cs gamma-ray source, lead collimator and a 3×3 inches Sodium Iodide (NaI) detector placed inside a lead shield. The schematic diagram of the testing setup for nuclear radiation shielding is shown in Figure 3.16.



Figure 3.15: Gamma radiation shielding test, with and without specimen

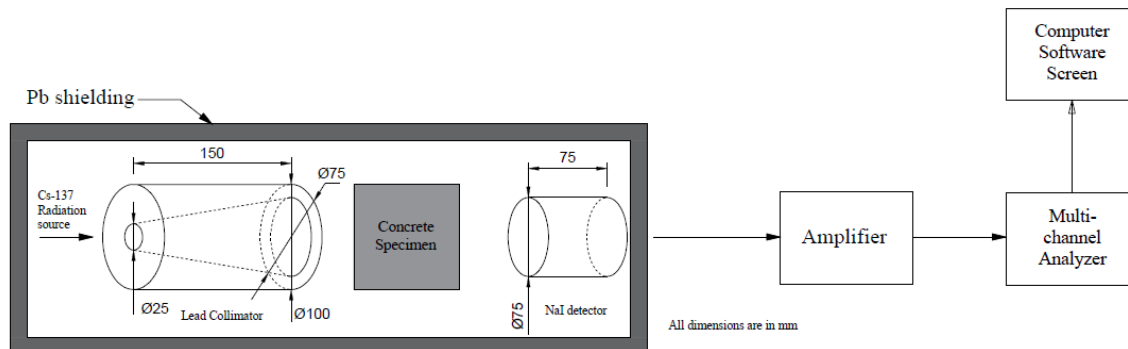


Figure 3.16: Schematic diagram of gamma radiation measurement setup

Gamma-ray source of 661 keV energy was used to irradiate the specimens. The gamma-ray spectrum was first acquired without any concrete specimen by capturing the unattenuated radiations from the Cs source using a PC based multichannel analyzer as shown in Figure 3.17. Afterwards, the specimen was placed between the radiation source and detector to obtain the attenuated gamma ray spectrum. Three replicates were tested for each concrete mixture and the average results were reported. The counting time of the radiation spectrum was kept long enough to ensure the error bar of less than 4%. The unattenuated gamma ray spectrum was obtained having a sharp peak (having 661 keV energy) as shown in Figure 3.17. Whereas, when the specimen was placed in between the radiation source and detector, the peak came down and became less sharp, indicating the attenuation of gamma radiations by the concrete specimen as shown in Figure 3.17.

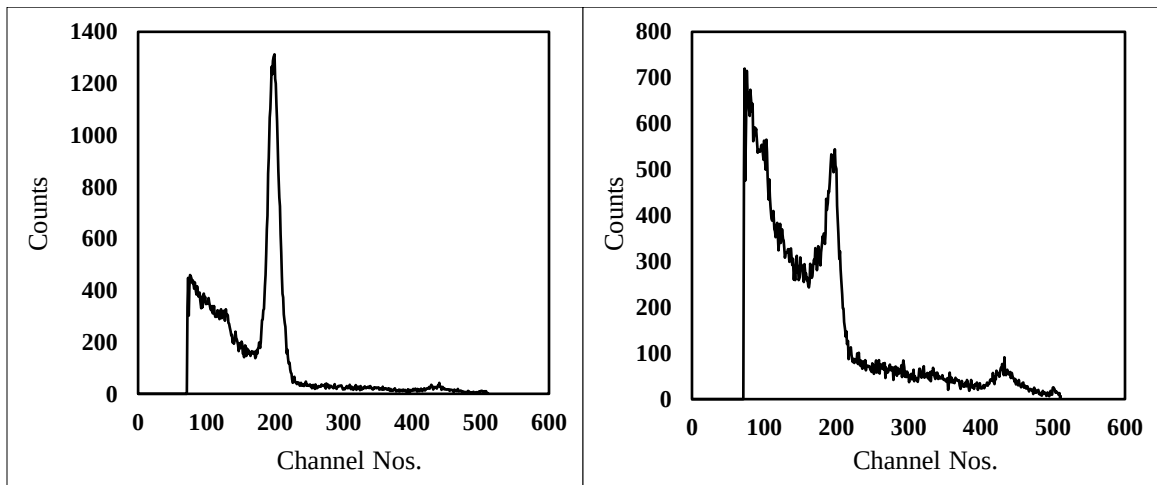


Figure 3.17: Unattenuated gamma ray spectrum of Cs-137 source (left), attenuated gamma ray spectrum of concrete specimen (right)

An adequate window on both sides of peak was selected and fixed for all the specimens to draw fair comparison (red shaded area in Figure 3.18). The width of the window was selected as such that it was larger than Full Width Half Maximum (FWHM) of the peak.

This is necessary to ensure that the complete behavior of gaussian curve is considered in the analysis. Figure 3.18 shows, a typical gamma ray spectrum attenuated by a concrete specimen.

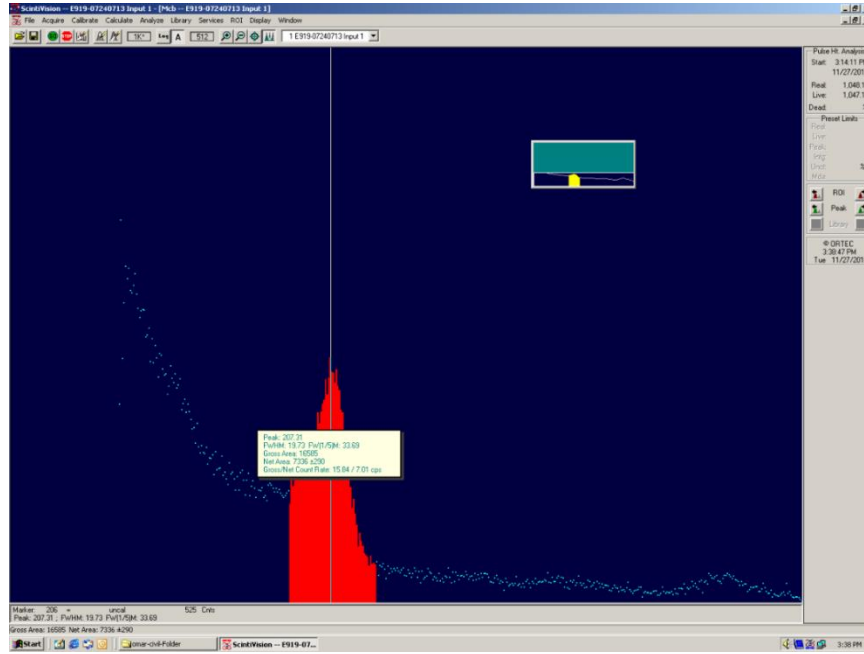


Figure 3.18: Gamma ray spectrum attenuated by a concrete sample

The area under the peak (red-shaded region shown in Figure 3.18) was integrated to calculate the gross count of the curve. It can be noticed from Figure 3.18, that the value of the count number was greater than zero at the end of the shaded region. In other words, the gaussian curve is not ending at zero and have some background count value. Therefore, these background values were subtracted from the gross count to obtain the net count values, which represents the gamma-ray transmitted intensity (I_x). These net count values were used in the calculation of attenuation coefficient and radiation shielding resistance of mixtures. The effective linear attenuation coefficient μ_{eff} , was calculated from the following relation, as given by L'Annunziata [69]

$$I_x = B I_o e^{-\mu t}$$

where,

μ = effective linear attenuation coefficient, mm^{-1}

I_x = gamma-ray attenuated intensity

I_o = gamma-ray un-attenuated intensity

B = build up factor, taken as 1 for good geometry

t = thickness of specimen, mm

Once the values of μ are obtained, then the thickness of the concrete specimen for 99% radiation attenuation ($I_x/I_o = 0.01$), can be calculated by using the same relationship given by L' Annunziata.

CHAPTER 4

DEVELOPMENT OF HWUHPC INCORPORATING

HEMATITE POWDER

The results and discussion presented in this chapter, focused mainly to investigate the effect of hematite content on the dry density, microstructure, and mechanical properties of the HWUHPC mixtures. The effect of fiber content on the mechanical properties (i.e. compressive strength, modulus of elasticity, flexural strength, and fracture toughness) of the HWUHPC (containing a minimum acceptable dosage of hematite content) is also discussed to justify the optimum dosage of the fiber to produce HWUHPC. The correlations were obtained through regression analysis between the variation in the mechanical properties with fiber content.

4.1 Flow of UHPC and HWUHPC mixtures

Flow table test was carried out on the fresh concrete as shown in Figure 3.2, to ensure that the all the mixtures meet the flow requirements in the range of $200 \text{ mm} \pm 20 \text{ mm}$. Figure 4.1 shows the plots of the flow table test results. All the UHPC and HWUHPC mixtures were found to achieve the acceptable flow.

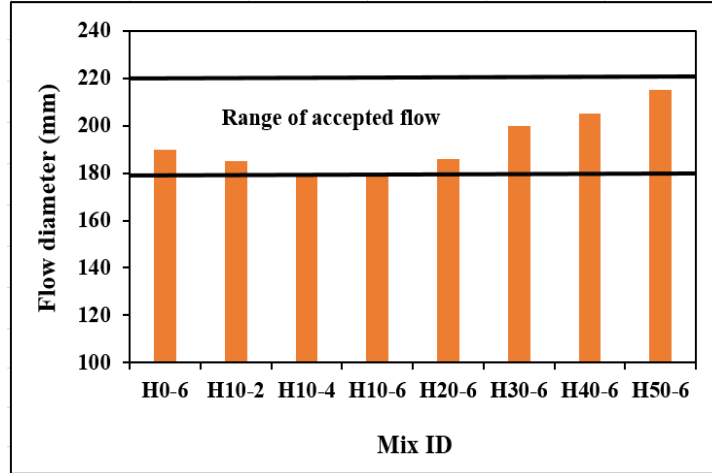


Figure 4.1: Flow table test for all mixtures

4.2 Dry density of HWUHPC mixtures

Heavy weight concrete (HWC) is characterized in the literature as a concrete having a dry density of 2600 kg/m^3 and higher [57]. From the data as shown in Figure 4.2, it is evident that all the concrete mixtures from H10-6 to H50-6 qualifies the criteria of heavy weight concrete. It can be noted that the minimum dosage of hematite powder content to produce a HWUHPC is about 10%. Further, the dry density of the HWUHPC mixtures increased linearly with increase in the hematite content.

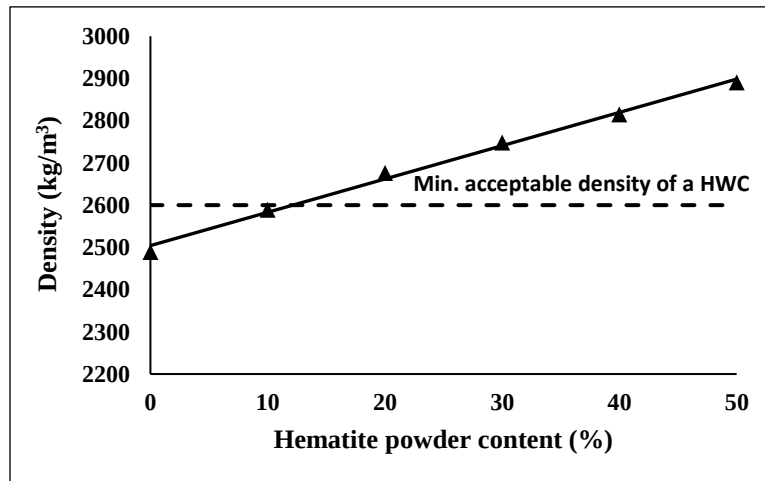


Figure 4.2: Variation of dry density with hematite content

The relationship between dry density and hematite content was obtained by regression analysis of the data shown in Figure 4.2, is given as follows:

$$\gamma = 7.89(HC) + 2504 \quad (R^2 = 0.99) \quad (4.1)$$

Eq. 4.1 can be effectively utilized to obtain the hematite content needed to achieve the targeted dry density of HWUHPC based on the requirements, for example, desirable degree of radiation shielding, in case the HWUHPC mixture is to be used in the structural elements of a nuclear installation.

4.3 Effect of hematite powder content on the microstructure of HWUHPC

As mentioned earlier, hematite powder used in the present work to develop the HWUHPC mixtures is the finest ingredient among other ingredients. It can be observed from Table 3.2, that the average particle size of hematite is almost 30 times smaller than that of the OPC. This ultra-fineness of hematite resulted into an improved particle packing and densifies the microstructure of the matrix of the HWUHPC. Microstructural analysis using the test results was performed to examine the effect of hematite powder on the morphology, elemental and mineral compositions of the HWUHPC mixtures. The results of the analysis of the microstructural information are discussed in the following subsections.

4.3.1 FESEM and EDS

The densification of the microstructure of HWUHPC mixtures due to the addition of hematite powder is evident from FESEM images of all mixtures, as shown in Figure 4.3.

The hematite powder has acted as a micro-filler material packing the voids in sand and sealing the pores in the hydrated products of the cementitious materials (i.e., OPC and SF) resulting into a highly densified microstructure. Figure 4.3 indicates that the microstructure is getting densified with an increase in the dosage of the hematite powder.

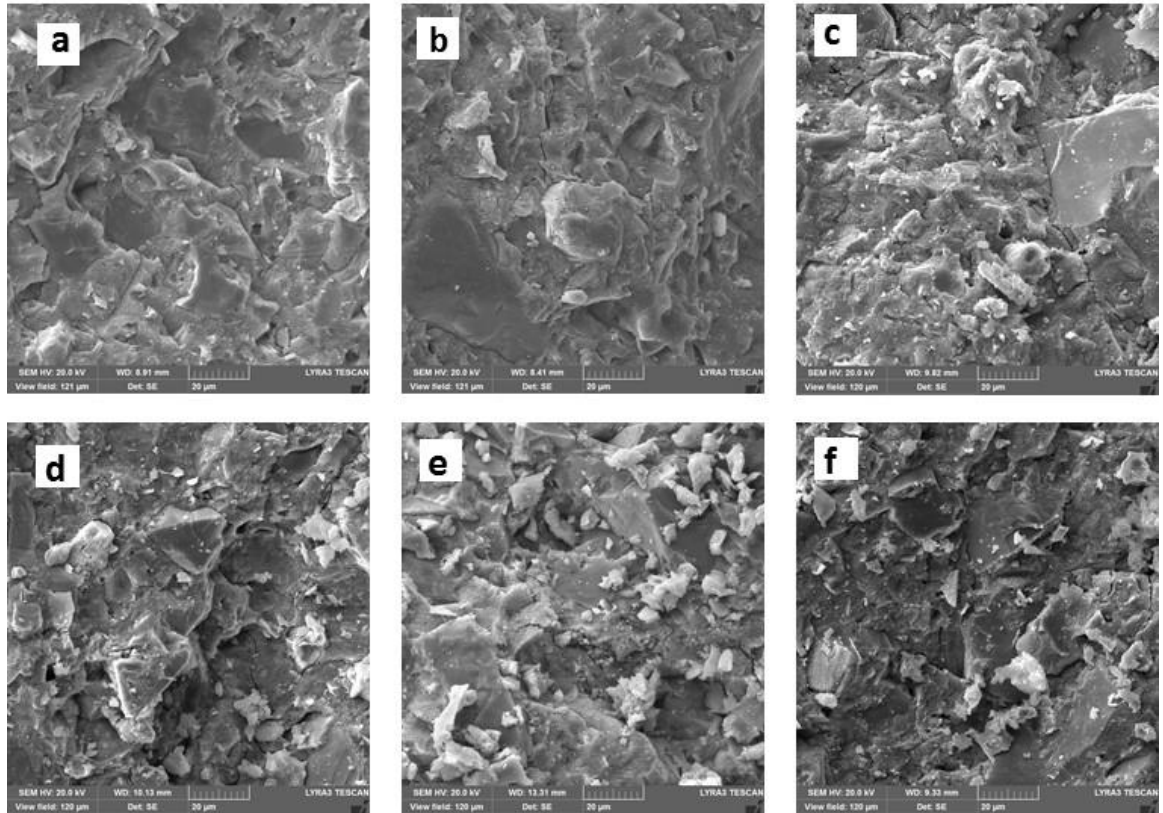


Figure 4.3: FESEM images of (a) H0-6, (b) H10-6, (c) H20-6, (d) H30-6, (e) H40-6 and (f) H50-6

The results of the EDS analysis conducted on the samples of all the mixtures of HWUHPC including the control UHPC mixture are presented in Table 4.1. A sharp increase in the quantity of iron (Fe) due to the addition of hematite powder is due to the fact that the hematite powder had a Fe_2O_3 content of 91.49%. The significant decrease in the silica (Si) content in the concrete matrix with increase in the level of replacement of sand by hematite powder is due to the fact that the sand as a major source of silica is

replaced by the hematite powder, which has a very low percentage of silica as compared to that of the sand. The results of the EDS analysis, as presented in Table 4.1, clearly indicates that the calcium and its oxides (which are responsible for achieving the strength of concrete) are not affected by the addition of hematite powder. Therefore, it can be noted that the hematite powder has no interference with the hydration of the cementitious materials rather it acts as an inert micro-filler material helping in densifying the concrete matrix that would improve the quality of the HWUHPC mixtures.

Table 4.1: EDS analysis of all mixtures

Element	Weight %					
	H0-6	H10-6	H20-6	H30-6	H40-6	H50-6
C	6.96	8.26	6.96	4.98	1.79	2.54
O	38.08	38.22	38.08	38.08	38.44	38.24
Al	1.11	1.00	1.11	1.21	1.20	1.38
Si	16.84	14.92	12.30	10.24	9.88	8.13
Ca	19.34	18.99	18.96	19.12	19.46	19.18
Fe	0.78	4.28	7.82	12.36	15.39	17.68
Au	16.87	14.30	14.74	13.89	13.84	12.81

4.3.2 XRD analysis

In order to verify the observations made through EDS analysis regarding the effect of hematite powder as an inert micro-filler material; XRD tests were performed to identify the phases developed in the matrix of UHPC and HWUHPC. Stacked XRD pattern of all the mixtures are shown in Figure 4.4.

For control UHPC mixture prepared without addition of hematite (H0-6), the peaks corresponding to Quartz (JCPDS # 00-033-1161), Calcium Oxide (JCPDS # 00-017-0912), Carbon Oxide (JCPDS # 01-071-2912) and Wustite (an oxide of iron, JCPDS # 01-074-1881) were recorded. Sharp peaks of Quartz were observed at 20.8°, 26.65°, 36.54°, 42.46°

and 50.61° corresponding to the planes (100), (101), (110), (200) and (003), respectively. Moreover, some small peaks of quartz were also observed between $50-60^\circ$. Similarly, one sharp peak of calcium oxide was observed at 29.61° corresponding to plane (131). For carbon oxide, peaks were observed at 32.15° , 33.09° , 34.2° and 36.52° corresponding to the plane (002), (121), (110) and (100), respectively. Finally, two sharp peaks of Wustite were also observed at 36.21° and 42.06° corresponding to the planes (111) and (200), respectively.

It can be seen from the analysis of XRD pattern, as shown in Figure 4.4, that the phases of Quartz, Calcium Oxide, Carbon Oxide and Wustite were developed for H10-6 mixture similar to that of control mixture (H0-6). However, an additional phase of Hematite (JCPDS # 01-072-6225) was also identified. The peaks of hematite were observed at 33.33° , 41.04° and 54.35° corresponding to the planes (104), (113) and (116), respectively. It was also observed that the number of peaks observed for Quartz in H10-6 was less than that of the control mixture (H0-6). Only two sharp peaks were observed for quartz at 20.63° and 26.38° corresponding to the planes (101) and (110), respectively. Similar trends were observed for the remaining HWUHPC mixtures (H20-6 through H50-6).

From the XRD analysis, it is evident that the hematite powder is present in the concrete matrix in its mineralogical form and acting as an inert material. Similar observations were obtained from previous characterization techniques and are verified by XRD analysis as well.

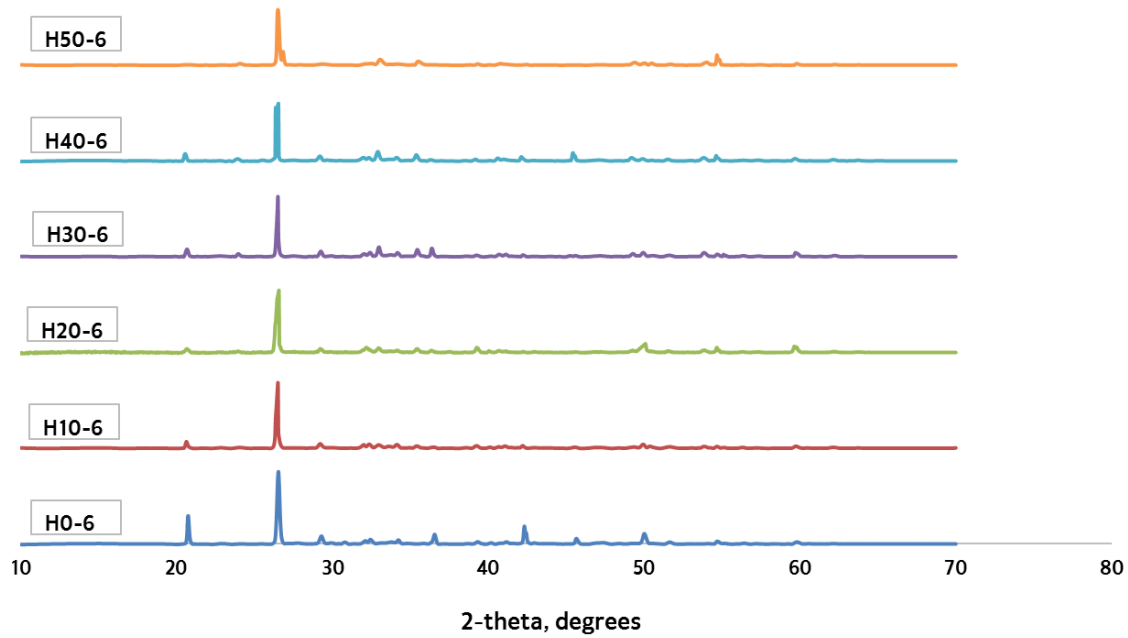


Figure 4.4: Stacked XRD pattern of all mixtures

4.4 Effect of fiber content and optimum dosage of fiber

As described earlier, three mixtures (H10-2, H10-4 and H10-6), all incorporating 10% of hematite powder but having different fiber content (2%, 4% and 6% by mass of HWUHPC) were prepared, cured and tested for studying the effect of fiber content on the mechanical properties with the main objective of obtaining an optimum fiber content for producing the HWUHPC mixtures. The steel fibers added to the UHPC mixtures act as a micro-reinforcement and allow the specimen to bear higher stresses before failure enhancing the mechanical properties of UHPC, mainly the ductility and the fracture toughness.

It can be observed from the plots of the stress-strain data, as shown in Figure 4.5, that the fiber content has effects on both, the compressive strength and the ductility of the UHPC mixtures, as evident from the higher peaks and more softening behavior with

increase in the fiber content. Similarly, the load-deflection curves obtained for different fiber contents, as shown in Figure 4.6, indicate a very significant effect of the fiber content on the flexural strength and ductility, as evident from higher peaks and more softening effect at higher fiber content. The effects of fiber content on stress-strain and load-deflection behavior are in agreement with the observations made by several researchers [1], [8], [9], [14], [48].

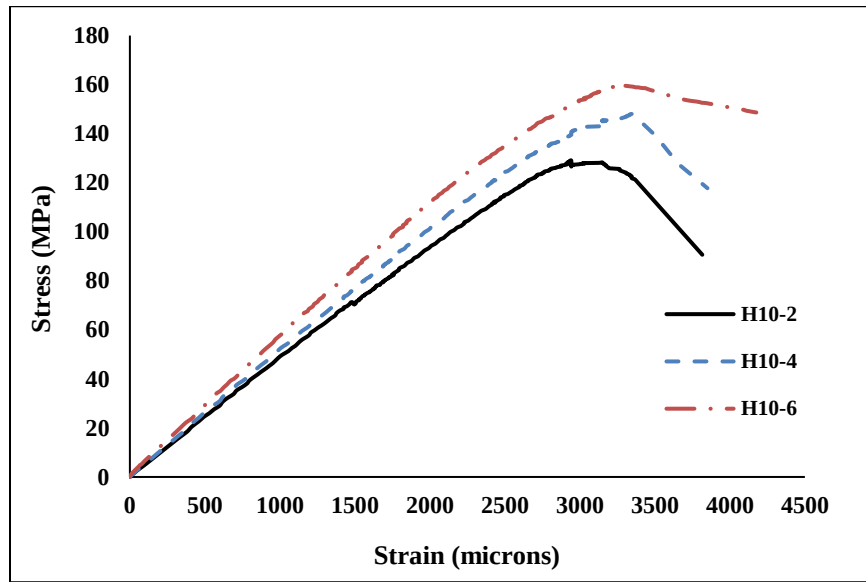


Figure 4.5: Stress-strain curves for UHPC/HWUHPC mixtures with different fiber contents

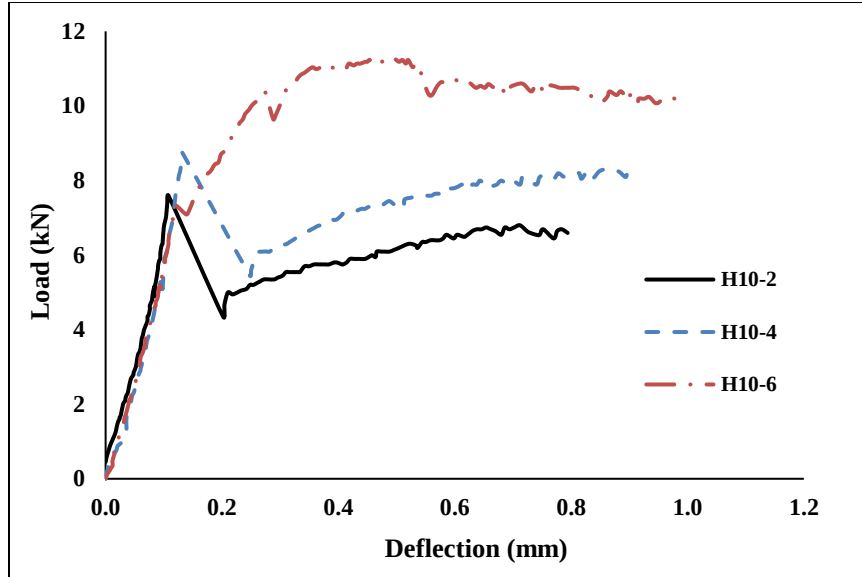


Figure 4.6: Load-deflection curves for UHPC/HWUHPC mixtures with different fiber contents

It can be noted from the stress-strain plots shown in Figure 4.5, that the compressive strength (corresponding to the peak stresses) of the HWUHPC mixtures containing 2 and 4% fibers contents are less than 150 MPa, which is the minimum acceptable value of the 28-day compressive strength of any UHPC mixture. However, the compressive strength of the HWUHPC mixture containing 6% fiber content went well above 150 MPa. Therefore, the minimum required dosage of the fiber should be taken as 6%. The performance of HWUHPC can be slightly improved by increasing the fiber content beyond 6%, however, the cost will be significantly increased. Therefore, 6% fiber content can be considered as the optimum dosage that can satisfy the requirements of strength as well as heavy weight concrete even at a minimum 10% hematite powder content

4.4.1 Correlation between fiber content and compressive strength

The variation of compressive strength with fiber content is shown in Figure 4.7. It can be observed that while the increase in the compressive strength (by 18%) when fiber

content was increased from 2 to 4%, the increase in the compressive strength was only about 6% when fiber dosage was increased from 4 to 6%. It clearly shows that the increase in compressive strength is not linearly proportional to the fiber content. These findings are consistent with the studies reported in literature [6], [48]. The relationship between compressive strength and fiber content, obtained through the regression analysis, is as follows:

$$f_c' = 114.7(FC)^{0.211} \quad (R^2 = 0.98) \quad (4.2)$$

where,

f_c' = 28-day compressive strength of HWUHPC (MPa)

FC = fiber content (% by mass of HWUHPC)

Very high value of the regression coefficient, R^2 , for Eq. 4.2 indicates an excellent degree of fit.

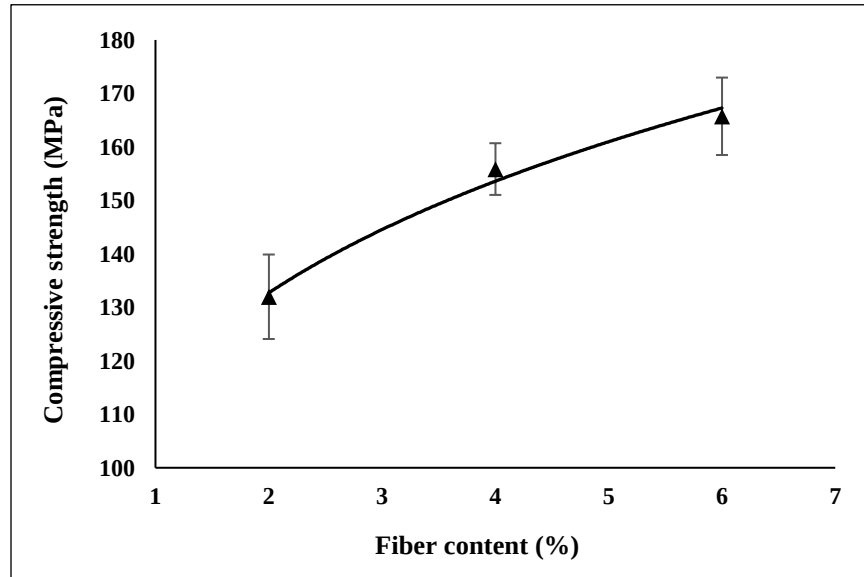


Figure 4.7: Variation of compressive strength with fiber content

4.4.2 Correlation between fiber content and modulus of elasticity

The variation of modulus of elasticity with fiber content is shown in Figure 4.8. Similar to the compressive strength, an increase in the modulus of elasticity with increase in the fiber content can be observed from Figure 4.8. However, the influence of fiber content on the compressive strength is more than that on the modulus of elasticity. It can be noted from the data plotted in Figure 4.8, that the modulus of elasticity increased by only 6% when fiber content was increased from 2 to 4% and a very little improvement in the modulus of elasticity (by 3%) when fiber content was increased from 4 to 6%, against 18 and 6% increase in the compressive strength with corresponding increase in the fiber content. It shows that the resistance of the fiber is more against crushing than its resistance against deformation. Like compressive strength, the modulus of elasticity is also not linearly proportional to the fiber content. The relationship between modulus of elasticity and fiber content, obtained using regression analysis, is given as follows:

$$E = 44.5(FC)^{0.082} \quad (R^2 = 0.99) \quad (4.3)$$

where,

E = 28-day modulus of elasticity of HWUHPC (GPa)

FC = fiber content (% by mass of HWUHPC)

Very high value of the regression coefficient, R^2 , for Eq. 4.3 indicates an excellent degree of fit.

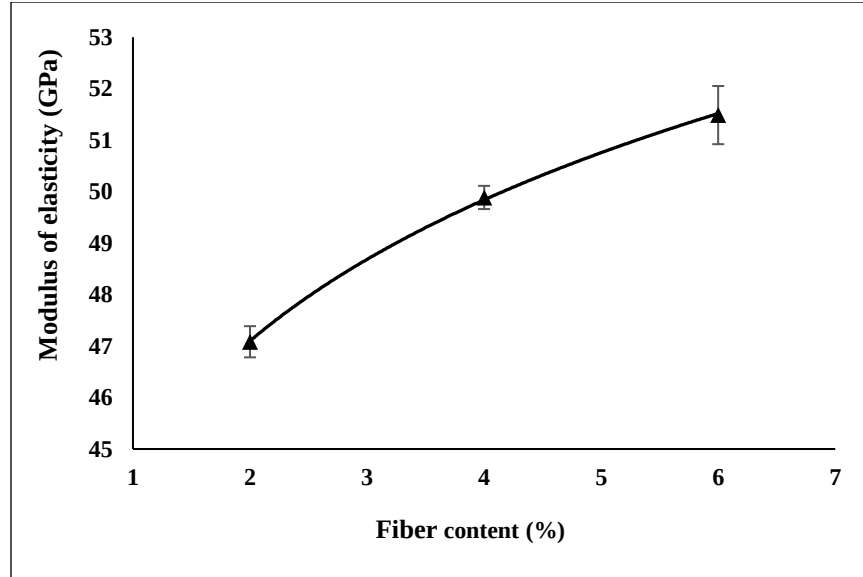


Figure 4.8: Variation of modulus of elasticity with fiber content

4.4.3 Correlation between fiber content and flexural strength

Effect of fiber content on flexural strength is shown in Figure 4.9. Like compressive strength and modulus of elasticity, the flexural strength is also increasing significantly with increase in the fiber content. However, it can be noted that the effect of the fiber content on the flexural strength is more than that on the compressive strength and modulus of elasticity. The flexural strength increased by 32% with an increase in the fiber content from 2 to 4% and the flexural strength increased by about 14% when the fiber content was increased from 4 to 6%. The high resistance of the fiber against flexural action is because of the fact that once the concrete is cracked, fibers start taking the stresses causing strain hardening, thus increasing the flexural capacity of the concrete. Similar observations have been reported in [1], [8], [9], [48], [14].

Regression analysis of the fiber content versus flexural strength data gave the following relationship between flexural strength and fiber content:

$$f_r = 10.9(FC)^{0.368} \quad (R^2 = 0.99) \quad (4.4)$$

where,

f_r = 28-day flexural strength of HWUHPC (MPa)

FC = fiber content (% by mass of HWUHPC)

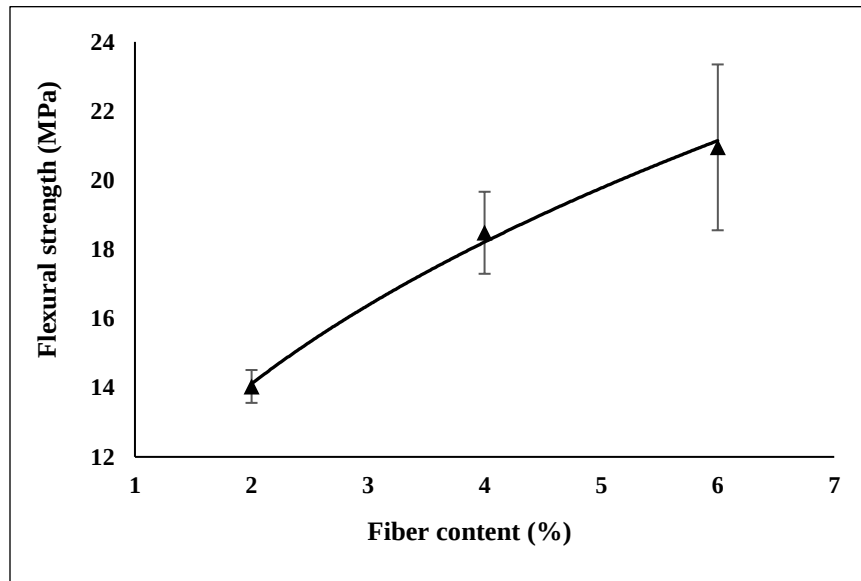


Figure 4.9: Variation of flexural strength with fiber content

Very high value of the regression coefficient, R^2 , for Eq. 4.4 indicates an excellent degree of fit.

4.4.4 Correlation between fiber content and fracture toughness

The fracture toughness of UHPC purely rely on the ability to absorb energy and restricting crack growth. Steel fibers in UHPC behave as micro-reinforcement and hence allow the structure to sustain higher impact loads with less disintegration. The positive effect of fiber content on the fracture toughness (expressed in terms of critical stress

intensity factor, K_{IC}) is evident from the plot of the results shown in Figure 4.10. Unlike the variation of the compressive strength, modulus of elasticity, and flexural strength with fiber content (showing the diminishing effect of fiber content at higher dosage), the K_{IC} increases exponentially with increase in the fiber content, as can be seen from the plot in Figure 4.10. The value of K_{IC} increased by about 100% when the fiber content was increased from 2 to 6%. Exponential increase in the fracture toughness with increase in the fiber content is attributed to the fact that the steel fibers offers a high resistance against propagation of the crack in concrete. Since the steel fibers have very high tensile strength as compared to concrete, the reinforcing action of the fibers will be higher in presence of more quantity of fibers. Similar observations have been reported in literature [1], [70]–[72].

Following relationship between K_{IC} and fiber content was obtained by regression analysis:

$$K_{IC} = 0.887e^{0.175FC} \quad (R^2 = 0.93) \quad (4.5)$$

where,

K_{IC} = 28-day critical stress intensity factor of HWUHPC ($\text{MPa}\sqrt{m}$)

FC = fiber content (% by mass of HWUHPC)

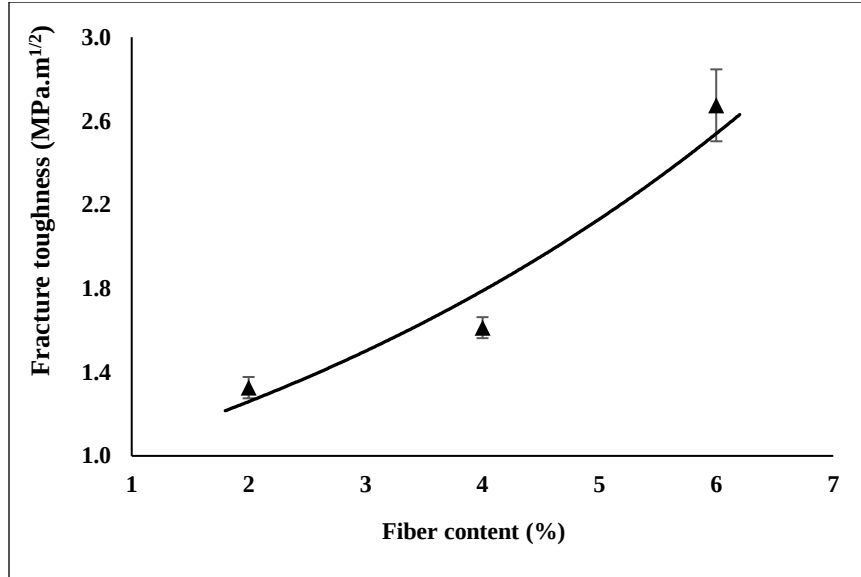


Figure 4.10: Variation of fracture toughness with fiber content

4.5 Effect of hematite powder content on the mechanical properties of HWUHPC

The stress-strain curves for all the HWUHPC mixtures including control mixture are presented in Figure 4.11. It can be observed that the HP content have no pronounced effect on the initial elastic behavior as well as post-peak ductile behavior of the mixtures. This indicates that the stress-strain behavior of all the HWUHPC mixtures is comparable with the control UHPC mixture indicating no adverse effect of incorporation of HP on the compressive strength and modulus of elasticity, rather there is slight improvement. The load-deflection curves for different dosage of HP, as shown in Figure 4.12, also indicates positive effect of replacing sand by HP instead of any adverse effect. As compared to the stress-strain behavior, there is a higher enhancement in load-deflection behavior with increase in the dosage of HP indicating slight increase in the flexural strength and ductility at higher dosages of HP. This can be attributed to the fact that there is a reduction in the

pores due to the filling effect of the ultra-fine particles of HP, offering a higher resistance against crack initiation caused by opening of the pores when flexural load is applied.

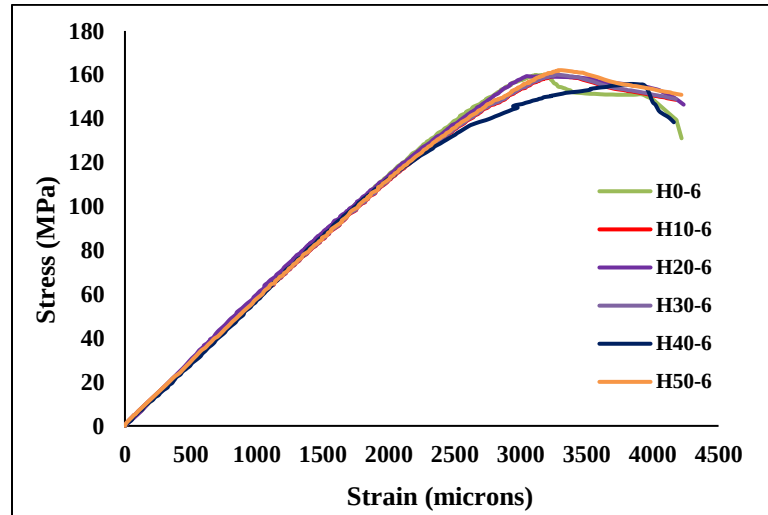


Figure 4.11: Stress-strain curves for UHPC/HWUHPC mixtures at different HP contents

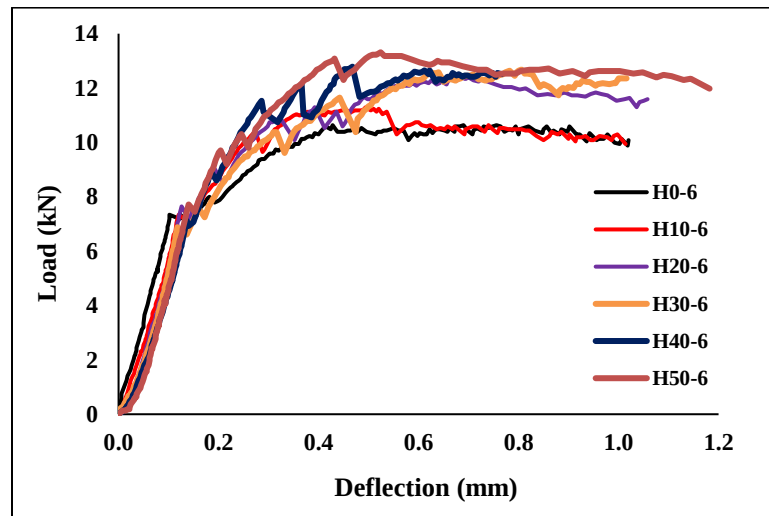


Figure 4.12: Load-deflection curves for UHPC/HWUHPC mixtures at different HP contents

From the above discussion based on the plots shown in Figure 4.11 and Figure 4.12, it is noted that the addition of hematite powder did not impair the mechanical properties of UHPC. In fact, the mechanical properties were slightly enhanced with increase in the hematite content. The plots of average values of 28-day compressive strength, modulus of

elasticity, flexural strength, and critical stress intensity factor, as shown in Figure 4.13 to Figure 4.16, indicate that while the enhancement in compressive strength and modulus of elasticity with increasing dosage of HP is negligible, the flexural strength and fracture toughness got slightly improved.

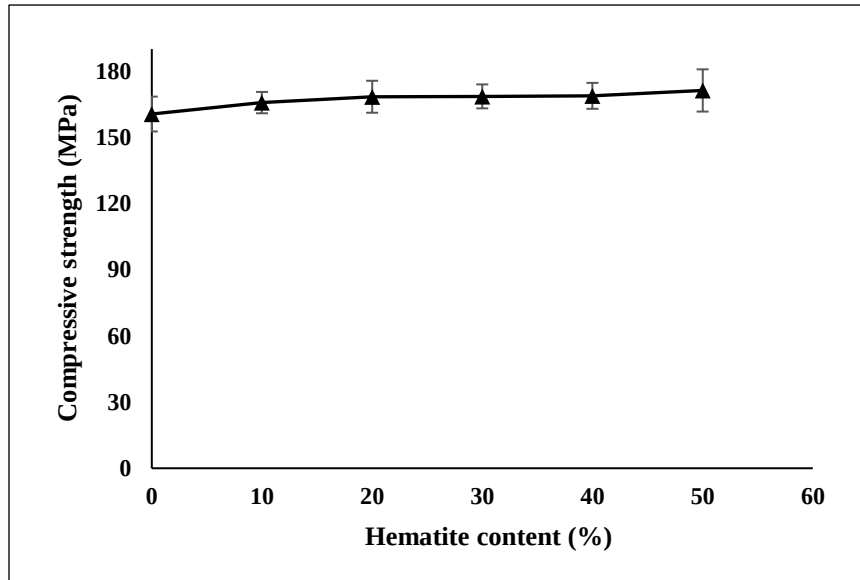


Figure 4.13: Variation of compressive strength with hematite content

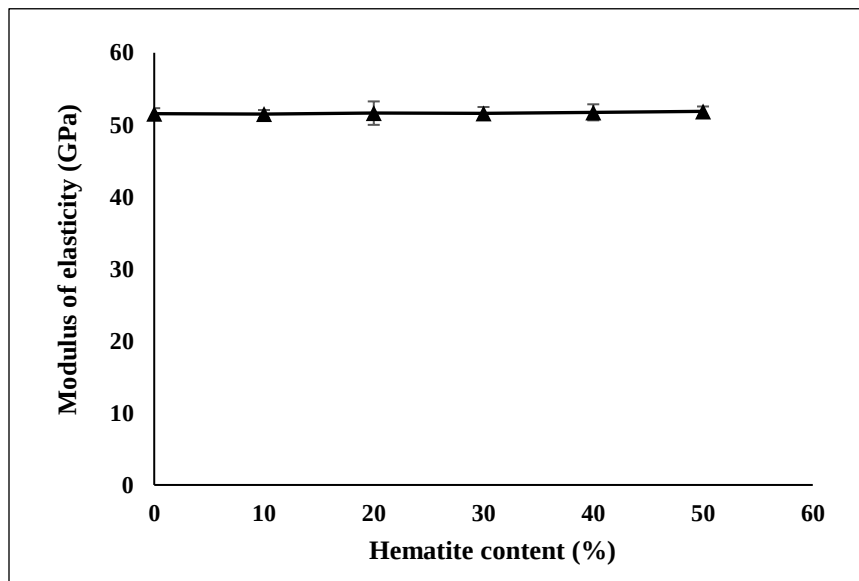


Figure 4.14: Variation of modulus of elasticity with hematite content

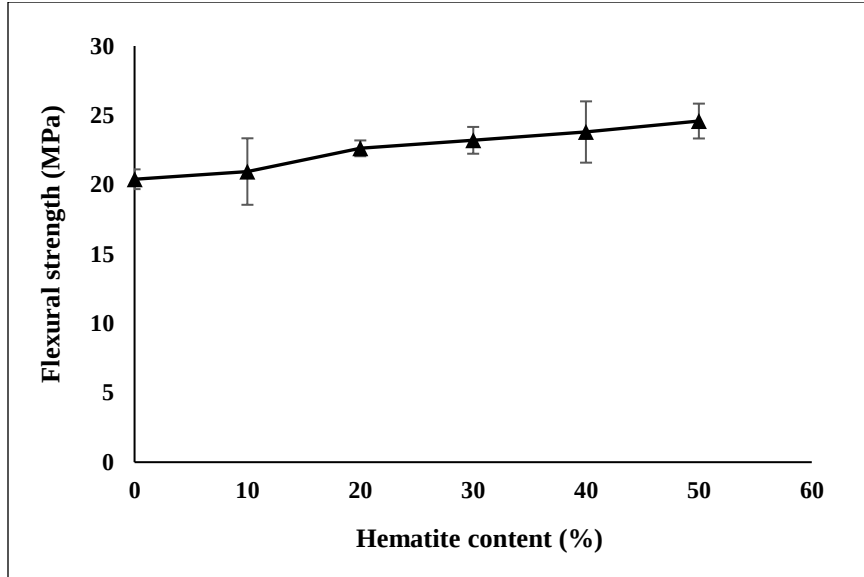


Figure 4.15: Variation of flexural strength with hematite content

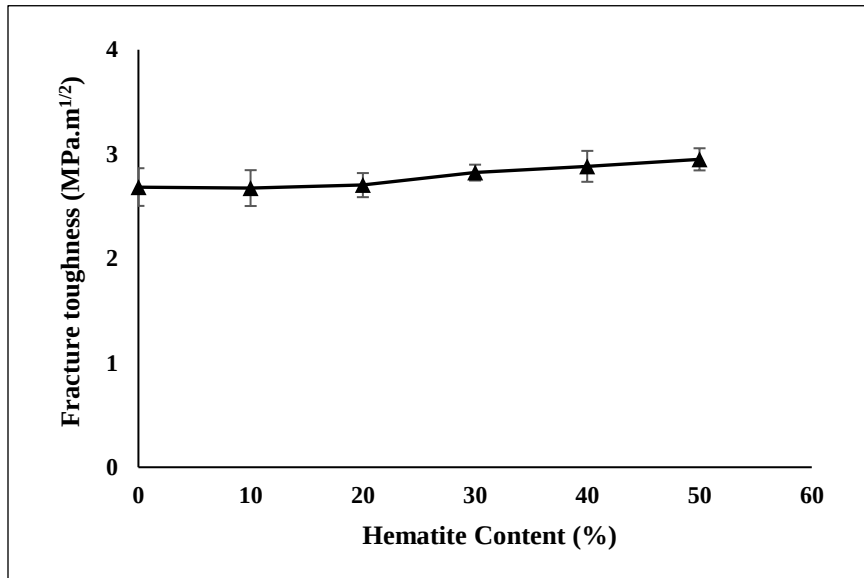


Figure 4.16: Variation of fracture toughness with hematite content

Tufekci and Gokce [32] developed heavyweight high performance fiber reinforced cementitious composites (HPFRCC) using granulated ferrous waste and barite as fine aggregate. They have also reported the enhancement of mechanical properties along with improvement in density. Since very little work had been reported in the area of

development of HWUHPC, the observations made in the present work would be useful in developing HWUHPC mixtures.

CHAPTER 5

PERFORMANCE OF HWUHPC MIXTURES UNDER

IMPACT LOADING

This chapter comprises of two portions: experimental investigations and finite element modeling. The experimental results will be presented in further two parts. In the first part; the results of the mechanical properties for all nine mixtures: i.e. dry unit weight, compressive strength, modulus of elasticity, flexural strength, direct tensile strength and fracture toughness will be presented and discussed. Moreover, the results of the impact test on slabs will be discussed in the following section.

In the second part, the finite element formulation will be explained in detail. A brief discussion is also provided regarding different modeling techniques reported in the literature for modeling the UHPC and impact loads. Finite element modeling was performed in ABAQUS® to simulate the behavior of slabs under low-velocity impact loading. Finally, the comparison between the experimental results and numerical results obtained using FEM will be presented.

The results of the mechanical properties for all mixtures are summarized in Table 5.1. The detailed discussions are given in following individual sub-sections.

Table 5.1: Mechanical properties of all concrete mixtures

Mixture ID	Dry unit weight (kg/m³)	f'_c (MPa)	E (GPa)	f_t (MPa)	Direct tensile strength, Dog-bone, f_r (MPa)	Critical Stress Intensity Factor, K_{Ic} (MPa.m^{1/2})
H0-6	2489	161	51.56	20.40	9.89	2.68
H10-2	2523	132	47.16	15.30	4.58	1.29
H10-4	2557	156	48.42	18.50	7.12	1.61
H10-6	2589	166	51.49	20.80	10.06	2.68
H20-6	2676	168	51.62	22.60	10.14	2.70
H30-6	2748	169	51.58	23.20	10.27	2.82
H40-6	2815	169	51.73	23.80	10.45	2.88
H50-6	2891	171	51.87	24.00	10.75	3.01

5.1 Mechanical properties

The mechanical properties of conventional high-performance concrete (compressive strength = 56 MPa; modulus of elasticity = 29.8 GPa; and flexural strength = 6.14 MPa), were far less than the UHPC and HWUHPC. This clear advantage of ultra-high performance concrete over conventional concrete, makes it possible to use them in vast applications where conventional concrete show limitations due to weak tensile and toughness properties, such as blast and impact loads. Heavy weight concrete (HWC) is characterized in the literature as a concrete having a dry density of 2600 kg/m³ and higher [57]. From the data presented in Table 5.1, it is evident that all the concrete mixtures from H10-6 to H50-6 qualifies the criteria of heavy weight concrete. It can be noted that the minimum dosage of hematite powder content to produce a HWUHPC is about 10%.

5.1.1 Effect of fiber content on mechanical properties

As described earlier, three mixtures (H10-2, H10-4 and H10-6), all incorporating 10% of hematite powder but having different fiber content (2%, 4% and 6% by mass) were prepared, cured and tested for studying the effect of fiber content on the mechanical properties. The steel fibers added to the UHPC mixtures act as a micro-reinforcement and allow the specimen to bear higher stresses before failure enhancing the mechanical properties of UHPC, mainly the ductility and the fracture toughness.

The variation of compressive strength with fiber content is evident from the results presented in Table 5.1. It can be observed that there was an increase in the compressive strength (by 18%) when fiber content was increased from 2 to 4%, whereas, the increase in the compressive strength was only about 6% when fiber dosage was increased from 4 to 6%. It clearly shows that the increase in compressive strength is not linearly proportional to the fiber content. These findings are consistent with the studies reported in literature [6], [48]. Similarly, an increase in the modulus of elasticity with increase in the fiber content can be observed from Table 5.1. However, the influence of fiber content on the compressive strength is more than that on the modulus of elasticity. It can be noted that the modulus of elasticity increased by only 6% when fiber content was increased from 2 to 4% and a very little improvement in the modulus of elasticity (by 3%) when fiber content was increased from 4 to 6%, against 18 and 6% increase in the compressive strength with corresponding increase in the fiber content. It shows that the resistance of the fiber is more against crushing than its resistance against axial deformation. Like compressive strength, the modulus of elasticity is also not linearly proportional to the fiber content.

The flexural strength also increased with increase in the fiber content. However, it can be noted that the effect of the fiber content on the flexural strength is more significant than that on the compressive strength and modulus of elasticity. The flexural strength increased by 32% with an increase in the fiber content from 2 to 4% and the flexural strength increased by about 14% when the fiber content was increased from 4 to 6%. The high resistance of the fiber against flexural action is because of the fact that once the concrete is cracked, fibers start taking the stresses causing strain hardening, thus increasing the flexural capacity of the concrete. Similar observations have been reported in [1], [8], [9], [48], [14]. Furthermore, the effect of fiber content is even more pronounced in direct tensile strength obtained from dog-bone test. The direct tensile strength increased by 55% with an increase in the fiber content from 2 to 4% and the increased was about 41% when the fiber content was increased from 4 to 6%. This is consistent with the nature of the test, where in later, fibers are directly active in resisting the load through the bond between fibers and the concrete matrix. The fracture toughness of UHPC purely rely on the ability to absorb energy and restricting crack growth. Steel fibers in UHPC behave as micro-reinforcement and hence allow the structure to sustain higher impact loads with less disintegration. The positive effect of fiber content on the fracture toughness (expressed in terms of critical stress intensity factor, K_{IC}) is evident from the results shown in Table 5.1. Unlike the variation of the compressive strength, modulus of elasticity, and flexural strength with fiber content (showing the diminishing effect of fiber content at higher dosage), the K_{IC} increases exponentially with increase in the fiber content. The value of K_{IC} increased by about 100% when the fiber content was increased from 2 to 6%. Exponential increase in the fracture toughness with increase in the fiber content is attributed to the fact that the steel fibers

offers a high resistance against propagation of the crack in concrete. Since the steel fibers have very high tensile strength as compared to concrete, the reinforcing action of the fibers will be higher in presence of more quantity of fibers. Similar observations have been reported in literature [1], [70]–[72]

5.1.2 Effect of HP content on mechanical properties

The addition of hematite powder did not impair the mechanical properties of UHPC. In fact, the mechanical properties were slightly enhanced with increase in the hematite content. It is evident from the results presented in Table 5.1, that while the enhancement in compressive strength and modulus of elasticity with increasing dosage of HP is negligible, the flexural strength and fracture toughness got slightly improved. This could be attributed to the very fine particle size of the hematite powder, which acts as an inert ultra-fine filler material and densifies the concrete matrix by improved particle packing. Tufekci and Gokce [32] developed heavyweight high performance fiber reinforced cementitious composites (HPFRCC) using granulated ferrous waste and barite as fine aggregate. They have also reported the enhancement of mechanical properties along with improvement in dry density. Since very little work had been reported in the area of development of HWUHPC, the observations made in the present work would be useful in developing HWUHPC mixtures.

5.2 Impact test on slab specimen

The measurements of the deflections were recorded after each drop at 10 pre-determined locations under the slabs as shown in Figure 3.12. As the conventional concrete

has significantly low toughness properties in comparison to UHPC, therefore, the loading protocols were altered (reduced) to capture the behavior of deflections under impact loads and the test was started from smaller drop heights. The results of all slabs are presented in Table 5.2 to Table 5.10. The drop number corresponds to the loading protocol presented in Table 3.12. The effect of fiber content and hematite powder content on the impact performance of slabs are discussed in following individual sections.

Table 5.2: Displacement results of slab H10-2

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.78	0.46	0.01	0.27	0.01	0.45	0.01	0.44	0.29	0.49
2	1.67	1.08	0.08	0.69	0.07	1.05	0.07	1.03	0.72	1.13
3	2.59	1.74	0.48	1.20	0.46	1.69	0.48	1.66	1.19	1.80
4	3.53	2.65	0.99	2.09	0.96	2.56	1.43	2.53	2.06	2.74
5	4.62	3.62	1.63	3.02	1.58	3.51	2.40	3.47	3.04	3.76
6	5.76	4.73	2.46	4.01	2.41	4.47	3.51	4.43	4.13	4.72
7	7.10	5.91	3.61	5.19	3.35	5.76	4.71	5.64	5.39	6.13
8	8.95	7.51	4.99	6.61	4.64	7.11	6.69	6.87	6.71	7.61

Table 5.3: Displacement results of slab H10-4

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.01	0.11	0.03	0.04	0.06	0.10	0.03	0.10	0.04	0.11
2	0.03	0.14	0.06	0.08	0.16	0.13	0.06	0.13	0.09	0.14
3	0.44	0.24	0.17	0.20	0.25	0.23	0.17	0.22	0.20	0.24
4	0.98	0.36	0.31	0.35	0.38	0.34	0.31	0.34	0.36	0.36
5	1.52	0.67	0.49	0.66	0.52	0.64	0.47	0.64	0.66	0.66
6	2.17	1.00	0.77	0.99	0.76	0.96	0.73	0.96	0.98	1.00
7	2.97	1.38	1.15	1.38	1.05	1.33	1.12	1.36	1.35	1.40
8	3.78	1.89	1.57	1.89	1.36	1.82	1.55	1.89	1.81	1.94
9	4.60	2.40	2.08	2.40	1.85	2.31	2.07	2.42	2.31	2.46
10	5.56	3.27	2.95	3.28	2.71	3.20	2.94	3.27	3.18	3.31
11	6.76	4.34	4.02	4.35	3.77	4.30	4.03	4.31	4.23	4.35
12	10.65	7.88	6.20	7.05	5.21	7.91	6.26	7.74	6.87	7.64

Table 5.4: Displacement results of slab H10-6

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.15	0.13	0.10	0.12	0.08	0.13	0.09	0.13	0.13	0.12
2	0.32	0.30	0.25	0.30	0.19	0.29	0.24	0.29	0.30	0.28
3	0.63	0.60	0.40	0.58	0.31	0.59	0.39	0.57	0.59	0.55
4	1.05	0.96	0.71	0.92	0.45	0.96	0.69	0.91	0.94	0.88
5	1.52	1.36	1.08	1.30	0.64	1.34	1.05	1.29	1.33	1.25
6	2.03	1.79	1.51	1.73	0.83	1.76	1.46	1.70	1.77	1.65
7	2.57	2.27	1.93	2.18	1.03	2.21	1.87	2.16	2.23	2.09
8	3.14	2.79	2.44	2.70	1.26	2.72	2.37	2.65	2.75	2.57
9	3.81	3.32	2.96	3.22	1.50	3.29	2.87	3.15	3.28	3.05
10	4.55	3.86	3.48	3.75	1.76	3.88	3.37	3.67	3.83	3.55
11	5.29	4.42	4.03	4.31	2.05	4.42	3.91	4.20	4.39	4.07
12	6.16	5.08	4.60	4.92	2.41	5.05	4.46	4.82	5.02	4.67
13	7.47	5.76	5.22	5.58	2.81	5.72	5.07	5.47	5.69	5.30
14	8.88	6.82	6.04	6.51	3.26	6.75	5.85	6.48	6.64	6.28
15	10.45	7.90	6.89	7.47	3.72	7.77	6.68	7.50	7.62	7.26
16	12.26	8.98	7.82	8.48	4.37	8.81	7.58	8.53	8.65	8.26
17	14.14	10.50	8.83	9.75	5.16	10.28	8.56	9.98	9.94	9.66
18	17.43	12.26	10.11	11.14	6.19	12.18	9.81	11.64	11.36	11.28
19	21.51	14.25	11.96	13.04	7.99	14.14	11.60	13.54	13.30	13.11

Table 5.5: Displacement results of slab H20-6

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.10	0.04	0.02	0.03	0.02	0.03	0.02	0.03	0.03	0.03
2	0.34	0.23	0.09	0.15	0.04	0.21	0.08	0.20	0.15	0.22
3	0.65	0.45	0.18	0.34	0.08	0.41	0.17	0.39	0.33	0.42
4	1.01	0.73	0.28	0.54	0.12	0.66	0.26	0.62	0.53	0.66
5	1.38	1.03	0.44	0.84	0.20	0.93	0.40	0.90	0.82	0.97
6	1.80	1.43	0.60	1.22	0.35	1.29	0.55	1.27	1.19	1.35
7	2.27	1.89	0.79	1.64	0.52	1.70	0.73	1.73	1.61	1.85
8	2.80	2.37	1.04	2.08	0.72	2.13	0.96	2.23	2.04	2.39
9	3.35	2.88	1.37	2.53	0.93	2.59	1.26	2.67	2.48	2.85
10	3.92	3.40	1.83	2.99	1.26	3.06	1.68	3.11	2.93	3.33
11	4.66	4.03	2.37	3.58	1.63	3.63	2.18	3.65	3.51	3.91
12	5.64	4.72	2.95	4.23	2.14	4.25	2.71	4.20	4.15	4.49
13	6.66	5.72	3.52	4.94	2.65	5.15	3.24	5.08	4.84	5.43
14	8.13	6.86	4.13	5.97	3.24	6.17	3.80	6.16	5.85	6.59
15	9.78	8.31	4.94	7.09	3.86	7.48	4.54	7.40	6.94	7.92
16	11.69	9.78	5.83	8.22	4.47	8.80	5.37	8.65	8.06	9.25
17	13.78	11.75	6.84	9.82	5.45	10.57	6.29	10.32	9.62	11.04
18	17.24	14.20	8.68	11.67	6.51	12.78	7.99	12.40	11.43	13.27
19	21.52	17.18	10.57	13.76	8.37	15.46	9.72	14.93	13.49	15.98

Table 5.6: Displacement results of slab H30-6

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.20	0.13	0.08	0.10	0.00	0.00	0.09	0.00	0.11	0.00
2	0.41	0.29	0.21	0.25	0.06	0.06	0.21	0.07	0.26	0.06
3	0.72	0.52	0.42	0.48	0.25	0.29	0.43	0.31	0.49	0.27
4	1.09	0.76	0.64	0.72	0.44	0.53	0.66	0.56	0.72	0.49
5	1.50	1.03	0.89	0.98	0.64	0.80	0.91	0.84	0.98	0.72
6	1.98	1.37	1.14	1.29	0.84	1.14	1.17	1.20	1.27	1.04
7	2.49	1.73	1.40	1.61	1.05	1.50	1.42	1.58	1.58	1.37
8	3.01	2.16	1.66	1.93	1.25	1.93	1.67	2.02	1.89	1.75
9	3.57	2.70	1.95	2.26	1.49	2.48	1.96	2.61	2.23	2.26
10	4.13	3.25	2.28	2.63	1.79	3.05	2.27	3.20	2.62	2.77
11	4.70	3.82	2.61	3.01	2.09	3.61	2.60	3.79	3.01	3.29
12	5.37	4.39	2.97	3.43	2.43	4.18	2.95	4.39	3.44	3.80
13	6.26	5.00	3.35	3.90	2.79	4.79	3.31	5.03	3.92	4.36
14	7.68	5.69	3.90	4.51	3.27	5.41	3.84	5.68	4.51	4.92
15	9.23	6.50	4.53	5.21	3.83	6.22	4.46	6.53	5.19	5.66
16	11.10	7.81	5.24	6.10	4.46	7.53	5.15	7.91	6.05	6.85
17	13.08	9.46	6.01	7.03	5.21	9.18	5.97	9.64	6.95	8.36
18	15.51	11.85	7.24	8.57	5.98	11.57	7.30	12.15	8.45	10.53
19	20.19	15.76	10.37	12.16	6.89	15.16	10.30	15.91	11.75	13.79

Table 5.7: Displacement results of slab H40-6

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.12	0.09	0.02	0.06	0.02	0.08	0.02	0.09	0.06	0.08
2	0.36	0.20	0.04	0.14	0.04	0.19	0.04	0.20	0.14	0.18
3	0.60	0.34	0.10	0.27	0.08	0.31	0.10	0.33	0.26	0.29
4	0.88	0.50	0.19	0.41	0.12	0.46	0.19	0.48	0.40	0.43
5	1.24	0.72	0.33	0.57	0.19	0.66	0.32	0.69	0.56	0.61
6	1.64	0.96	0.50	0.77	0.35	0.88	0.48	0.92	0.75	0.82
7	2.07	1.27	0.71	1.02	0.53	1.17	0.69	1.23	0.99	1.09
8	2.71	1.62	0.95	1.31	0.73	1.49	0.92	1.56	1.27	1.39
9	3.52	2.10	1.21	1.64	0.95	1.93	1.17	2.03	1.59	1.80
10	4.39	2.61	1.47	1.97	1.19	2.40	1.41	2.52	1.91	2.27
11	5.31	3.13	1.81	2.31	1.46	2.90	1.73	3.04	2.24	2.77
12	6.40	3.67	2.17	2.85	1.78	3.40	2.06	3.57	2.77	3.27
13	7.97	4.54	2.85	3.66	2.25	4.20	2.69	4.41	3.55	4.07
14	9.86	5.72	3.78	4.73	2.81	5.29	3.56	5.55	4.59	5.12
15	11.95	7.17	4.80	6.05	3.43	6.61	4.51	6.95	5.98	6.40
16	14.23	9.01	6.15	7.65	4.11	8.31	5.76	8.73	7.65	8.04
17	16.78	11.08	7.73	9.49	5.28	10.22	7.37	10.73	9.58	9.88
18	17.43	12.26	10.11	11.14	6.19	12.18	9.81	11.64	11.36	11.28
19	21.19	14.04	11.78	12.84	7.87	13.92	11.43	13.34	13.10	12.92

Table 5.8: Displacement results of slab H50-6

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.12	0.09	0.02	0.06	0.02	0.08	0.02	0.09	0.06	0.08
2	0.37	0.21	0.05	0.15	0.04	0.19	0.05	0.20	0.14	0.18
3	0.61	0.35	0.10	0.28	0.08	0.32	0.10	0.34	0.27	0.30
4	0.91	0.51	0.20	0.42	0.12	0.47	0.20	0.49	0.41	0.44
5	1.28	0.74	0.34	0.59	0.19	0.68	0.33	0.71	0.57	0.63
6	1.70	0.99	0.52	0.80	0.37	0.91	0.50	0.95	0.77	0.85
7	2.14	1.32	0.74	1.06	0.55	1.21	0.72	1.28	1.03	1.14
8	2.82	1.68	1.00	1.36	0.76	1.55	0.96	1.63	1.32	1.45
9	3.67	2.19	1.26	1.71	0.99	2.01	1.22	2.11	1.66	1.88
10	4.59	2.72	1.54	2.05	1.24	2.51	1.48	2.63	1.99	2.37
11	5.55	3.27	1.90	2.42	1.53	3.03	1.81	3.18	2.34	2.90
12	6.62	3.80	2.25	2.95	1.85	3.52	2.13	3.70	2.86	3.39
13	7.80	4.46	2.76	3.55	2.20	4.12	2.61	4.33	3.45	3.99
14	9.04	5.23	3.37	4.26	2.57	4.84	3.18	5.08	4.13	4.68
15	10.30	6.10	3.98	5.05	2.94	5.64	3.75	5.92	4.97	5.45
16	11.58	7.13	4.74	5.95	3.32	6.58	4.45	6.91	5.90	6.36
17	12.90	8.21	5.56	6.90	3.93	7.58	5.29	7.96	6.90	7.32
18	14.51	9.61	6.81	8.18	4.89	9.02	6.60	9.47	8.25	8.71
19	20.46	13.08	9.05	10.82	6.46	12.59	8.80	13.22	11.02	12.17

Table 5.9: Displacement results of UHPC slab (H0-6)

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	0.15	0.14	0.10	0.13	0.08	0.13	0.10	0.13	0.13	0.13
2	0.33	0.31	0.26	0.30	0.20	0.30	0.25	0.30	0.31	0.29
3	0.65	0.62	0.42	0.61	0.32	0.61	0.40	0.59	0.62	0.57
4	1.08	0.99	0.73	0.95	0.47	0.99	0.71	0.94	0.97	0.91
5	1.54	1.38	1.09	1.32	0.65	1.35	1.06	1.31	1.35	1.27
6	2.02	1.79	1.49	1.73	0.83	1.76	1.45	1.70	1.76	1.65
7	2.51	2.22	1.88	2.14	1.01	2.17	1.82	2.11	2.18	2.05
8	3.09	2.75	2.40	2.66	1.25	2.69	2.33	2.61	2.71	2.53
9	3.78	3.29	2.93	3.19	1.49	3.27	2.84	3.13	3.26	3.03
10	4.58	3.88	3.49	3.77	1.77	3.91	3.39	3.69	3.85	3.57
11	5.39	4.49	4.09	4.38	2.09	4.50	3.97	4.27	4.46	4.13
12	6.24	5.13	4.65	4.98	2.44	5.12	4.51	4.88	5.08	4.72
13	7.59	5.84	5.29	5.65	2.85	5.80	5.14	5.55	5.77	5.37
14	9.04	6.93	6.13	6.62	3.32	6.87	5.95	6.59	6.75	6.38
15	10.65	8.03	7.00	7.60	3.78	7.90	6.79	7.63	7.75	7.38
16	12.46	9.11	7.93	8.61	4.44	8.94	7.69	8.66	8.78	8.38
17	14.39	10.68	8.97	9.91	5.25	10.46	8.70	10.14	10.11	9.82
18	17.78	12.48	10.29	11.35	6.31	12.42	9.98	11.86	11.57	11.49
19	22.06	14.58	12.23	13.34	8.20	14.47	11.87	13.85	13.61	13.41

Table 5.10: Displacement results of NC slab

Drop No.	Cumulative Deflection (mm)									
	0	1	2	3	4	5	6	7	8	9
1	1.25	0.61	0.44	0.57	0.38	0.59	0.43	0.58	0.58	0.56
2	1.43	0.80	0.70	0.80	0.50	0.76	0.68	0.76	0.81	0.73
3	2.59	1.40	0.73	1.36	0.58	1.40	0.71	1.33	1.39	1.29
4	3.47	1.64	1.42	1.53	0.64	1.73	1.38	1.56	1.56	1.51
5	Collapse !									

5.2.1 Effect of fiber content

The effect of fiber content on impact energy is shown in Figure 5.1. The impact energy carrying capacity of slabs improved exponentially with increasing fiber content. There was an increment of 82% and 308% in impact energy capacity for slabs with 4% and 6% fiber content, respectively, in comparison to the slab with 2% fiber content. Similar observations have been reported by several researchers [18], [37], [73], [74]. This can be attributed to the fact that the fiber acts as a micro-reinforcement and slabs with higher percentages of steel fiber can undergo large deflections without disintegration. Therefore, a large amount of energy is dissipated in terms of work done by the slab, hence improving its impact energy carrying capacity. The relationship between impact energy and fiber content, obtained through the regression analysis, is as follows:

$$E = 748.5 e^{0.352(FC)} \quad (R^2 = 0.99) \quad (5.1)$$

where,

E = energy carrying capacity of slab (J)

FC = fiber content (% by mass)

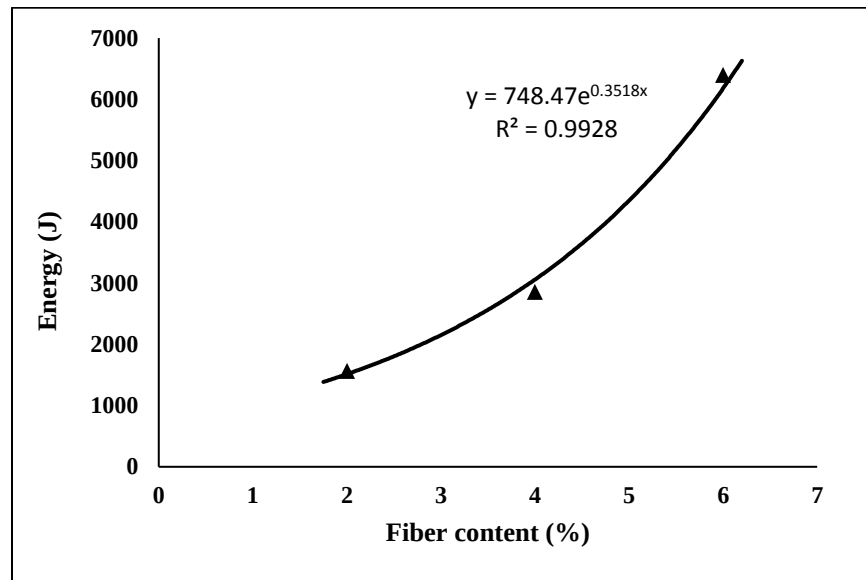


Figure 5.1: Effect of fiber content on impact energy of slab under impact loading

Figure 5.1, shows the central deflection of slabs due to impact loading with different fiber content.

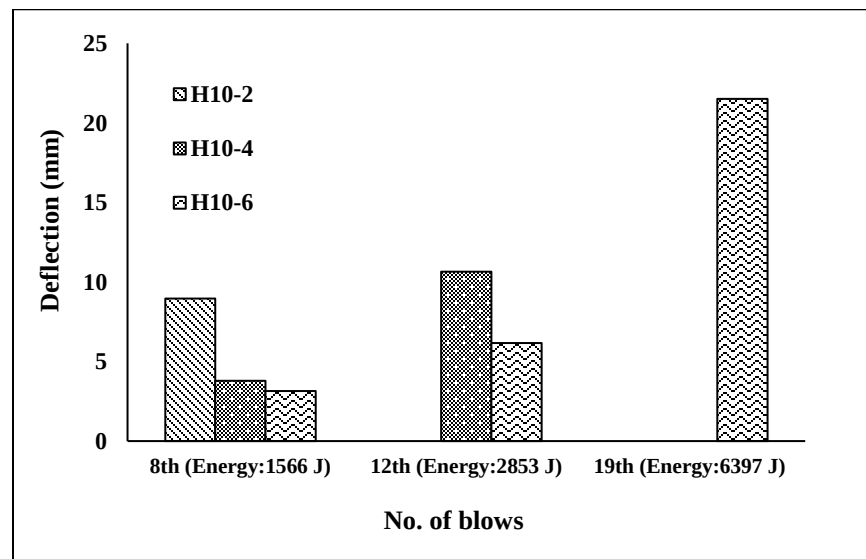


Figure 5.2: Effect of fiber content on central deflection of slab under impact loading

It is evident from Figure 5.2, that the mid-span deflection of the slab decreases with increasing fiber content for the similar no. of blows. For example, after 8th blow, the deflection in H10-2 was 8.95 mm against 3.78 mm for H10-4 and 3.14 mm for H10-6. The test was discontinued for slab H10-2 after 8th blow due to excessive damage. Similarly, after 12th blow, the central deflection in slab H10-4 was 10.65 mm, which was 73% more than the deflection of slab H10-6. Moreover, the test was discontinued for slab H10-4 after 12th blow due to excessive damage. Slab H10-6 was kept tested till the complete loading protocol. And a clear advantage in terms of central deflection without excessive failure was observed. The bottom surfaces of all the slabs are shown in Figure 5.3 for comparison.

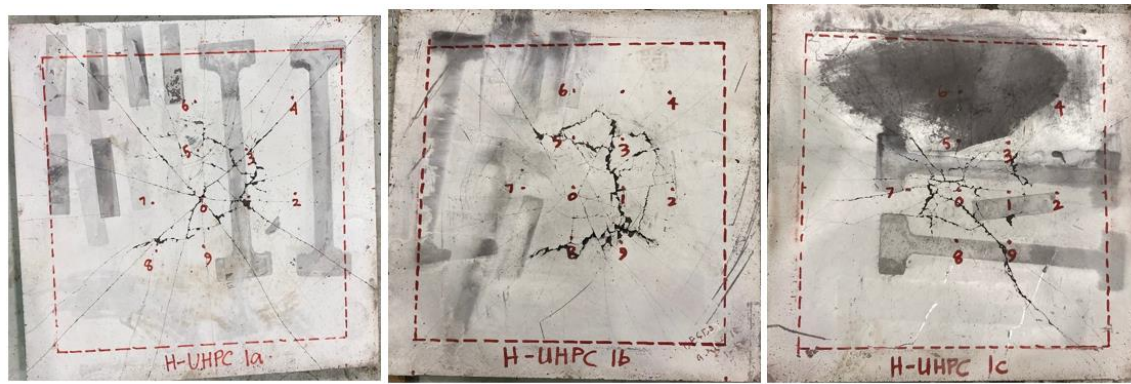


Figure 5.3: Bottom surfaces of the slabs after impact testing 2% fibers (left), 4% fibers (middle) and 6% fibers (right)

The deflection curves for the three slabs with different fiber content is shown in Figure 5.4. Furthermore, the relationships between the central deflection and impact energy were obtained through the regression analysis, at all three levels of fiber contents. For the slab with 2% fiber content, a linear relationship (Eq.5.2), was obtained between the deflection and impact energy with a very high regression coefficient ($R^2 = 0.99$), whereas, for the slabs with 4 and 6% fiber contents, polynomial functions (Eq.5.3 and Eq. 5.4, respectively) of order two, were found to be the best fit. The relationships are given as follows:

$$\Delta = 0.0055E + 0.1283 \quad (R^2 = 0.99) \quad (5.2)$$

$$\Delta = 9 \times 10^{-7} E^2 + 0.0009E - 0.02 \quad (R^2 = 0.97) \quad (5.3)$$

$$\Delta = 3 \times 10^{-7} E^2 + 0.0012E - 0.25 \quad (R^2 = 0.99) \quad (5.4)$$

where,

Δ = deflection under the impact load (mm)

E = energy carrying capacity of slab (J)

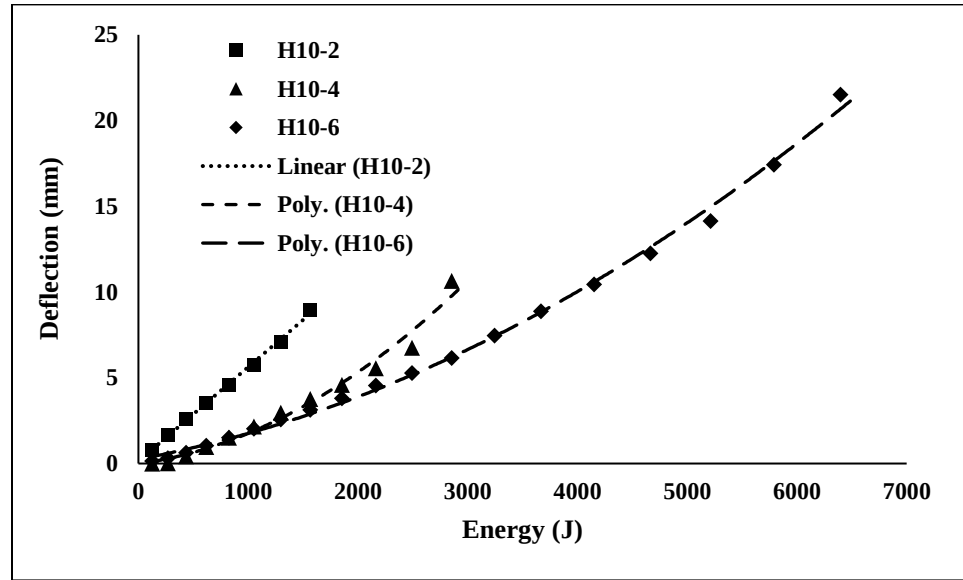


Figure 5.4: Deflection vs. energy for different fiber content

5.2.2 Effect of hematite powder replacement

All the slabs with 6% fiber content withstood the complete loading protocol. The complete deflection curves against impact energy are shown in Figure 5.5. It is evident from Figure 5.5, that the addition of hematite powder for increasing the dry density of conventional UHPC mixture, have no significant effect on the resistance against impact

loadings. The deflections sustained by the slabs with different HP content were very close and lies within the error bar range. Furthermore, the average deflection values of all the slabs with 6% fiber content were used to generate a correlation between deflection under impact load and impact energy. The values of average deflections are plotted in Figure 5.6.

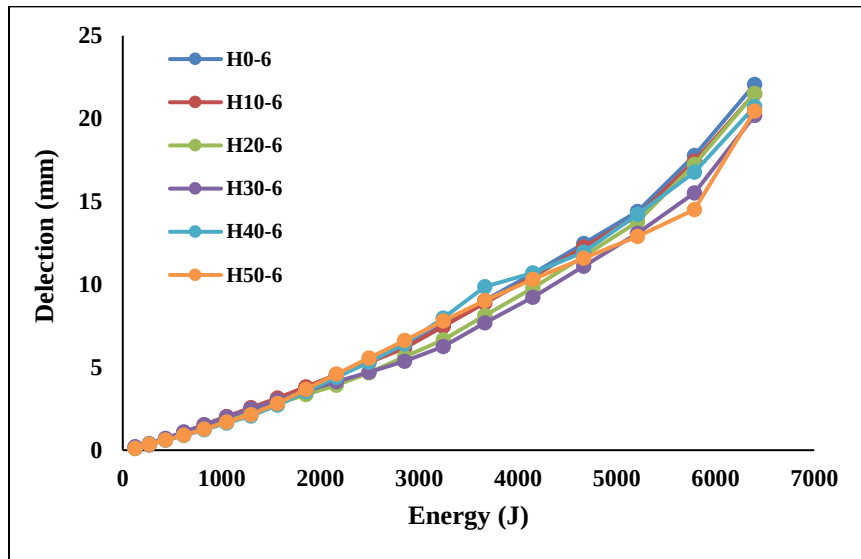


Figure 5.5: Deflection vs. impact energy for different HP content

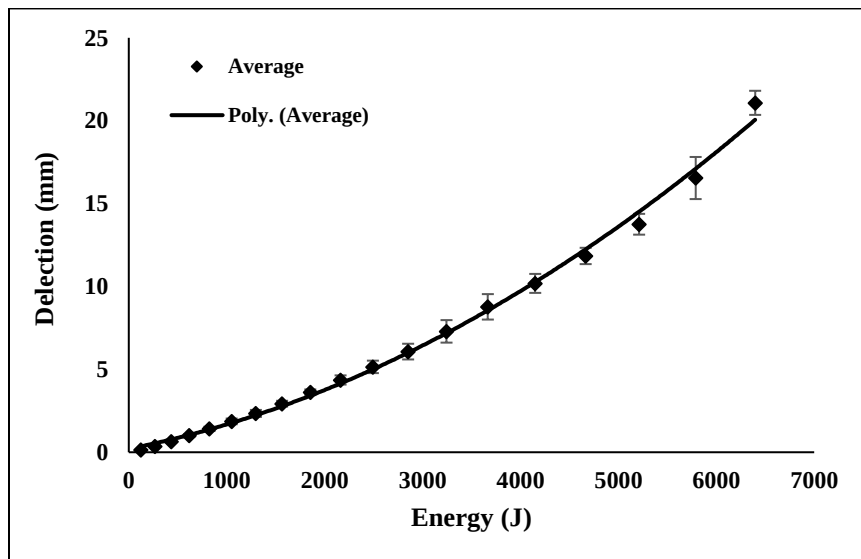


Figure 5.6: Average deflection vs. impact for all the slabs with 6% fiber content

The relationship between the deflection under the impact loading and impact energy, obtained through the regression analysis, is as follows:

$$\Delta = 3 \times 10^{-7} E^2 + 0.0012 E - 0.2 \quad (R^2 = 0.99) \quad (5.5)$$

where,

Δ = deflection under the impact load (mm)

E = energy carrying capacity of slab (J)

Therefore, it can be concluded that incorporation of hematite powder into the conventional UHPC did not impair its resistance towards impact loading.

5.2.3 Comparison of normal concrete with UHPC and HWUHPC

Normal concrete is inherently weak in tension and its limitations are exposed even more when subjected to impact loadings. Figure 5.7 and Figure 5.8 show the comparison of NC with UHPC and HWUHPC slabs with 6% fiber content, in terms of central deflection and impact energy respectively.

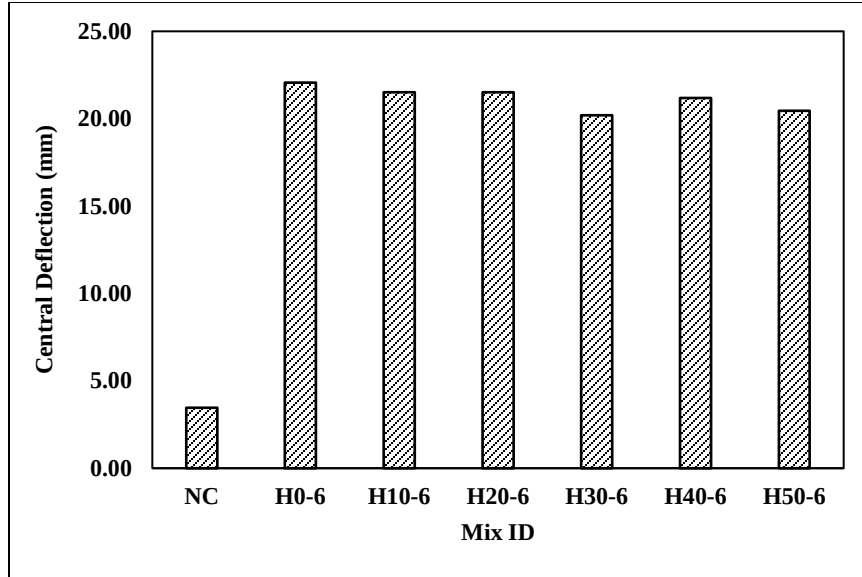


Figure 5.7: Comparison of final central deflection for NC and UHPC/HWUHPC slabs

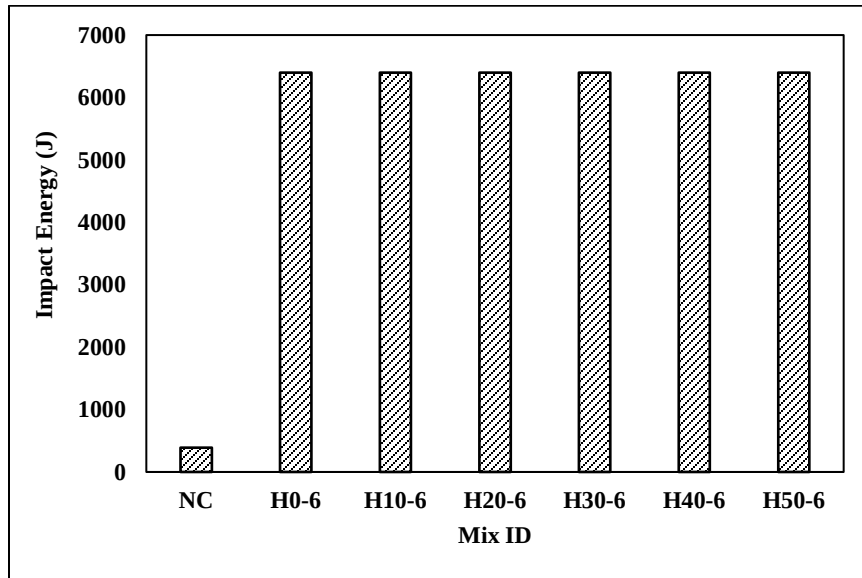


Figure 5.8: Comparison of impact energy for NC and UHPC/HWUHPC slabs

Picture speaks more than a thousand words! It is evident from Figure 5.7 and Figure 5.8, that normal concrete stands no chance against fiber concretes when it comes to the comparison of the performance under impact loading. On an average the concretes with 6% fiber content undergoes 6.5 times larger deflection and absorbs almost 16.5 times more

impact energy. Moreover, the impactor penetrated through the NC slab as shown in Figure 5.9, whereas all other slabs held on their self against impact loading.



Figure 5.9: The impactor penetrates through the normal concrete slab

5.3 Finite element modeling of slabs subjected to low-velocity impact loading

The finite element modeling is carried out using ABAQUS[®]/Explicit, version 6.14 [52]. Concrete Damage Plasticity (CDP) model is used to define the complete behavior of both UHPC and HWUHPC materials. CDP was initially introduced for monotonic loading by Lubliner et al. [50]. Afterwards, Lee and Fenves [51] adopted it for cyclic and dynamic loadings. The complete mathematical formulation of CDP can be found in [50]–[52]. CDP can be used to model various types of concrete, by inputting the experimentally measured parameters. These parameters are well defined for normal concrete but the performance of UHPC is a topic of research.

The input parameters of UHPC and HWUHPC are defined using macro-level mechanical properties, based on the assumption that the steel fibers are uniformly distributed. In CPD both elastic and non-linear properties are defined. The elastic properties were obtained from the experimental results of modulus of elasticity and Poisson's Ratio of 0.2. The non-linear parameters were also extracted from the experimental curves obtained from modulus of elasticity test and dog-bone test for uniaxial direct tension. The stiffness degradation is accounted in CDP by defining two scalar parameters; compression damage (d_c) and tensile damage (d_t). These damage parameters are the function of plastic strains. The value of the damage parameters ranges from 0 to 1. The value of 1 means complete damage. The complete procedure for the calculation of compression damage parameters is given by Birtel & Mark [75] and for tension damage parameters by Wahalathantri et al. [76].

Following four parameters are required in CDP to fully describe the yield surface and the flow rule:

- Dilation angle (φ)
- Plastic flow potential eccentricity (ϵ)
- Ratio of biaxial to uniaxial compressive strengths (σ_b / σ_o)
- Shape factor (K_c)

The values of these parameters are obtained from the literature [77] and shown in Table 5.11.

Table 5.11: CDP parameters for FEM

Dilation angle (φ)	eccentricity (ϵ)	σ_b / σ_o	K_c
36	0.1	1.16	0.667

5.3.1 Model preparation and meshing

A mesh size of 6.25 mm (8 element across the depth of 50 mm) was used after performing the mesh convergence as shown in Figure 5.10. The time step for the explicit analysis is approximately 2 microseconds estimated automatically by ABAQUS/Explicit. The “restart analysis” option is implemented to model multi-impacts by defining the new impact velocity of the drop weight and using the material properties from the termination point of previous analysis step.

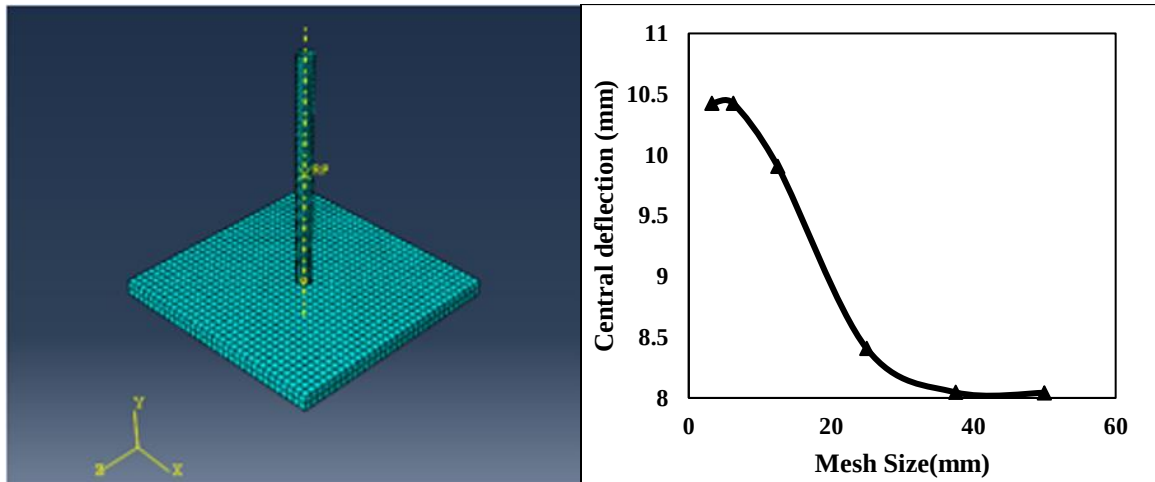


Figure 5.10: FEM model (left), mesh convergence of slab (right)

5.3.2 Comparison of experimental and numerical results

A good agreement was found between the experimental results and numerical results obtained from FEM. The comparison of mid-span deflection of slab between experimental

and FEM results, for the slabs with different fiber content, is shown in Figure 5.12. Similarly, the comparison of experimental and numerical results for the slabs with different hematite powder content is shown in Figure 5.12. It is evident from Figure 5.11 and Figure 5.12, that concrete damage plasticity model, can be used effectively to model the behavior of UHPC slabs subjected to impact loading.

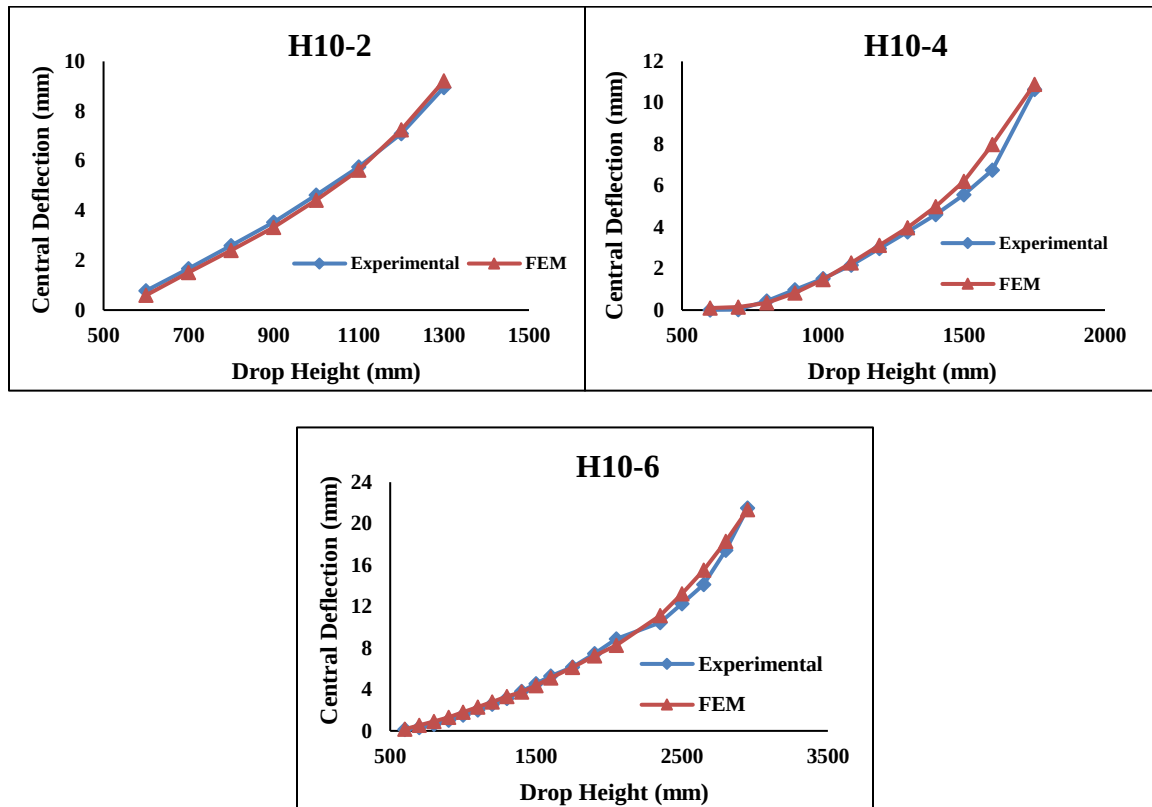


Figure 5.11: Comparison between experimental and FEM results of deflection at mid-span for slabs with different fiber content

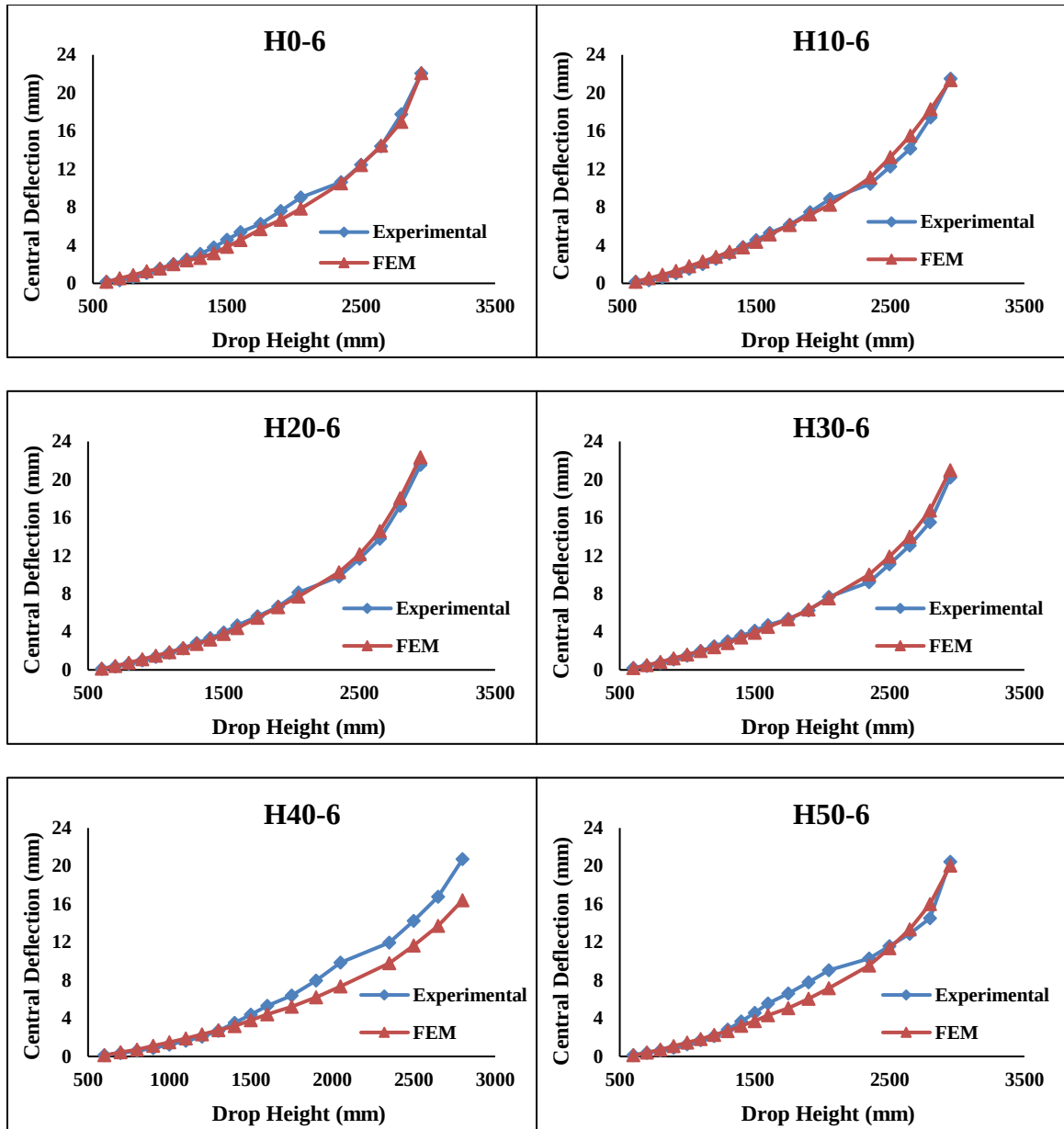


Figure 5.12: Comparison between experimental and FEM results of deflection at mid-span for slabs with different HP content

Similarly, the FEM was successfully able to capture the crack pattern and damage evolution of the experimental test results as shown in Figure 5.13.

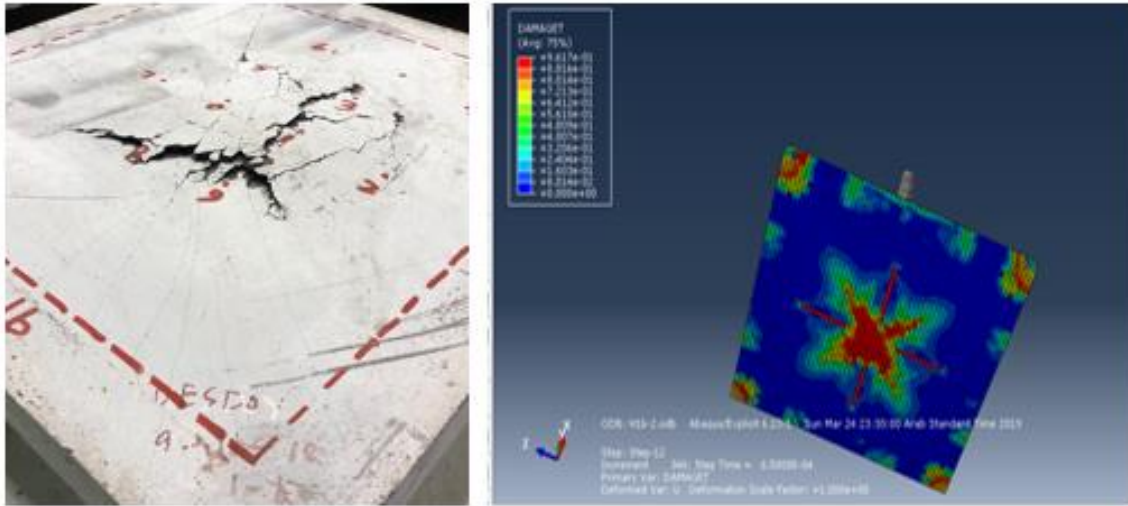


Figure 5.13: Comparison of crack pattern and damage between experimental and FEM results

CHAPTER 6

PERFORMANCE OF HWUHPC AGAINST NUCLEAR

RADIATION

In the past, accidents (natural or manmade) have been witnessed in special structures, such as, in nuclear power plants leading to catastrophic effects. Recently, in 2011, Fukushima nuclear accident occurred in Japan due to Tsunami waves, which were generated by the massive earthquake. Initially, two explosions occurred in the outer containment buildings enclosing reactors 1 and 3 on March 12 and March 14, 2011, respectively resulting from the buildup of pressurized hydrogen gas. Following this accident, some 47,000 residents left their homes, many people in areas adjacent to the 20-km evacuation warning zone also prepared to leave.

Since the heavy weight ultra high performance concrete mixtures were developed in the current study, an opportunity was taken to study their behavior against radiation shielding. The outcomes of the present study would be very useful for optimal design of the mixtures of HWUHPC for meeting the structural as well as radiation shielding requirements of the special structures, for example, for structural members of a nuclear power plant where the structural members are susceptible to both, accidental loads and nuclear radiation. In this chapter, results and discussions are presented about the performance of HWUHPC against radiation shielding.

6.1 Gamma radiation shielding

The radiation shielding resistance of all six mixtures of concrete were measured in terms of attenuated gamma ray spectra (I_x) and attenuation coefficients (μ). It was observed that the gamma ray attenuation ability of concrete is directly proportional to the dry density of concrete. The results of radiation shielding are given in Table 6.1, and the gamma-ray intensity spectra of all mixtures along with the unattenuated spectra of ^{137}Cs gamma-ray source, are given in Figure 6.1.

Table 6.1: Net counts and attenuation coefficients of all concrete mixtures

$I_o = 44627$				
Mixture ID	Dry density (kg/m ³)	I_x	μt	μ (mm ⁻¹)
H0-6	2489	6890	1.87	0.0187
H10-6	2589	6161	1.98	0.0198
H20-6	2676	5978	2.01	0.0201
H30-6	2748	5776	2.04	0.0204
H40-6	2815	5312	2.13	0.0213
H50-6	2891	4898	2.2	0.022

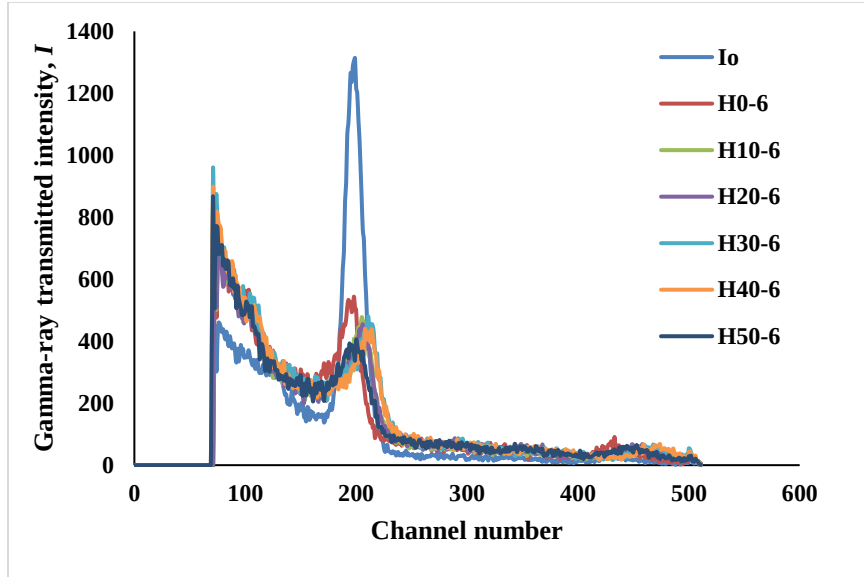


Figure 6.1: Gamma-ray spectrum of all mixtures

It can be observed from Table 6.1, that the net count (I_x) of concrete decreases and attenuation coefficient increases with increasing dry density. Similarly, it can be observed from Figure 6.1, that the highest peak of gamma-ray intensity was attained in the absence of concrete sample. The radiations were passing unattenuated through air only. However, as soon as the concrete sample was placed between the source and the detector, the attenuation of gamma radiation increased, and the peak came down significantly. Furthermore, as the dry density of the mixture increases, the peak shifts downwards, emphasizing the fact that as the dry density of the mixture increases, its attenuation/shielding ability improves.

The variation in net count values (I_x), ratio of gamma-ray transmittance (I_x/I_0) and the attenuation coefficients obtained through the procedure provided in section 3.7.8, are plotted in Figure 6.2 to Figure 6.4, respectively.

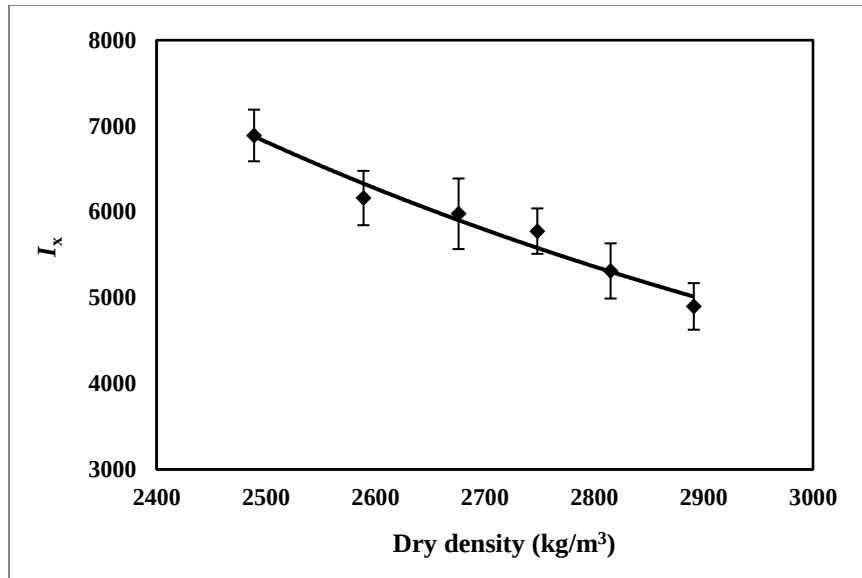


Figure 6.2: Variation in net counts with dry density

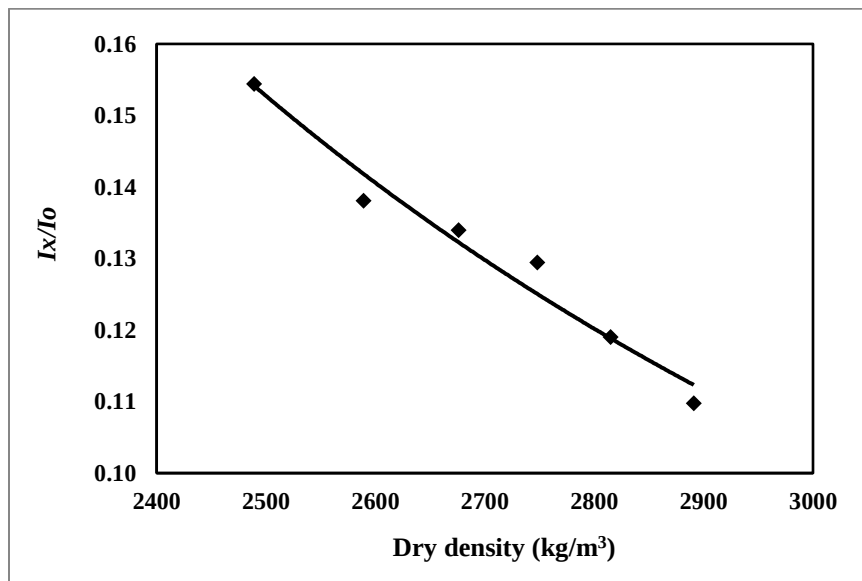


Figure 6.3: Variation in gamma-ray transmittance with dry density

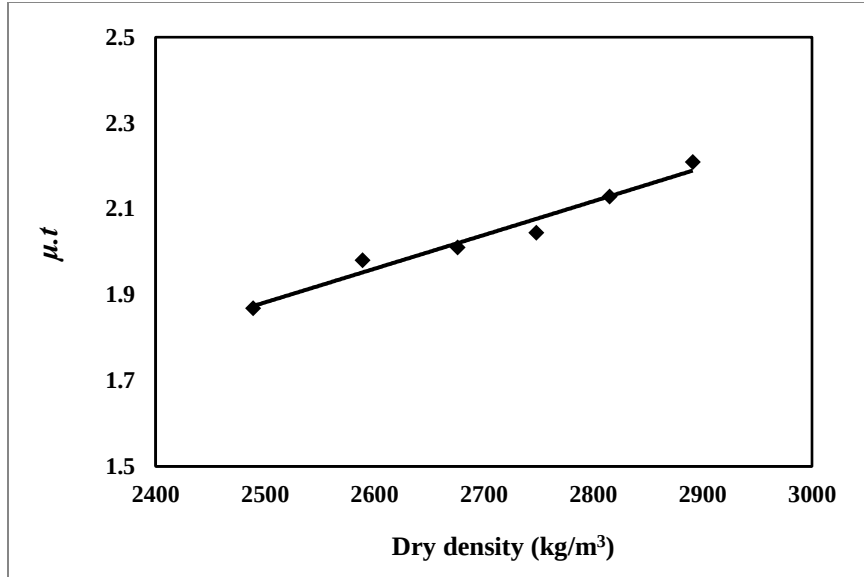


Figure 6.4: Variation in attenuation coefficient with dry density

A good correlation was obtained from Figure 6.3, between the dry density and gamma-ray transmittance ratio. An empirical equation (Eq. 6.2), obtained through the regression analysis of the unit weight versus I_x/I_o ratio data, can be used to calculate the I_x/I_o ratio (its lower value indicative of the higher radiation shielding) by substituting the unit weight of concrete.

$$\frac{I_x}{I_o} = \frac{2 \times 10^6}{W_c^{2.115}} \quad (R^2 = 0.96) \quad (6.1)$$

where,

I_x/I_o = ratio of attenuated to un-attenuated gamma-ray transmittance intensities

W_c = dry density of the concrete mixture (kg/m³)

6.1.1 Required thickness of concrete mixtures for a targeted level of radiation shielding

Table 6.2 presents the minimum thicknesses required for all concrete mixtures to attenuate 99% of gamma radiations. These thicknesses were calculated by solving equation given by L'Annunziata [69] in section 3.7.8, for $I_x / I_o = 0.01$ (radiation shielding of 99 %). The variation of the required thickness with the dry density is shown in

Table 6.2: Required thicknesses for 99% radiation shielding for all mixtures

Mixture ID	Required thickness, t (mm)
H0-6	247
H10-6	233
H20-6	229
H30-6	225
H40-6	216
H50-6	208

A good correlation was obtained from Figure 6.5, between the dry density and required thickness of concrete structure for 99 % radiation shielding. An empirical equation (Eq. 6.2), obtained through the regression analysis of the unit weight versus required thickness data, can be used to determine the optimum thickness by substituting the unit weight of concrete.

$$t_r = \frac{838868}{W_c^{1.04}} \quad (R^2 = 0.97) \quad (6.2)$$

where,

t_r = ratio of attenuated to un-attenuated gamma-ray transmittance intensities

W_c = dry density of the concrete mixture (kg/m^3)

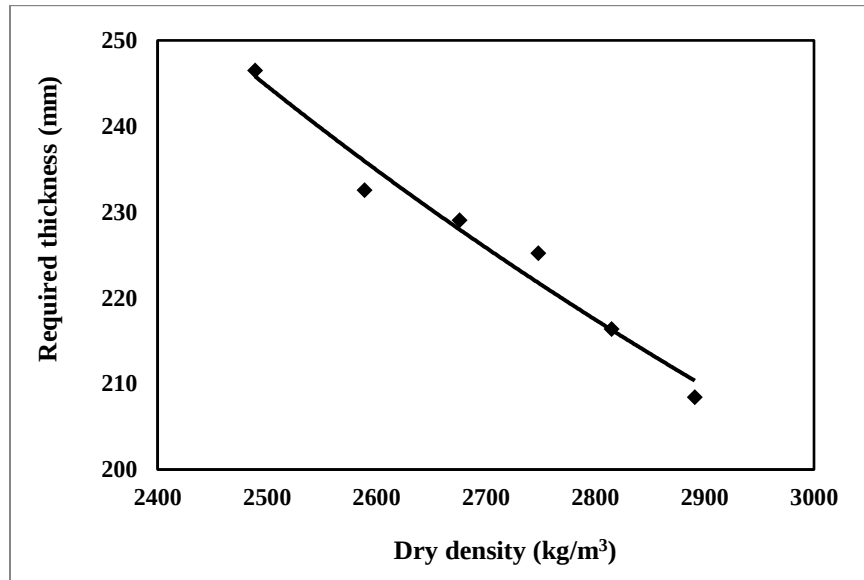


Figure 6.5: Variation of the required thickness for 99% radiation shielding, with the dry density

6.1.2 Comparison of radiation shielding of UHPC/HWUHPC and HW normal concrete

One of the main objectives of this research was to develop a concrete mix which is equally good in both mechanical/toughness properties and radiation shielding for the potential use in applications such as nuclear power plants. For this reason, hematite powder was added as a replacement of sand in conventional UHPC to increase its dry density. The newly developed HWUHPC showed excellent characteristics in the mechanical properties. And the mechanical properties of UHPC were not impaired but enhanced to a little extent by the addition of hematite powder. Moreover, the radiation shielding ability of the

HWUHPC increased with increasing the hematite powder dosage. There are very few studies reported in the area of radiation shielding of HWUHPC, however, similar findings have been reported in the limited available literature [33] [59] [60].

Oluwaseun et al. [78], developed heavy weight normal concrete (HWNC) mixtures with densities from 2600 to 3500 kg/m³ by incorporating high density coarse aggregates. They reported a correlation to determine the required thickness for 99% radiation shielding. The superior mechanical properties of UHPC are well reported in the literature. Therefore, an attempt has been made to compare the radiation shielding ability of HWNC and HWUHPC to see the effectiveness of HWUHPC in terms of radiation shielding. In order to make a fair comparison, the required thicknesses are plotted from 2600 to 3000 kg/m³, because in the current study, the maximum dry density achieved for HWUHPC is about 2900 kg/m³. The values of required thicknesses to obtain 99% radiation shielding for HWNC and HWUPC are provided in Table 6.3 and plotted in Figure 6.6.

Table 6.3: Required thicknesses for 99 % radiation shielding

Dry density (kg/m³)	t, HWUHPC (mm)	t, HWNC (mm)	t, HWUHPC / t, HWNC
2600	220	365	0.60
2700	211	344	0.61
2800	203	325	0.63
2900	196	308	0.64
3000	189	292	0.65

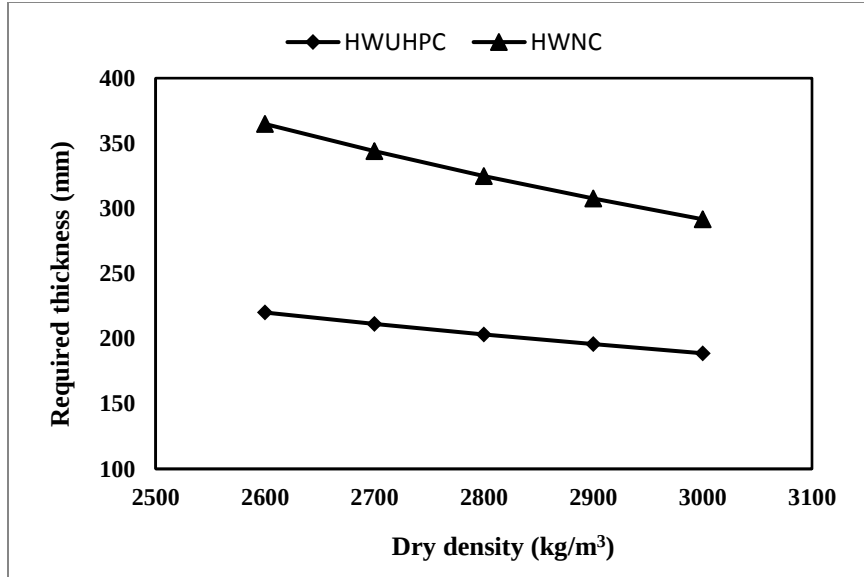


Figure 6.6: Comparison of required thicknesses for HWUHPC and HWNC

It is evident from Table 6.3 and Figure 6.6, that HWUHPC outperformed HWNC in radiation shielding. The required thickness of HWUHPC for 99 % radiation shielding is on an average 40% less than HWNC. This can be attributed to the fact, that HWUHPC has very dense microstructure. The particle size of HP (Table 3.2) is extremely fine, which fills minute pores in the concrete matrix and provide a very dense microstructure. Gencel et al. [55] and Zhen et al. [56] have concluded that, the shielding properties of the concrete can be improved by utilizing suitable materials (heavy aggregates comprising of higher atomic number) and densifying the concrete matrix by reducing the number and sizes of pores. The filler materials fill the voids in the concrete due to the fineness, and enhances the interaction between radiations and absorbent materials due to high specific surface area [56]. Therefore, it may be concluded that the same level of radiation shielding can be attained by HWUHPC by 40 % less thickness required by HWNC. This will lead to remarkable reduction in dead load of the structure and the foundation design of the structure will be more economical. It may also be noted, that the mechanical properties of

HWNC's are just comparable to normal concrete. However, the mechanical properties of HWUHPC are way more superior than normal concrete and HWNC for the matter of fact. Therefore, with even almost 40 % less thickness of HWUHPC (which will provide equal radiation shielding as HWNC), the superior mechanical properties of HWUHPC can easily satisfy the structural requirements.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this research work HWUHPC mixtures were successfully developed by partially replacing sand with ultra-fine and heavy material (hematite powder). Based on the analysis of the experimental data pertaining to mechanical and radiation shielding properties of HWUHPC, following conclusions are drawn:

1. All HWUHPC mixtures, produced by partially replacing the sand with hematite powder in the dosages ranging from 10 to 50 %, fulfilled the flow requirement and attained the dry densities in the range of about 2600–2900 kg/m³ meeting the requirements of a heavy-weight concrete. The dry density increased linearly with the hematite powder content and a correlation equation was obtained with a very high degree of fit. This equation can be effectively utilized to obtain the hematite content needed to achieve the targeted dry density of HWUHPC based on the requirements, for example, desirable degree of radiation shielding, in case the HWUHPC mixture is to be used in the structural elements of a nuclear installation.
2. The fiber content had significant effect on the mechanical properties of the UHPC and HWUHPC mixtures in the following decreasing order: fracture toughness, flexural strength, compressive strength, and modulus of elasticity. Since the fiber content showed diminishing positive effect of the fiber on strength and elasticity

when the fiber content was increased from 4 to 6%, the optimum fiber content was taken as 6%.

3. The hematite powder had two positive effects in developing the HWUHPC mixtures. Firstly, it increased the dry density of the mixtures due to its high specific gravity (about two times more than that of sand). Secondly, due to its ultra-fine particle size (about 30 times smaller than that of OPC), it heavily densified the micro-structure of the concrete matrix as evident from the morphological investigations using FESEM.
4. Since the hematite powder mainly contained Fe_2O_3 , it had no adverse effect on the hydration of cementitious materials as evident from the results of EDS analysis. The XRD results also indicates that the hematite powder is present in the concrete matrix in its mineralogical form and acted as an inert material. Therefore, the incorporation of hematite powder had no adverse effect on the mechanical properties of HWUHPC. Rather it slightly improved the mechanical properties due to its pore filling/ densifying effect.
5. There was an increase of 82% and 308% in impact energy capacity for slabs with 4% and 6% fiber content respectively compared to the slabs with 2% fiber content
6. Both UHPC and HWUHPC have far superior properties than normal concrete in mechanical strength and impact resistance
7. Good agreement was found between the experimental observations and numerical modeling (FEM) results and concrete damage plasticity model can effectively simulate the both UHPC and HWUHPC mixes

8. As expected, it was observed through the analysis of the experimental data that the radiation shielding increased with increase in the dry density of the HWUHPC mixtures. However, an important observation made through this study is worth noting. That is, at a same dry density, the radiation shielding of the HWUHPC mixtures was found to be around 40% higher as compared to that of the heavy-weight conventional concrete, indicating that the denseness of the microstructure also improves the radiation shielding besides the dry density of concrete, which has not been reported yet in context to the HWUHPC.
9. Empirical correlations between the dry density of the HWUHPC and different indicators of the radiation shielding were obtained through regression analysis utilizing the experimental data.
10. HWUHPC mixtures performed best in all the aspects. They showed excellent strength and elasticity, better impact resistance and fracture toughness, and radiation shielding. Therefore, they are suitable materials in special applications such as nuclear power plants.

7.2 Recommendations

Following recommendations are made for incorporation in future works:

1. Long term durability studies should be performed to see the effectiveness of HWUHPC
2. Effects of thickness of slab and percentages of longitudinal steel can be studied for impact loading

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